

Seals Flow Code Development

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*Proceedings of a workshop held at
NASA Lewis Research Center
Cleveland, Ohio
March 26, 1991*

NASA

NASA Conference Publication 10070

Seals Flow Code Development

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NASA Lewis Research Center
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March 26, 1991*

NASA

National Aeronautics and
Space Administration

Office of Management

**Scientific and Technical
Information Program**

1991

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SUMMARY

In recognition of a deficiency in the current modeling capability for seals, a seven-year effort was established in 1990 by NASA's Office of Aeronautics, Exploration, and Technology under the Earth-to-Orbit Propulsion program of the Civilian Space Technology Initiative to develop verified computational-fluid-dynamic (CFD) concepts, codes, and analyses for seals.

The objectives were to develop advanced concepts for the design and analysis of seals, to effectively disseminate the information to potential users by way of annual workshops, and to provide experimental verification for the models and codes under a wide range of operating conditions. The prime contractor for this effort is Mechanical Technology Incorporated (MTI); the subcontractor is CFD Research Corporation (CFDRC).

The first annual workshop on "Seals Flow Code Development" was conducted at the NASA Lewis Research Center in Cleveland, Ohio, on March 26, 1991. The purpose was to report the progress of this program and to provide a forum for information exchange with the potential end-users. The program accomplishments were presented; discussions were held on the accomplishments and the plans versus the objectives of this program. Workshop participants presented the activities of their respective organizations in the area of seals CFD.

Close to seventy technical managers and designers attended the 1991 seals workshop, including representatives from rocket engine companies, gas turbine companies, seals manufacturers, government agencies, consulting firms and academia. A peer review panel was formed prior to this workshop, representing experts from the user community who are knowledgeable in CFD analysis methods, seal designs, rotordynamics, and/or knowledge-based systems. The function of the peer review panel was to provide recommendations and guidance throughout the program.

The presented material is documented in this NASA Proceedings. The workshop agenda is included in Appendix A; the workshop attendance list is in Appendix B. The scope of the program and the discussions held at the workshop are summarized below.

KNOWLEDGE-BASED SYSTEM ARCHITECTURE

The approach to this program is to develop a knowledge-based system (KBS) for the design and analysis of seals. It involves two major activities: the development of codes for different seal types, and the integration of the various seals and analysis modules into the KBS framework.

The KBS contains and provides the linkage between two interdependent master seal codes: the industrial KBS code and the scientific KBS code. The industrial version is intended to accomplish expeditious analysis, design and optimization of seals; the scientific version is intended to enhance understanding of flow phenomena and mechanisms, to predict performance, to contribute design guidance for complex situations, and to furnish accuracy standards for less sophisticated analyses. Examples of seal types that will be included in the KBS are bushing and ring seals, face seals, labyrinth

seals, tip seals, damping seals, brush seals, electro-fluids seals and "smart" seals.

A master supervisory module (the System Supervisor) in the knowledge-based system provides the integration between the scientific and industrial codes. The interdependence between the two codes is also accomplished by a common database and knowledge-based system utilities, and by using the scientific version as the model which can be used to validate the industrial codes and establish their limits of applicability.

SYSTEM REQUIREMENTS

The hardware and software requirements of the knowledge-based system are dictated by its architectural design. The general objective is to accommodate the various features of the KBS, including seal type and analysis selections, optional program linkage for direct user selection, input modules, output post-processing, design guidance and optimization, and data management. The hardware is required to have sufficient computing capability for these features.

In addition, the system has to include the flexibility for integration, expansion and user access. It has to be designed for future users, anticipating the trends in computer hardware and software development.

The prime contractor, MTI, has devoted a significant effort in the first year of this program to formulate the architecture, define the features and develop the requirements for the system. The approach and the proposed hardware/software configuration were presented and discussed at the 1991 "Seals Flow Code Development" workshop by Dr. Bharat Aggarwal.

The hardware requirements are driven by the need for a graphical user interface as well as by the computational requirements of the scientific codes. The hardware is envisioned to be a desk-top computer or workstation, easily accessible, that will have sufficient memory space for executing the industrial software modules, individually or in a multitasking mode. It will have the capability to allow input/output communications with the scientific codes and to provide the computing power for the use of graphical user interfaces.

The primary hardware options that have been identified are high performance IBM PC compatible computers and Unix-based workstations. The options for a software development environment include: 1. MS-DOS Window 3.0, 2. OS/2 Presentation Manager, and 3. Unix with OSF/Motif Graphical Interface.

The OS/2 Presentation Manager environment has been recommended for software development in this program. This environment, like Unix, offers a powerful operating system and, like Window 3.0, is reasonably priced. The IBM PC compatible high performance computer has been selected as the hardware platform because it has a large installed base with the availability of innovative software development tools. The proposed hardware configuration includes the computer with a minimum of 6 megabyte RAM and 120 megabyte hard disc, Intel 80386 or 80486 processor, and a math coprocessor included for 80386 machines.

Unix-workstation users expressed their concerns about the PC-based choice and the OS/2 operating system as most of the high-technology users are in the process of converting to Unix workstations. The primary issue is whether the selected operating system can be portable across a PC-based computer and a workstation. A second issue is that, if the operating system is to accommodate multiple hardware platforms, similar criterion shall apply to the selection of the software development tools that are going to be used in the operating system.

The requirements and selection criteria that have been developed for the knowledge-based system, as presented at the workshop, provided the basis for the selection of a final system. Based on discussions and feedback from workshop participants, the final selection needs to ensure that it will have the flexibility to satisfy the means of all potential end-users. The program needs to address a wide spectrum of users, from the low-end technology users who do not have the mainframe capability, to the high-technology users who have access to a number of computer systems with unlimited computing power in the network. In addition, the knowledge-based system needs to be modular so that the users can acquire one or multiple modules from either version of the KBS and are able to execute the programs from a computer of their choice.

SEALS CODE DEMONSTRATION

Dr. Bharat Aggarwal, Dr. Antonio Artiles and Mr. Wilbur Shapiro of MTI demonstrated the capability of three industrial codes on a 386 computer. The demonstration also included the knowledge-based system (KBS) executive program and the graphical data display capability using current MS-DOS programs. The graphical capability will be ported to OS/2 and made an integral part of the KBS executive program (if OS/2 becomes the choice of operating system for software development).

The three codes demonstrated are for spiral-groove gas seals (SPIRALG), for gas cylindrical seals (GCYL), and for incompressible seals (ICYL). They are modified versions of existing industrial codes. Each code has been implemented on the KBS. The implementation of the code involves the development of the user interface for the knowledge-based system shell (or the executive program for the industrial version of the KBS).

CFD CODE DEVELOPMENT

Dr. Andrzej Przekwas of CFD Research Corporation reported the progress of the 3D CFD code for cylindrical seals and the proposed integration of this code into the KBS framework. The aim is to develop a 3D CFD code for the analysis of fluid flow in cylindrical seals and evaluation of the dynamic forces on the seals.

The plans to complete the 3D CFD code for cylindrical seals include modifications to the 3D base code, and incorporation into the 3D code of the physical models to treat turbulence, non-isotropic wall roughness, phase-change and cavitation, a brush-seal model, and the calculation of dynamic coefficients. This code will be demonstrated at the 1992 workshop.

Workshop participants expressed concerns about the users access to the CFD scientific codes. The CFD codes are computation-intensive. They can be best

executed on a large capacity computer and/or through a network, with input and output communications provided from a desk-top system. Currently, the 3D CFD code is being developed on an Alliant FX-8 computer with 256 megabytes of capacity. The approach is to eventually install the codes on the Cray and provide the necessary linkage between the Cray and the desk-top system. The connection could be local, in the case of high-technology users, or remote, e.g. via a modem or through a network. The procedure for CFD code integration and access will be presented at the 1992 workshop.

INDUSTRIAL INTERESTS

One of the purposes of the annual workshops is to provide interaction between the user community and the code developers, thereby promoting the seal models for practical applications. Close to twenty workshop participants presented seals-related work in their organizations. Other participants expressed interest in supplying test data for code verification and evaluation. Industrial support for this effort was evident and will be pursued as an integral part of this program.

Several major activities are currently in progress in the community in the area of brush seals. The advantage of the brush seal is its potential to reduce leakage. They are being investigated for rocket engine turbopumps, for small engine seals in the air flow systems, and for gas turbine engine applications. Test data are being collected for each application to study the parameters affecting the performance of brush seals. These data can potentially be used to evaluate the brush seal models that will soon be developed in this program.

The industry is continuously interested in the use of the traditional shaft and face seals. Load models and analytical tools are under development for these configurations to improve their performance. Suggestions were made by workshop participants to obtain the analysis of alternate groove patterns to spiral grooves on face seals, to include mechanical face seals, to evaluate the carbon face seal, and to provide means for predicting seal performance in two-phase flow conditions. Buffered seals, rim seals, advanced counter rotating/ultra high pressure noncontacting seals, and gas seals for 3600 rpm range were also among those recommended by workshop participants to be included in model evaluation.

One of the key items on the agenda for the 1992 workshop will be the issue of technology transfer. The users are anxious to acquire the codes that are developed in this program, and exercise them on their own designs and problems. Prompt technology transfer will provide benefits to the program in two ways: 1. the codes will be evaluated by actual test data over practical operating conditions and become more valuable, and 2. the users will have enhanced analytical capabilities and develop confidence in these codes for the analysis and design of seals.

Typically, NASA sponsored software tools are released via COSMIC, the Computer Software Management and Information Center operated by the University of Georgia for the Technology Utilization Office. In this program, the same mechanism will be used for the final release of the completed codes. In the interim, a technology transfer plan will be developed prior to the 1992 workshop to define a transfer-and-feedback mechanism for these codes so that

they can be released promptly to the user community for evaluation and verification prior to final delivery to COSMIC. The codes developed under this program are targeted for a wide user community. Through an effective technology transfer mechanism, they can be calibrated and become useful tools for commercial use.

Anita D. Liang
Workshop Chairman

INTRODUCTION

Anita D. Liang
NASA Lewis Research Center

NASA Contract NAS3-25644, "Numerical/Analytical/Experimental Study of Fluid Dynamic Forces in Seals", was initiated in 1990 by the NASA Lewis Research Center. It is a seven year program; the Mechanical Technology, Inc. (MTI) is the prime contractor and CFDRS is the subcontractor. Annual workshops are included as part of the program to provide the interaction between the user community and the contract team, and to disseminate the codes that are developed in this program to the potential end-users.

An introduction is made at the beginning of the first annual "Seals Flow Code Development" workshop to give the participants an overall description of the program. The program scope, the deliverables, the first-year accomplishments and the near term plans are presented.

- **Description of Contract, NAS3-25644
Numerical/Analytical/Experimental Study
of Fluid Dynamic Forces in Seals**
- **Program Status, Accomplishments and Plans**
- **Workshop Objective**

TEAM MEMBERS

NASA LeRC

Bob Hendricks

Anita Liang

Margaret Proctor

Julie Schlumberger

MTI

Bharat Aggarwal

Tony Artiles

Wilbur Shapiro

CFDRC

Mahesh Athavale

Andrzej Przekwas

Ashok Singhal

**PROGRAM OBJECTIVE - Develop Codes for Analyzing and Designing
Optimized Advanced Seals for Future Aerospace
and Advanced Rocket Engine Systems**

- **DEVELOP 3-D CFD SCIENTIFIC CODES**
- **COMPILE AND GENERATE SETS OF VERIFIED 2-D INDUSTRIAL CODES**
- **GENERATE A KNOWLEDGE BASED SYSTEM (KBS) TO BE COUPLED TO THE CODES**

PROGRAM OUTLINE

- SEVEN YEAR EFFORT
- PARALLEL PATHS
 - SCIENTIFIC CODE WILL CONTRIBUTE TO TECHNICAL DATA BASE AND PROVIDE AN ACCURACY STANDARD FOR LESS COMPLEX CODES
 - INDUSTRIAL CODES WILL PROVIDE SPEEDY ANALYSIS OF SEAL DESIGNS
- KBS IS UNIFYING MECHANISM
- TECHNOLOGY TRANSFER WILL BE ACCOMPLISHED VIA WORKSHOPS
- PROGRAM WORKPLAN WILL BE REVIEWED AND REVISED ANNUALLY

PROGRAM SCHEDULE

Description	1990	1991	1992	1993	1994	1995	1996
Task I Cylindrical Seals CFD Code	[Bar]						
Task II Cylindrical Code Augmentation			[Bar]				
Task III Face, Wave, & Grooved Seals					[Bar]		
Task IV Tip Contact & Non-continuous seals							[Bar]
Task V Code Verification and Design	[Bar]				[Bar]		
Task VI Design Optimiza- tion of KBS Seals					[Bar]		
Task VII Turbomachinery Test Data Feedback						[Bar]	
Task VIII Development of KBS Code (Scientific)							[Bar]
Task IX Development of KBS Code (Industrial)	[Bar]						
Task X Reports & Workshops	[Bar]						

COMMON SCOPE OF CODE DEVELOPMENT TASKS
(TASKS I THROUGH IV, AND TASK IX)

- LITERATURE SURVEY
- CODE FORMULATION
- OUTLINE FOR KBS INTEGRATION
- PROGRAMMING AND CODING
- VERIFICATION OF THE NUMERICAL ANALYSIS
- CODE DOCUMENTATION
- CODE INSTALLATION AND TECHNOLOGY TRANSFER

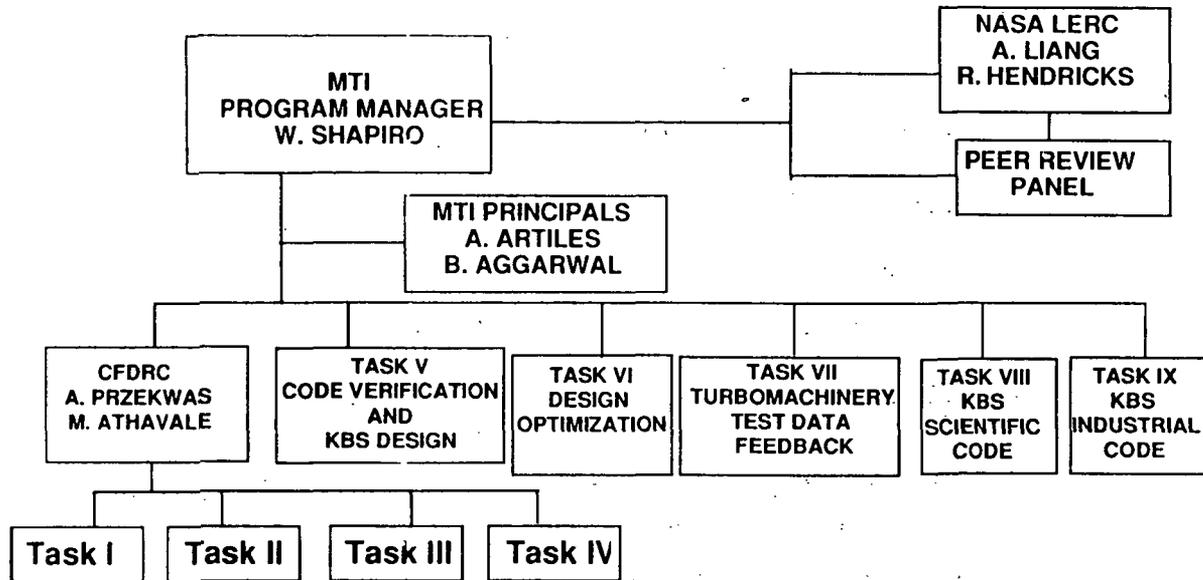
TASK V - CODE VERIFICATION AND DESIGN

CODE VERIFICATION

1. PUBLISHED LITERATURE
2. UNPUBLISHED INFORMATION FROM INDUSTRIAL SOURCES
3. CONSULTATION

DESIGN OF KBS CODES

PROGRAM ORGANIZATION



- Task I Cylindrical Seals Code
 Task II Cylindrical Code Augmentation (Labyrinth, Honeycomb, Damper, Brush)
 Task III Face, Wave, Grooved Seals
 Task IV Tip, Contact, Non-Continuous Seals

CODE DELIVERABLES

<u>CODE OR MODULE</u>	<u>APPROXIMATE DELIVERY DATE</u>
1. CFD Cylindrical Code	02/01/92
2. Augmented CFD Cylindrical Module	02/01/94
3. CFD Code, Face, Wave, Non-Continuous Module	09/01/95
4. CFD, Tip, Contact, Non-Continuous Module	09/01/96
5. GJOURN	02/01/91
6. ICYL	03/01/91
7. SPIRALG	04/01/91
8. IFACE	02/01/92
9. GFACE	03/01/92
10. SPIRALI	04/01/92
11. FACEDY	02/01/93
12. RINGDY	03/01/93
13. LABYRINTH	04/01/93
14. FACECON	02/01/94
15. DISTORTION	04/01/94
16. Additional Codes	04/01/95
17. Industrial KBS	04/01/96
18. Scientific KBS	04/01/96

ACCOMPLISHMENTS

- APPROVED THE BASE WORKPLAN
- COMPLETED 3 INDUSTRIAL CODES
 - ICYL
 - GCYL
 - SPIRALG (SPIRALGC + SPIRALGF)
- COMPLETED FORMULATION OF THE KBS
STARTED INTEGRATION OF THE 3 CODES
- DEVELOPED NEW AND MORE EFFICIENT ALGORITHMS
FOR CFD ANALYSIS
- FORMED THE PEER REVIEW PANEL
- ORGANIZED THE 1ST ANNUAL WORKSHOP

SEALS CODE USER COMMUNITY

ROCKET ENGINE COMPANIES

GAS TURBINE MANUFACTURERS

SEAL COMPANIES

CONSULTANTS

GOVERNMENT AGENCIES

UNIVERSITIES

PEER REVIEW PANEL

GEORGE BACHE - AEROJET

TED BENJAMIN - NASA MSFC

DARA CHILDS/GERALD MORRISON - TEXAS A&M UNIVERSITY

RONALD DAYTON - U.S. AIR FORCE

HAROLD GREINER - EG&G

EUGENE JACKSON/JOE SCHARRER - ROCKWELL

ALAN LEBECK - MECHANICAL SEAL TECHNOLOGY

CHARLES MERKLE - PENN STATE UNIVERSITY

JOHN MINER /SAADAT SYED - PRATT & WHITNEY

JOHN MUNSON - ALLISON GAS TURBINE DIVISION

NELSON POPE - GENERAL ELECTRIC

RICHARD SALANT - GEORGIA INSTITUTE OF TECHNOLOGY

WORKSHOP RESULTS

- NASA CONFERENCE PROCEEDINGS
 - WORKSHOP PRESENTATION MATERIAL
 - EXECUTIVE SUMMARY

- UPDATED WORKPLAN
 - QUESTIONNAIRE
 - PEER REVIEW RECOMMENDATIONS
 - WORKSHOP DISCUSSIONS

NEXT YEAR'S WORKSHOP

- **UPDATED WORKPLAN**
- **CYLINDRICAL CFD CODE**
- **IFACE, GFACE, SPIRALI INDUSTRIAL CODES**
- **FEEDBACK ON THE FIRST THREE CODES DELIVERED
IN 1991**
- **TECHNOLOGY TRANSFER AND UTILIZATION PLAN**
- **PRESENTATIONS BY PARTICIPANTS**

N92-15083

INDUSTRIAL CODE DEVELOPMENT

W. Shapiro
Mechanical Technology Inc.

The industrial codes will consist of modules of 2-D and simplified 3-D or 1-D codes, intended for expeditious parametric studies, analysis and design of a wide variety of seals. Integration into a unified system is accomplished by the industrial KBS, which will also provide User Friendly interaction, contact sensitive and hypertext help, design guidance and an expandable database.

Major seal types include Cylindrical Seals and Face Seals, and within each type are a wide variety of configurations. For example, cylindrical seals include uniform, step, taper, hydrostatic, segmented, damping, labyrinth, and spiral-groove configurations. More advanced types include brush seals, electro-fluids seals and smart seals.

The types of analyses to be included with the industrial codes are interfacial performance (leakage, load, stiffness, friction losses, etc.), thermoelastic distortions, and dynamic response to rotor excursions.

The first three codes to be completed and which are presently being incorporated into the KBS are the compressible spiral-groove codes, SPIRALG, the incompressible cylindrical code, ICYL, and the compressible cylindrical code, GCYL.

The spiral-groove codes analyzes both shaft seals and face seals with finite eccentricity and misalignment. Four degrees of freedom are included for cylindrical seals, and three for face seals. The code predicts load, flow, power loss, and cross-coupled dynamic spring and damping coefficients, shaft displacements and minimum film thickness.

The ICYL (Incompressible Cylindrical Code) is a 2-D isoviscous code that includes roughness, multiple geometries (steps, pockets, tapers, preloaded axes, and hydrostatic), turbulence, cavitation, and inertia at inlets to the film. Included are eccentricity and misalignment and variable grid specifications. Specified pressure and periodic boundary conditions can be applied. It produces pressures, flows, load, righting moments, film thickness, power loss and cross-coupled dynamic spring and damping coefficients.

GCYL is a gas cylindrical code that can treat varying geometries (steps, tapers, hydrostatic, lobed, segmented). Shaft eccentricity, misalignment, specified boundary pressures or periodic boundary conditions can be applied. The program produces the clearance distribution, pressure distribution, leakage, load, moments, power loss and cross-coupled dynamic spring and damping coefficients.

Objectives:

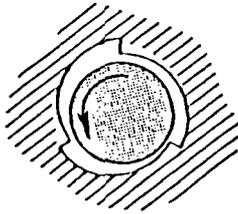
- **Compile and generate sets of verified 2D and simplified 3D or 1D codes**
 - **Codes are intended for expeditious parametric studies, analysis and design of a wide variety of seals**
 - **Integration is accomplished by the Industrial KBS.**
- Additional functions of the KBS are:**

- **User Friendly Interaction**
- **Contact Sensitive and Hypertext Help**
- **Design Guidance**
- **Expandable Database**

SEAL TYPES - COMPRESSIBLE OR INCOMPRESSIBLE

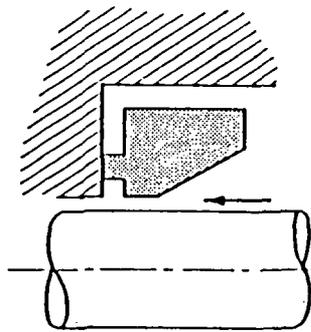
Bushing and Ring Seals

- **Uniform**
- **Axial Step**
- **Axial Taper**
- **Hydrodynamic Step**
- **Hydrodynamic Taper**
- **Self-Energized Hydrostatic**
- **Segmented**
- **Damping Seals**
- **Spiral Groove**

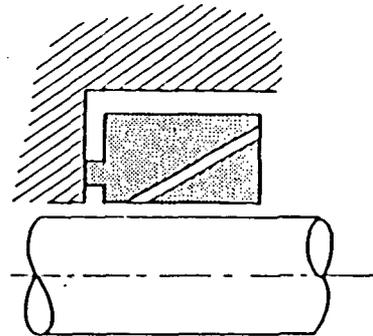


Circumferential Multilobe

(with or without grooves)

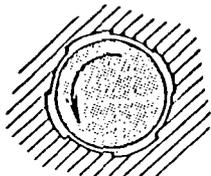


Tapered In Flow Direction

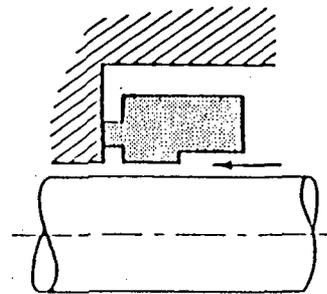


Self-Energized — Hydrostatic

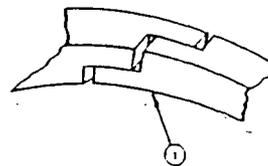
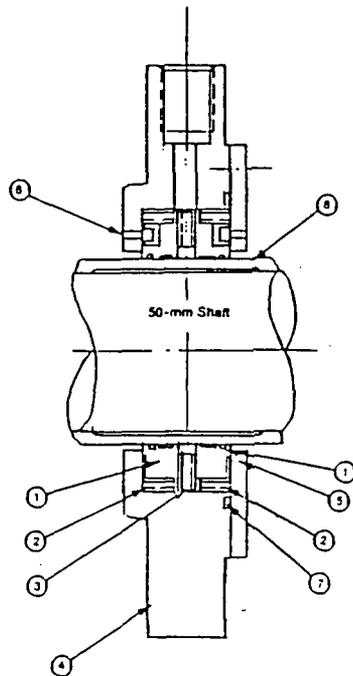
(Inherent Compensation
Orifice Compensation
Spot Orifices
Recesses)



Circumferential Rayleigh Step



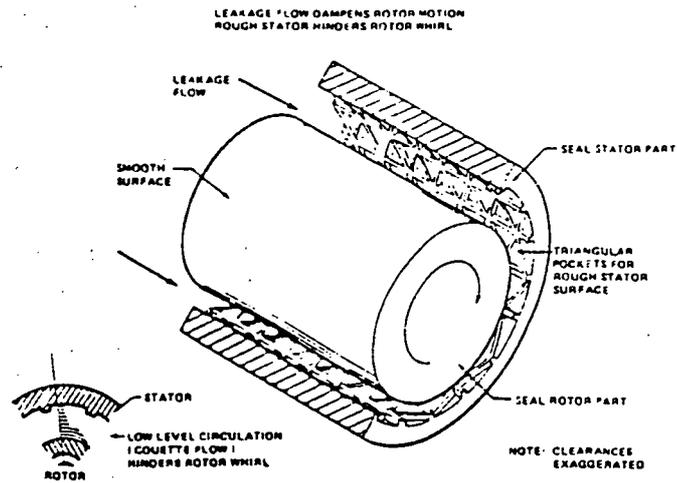
Rayleigh Step In Direction of Flow



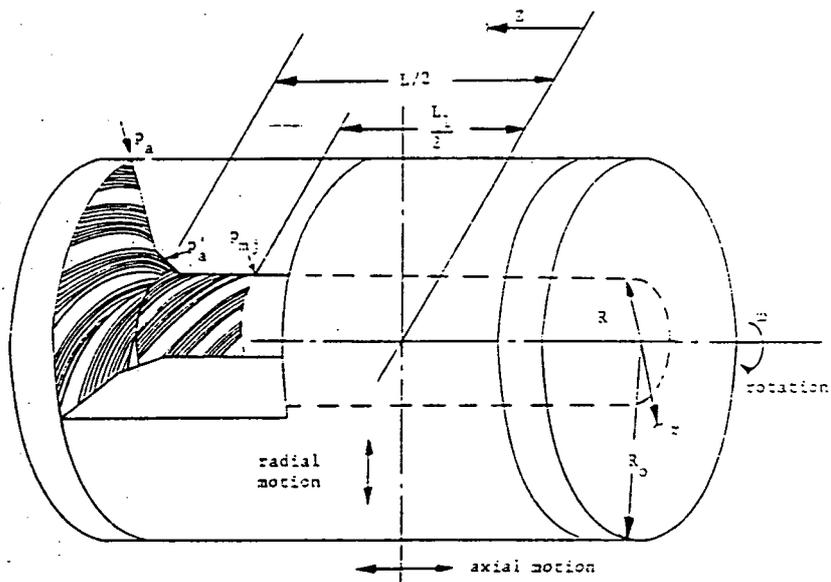
Item	Description	Material
1	Segmented Ring Rayleigh Step	Carbon
2	Spring-Radial	Inconel X-750
3	Spring-Axial	Inconel X-750
4	Housing	Stainless Steel 17-4 PH
5	Cover	Stainless Steel 17-4 PH
6	Stop Pin	Stainless Steel 17-4 PH
7	Seal	Teflon
8	Sleeve	Inconel 718 Hard Chromium Plated

SEGMENTED RING SEAL

ORIGINAL PAGE IS
OF POOR QUALITY



DAMPING SEAL-LEAKAGE FLOW DAMPENS ROTOR MOTION;
ROUGH STATOR HINDERS ROTOR WHIRL

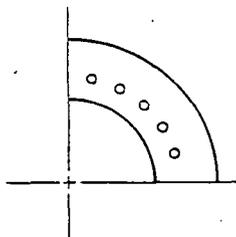


SPIRAL-GROOVE

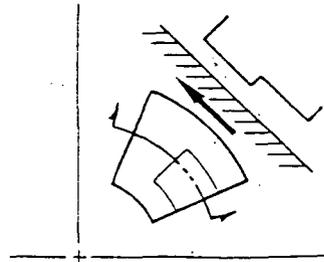
SEAL TYPES - COMPRESSIBLE OR INCOMPRESSIBLE

Face Seals

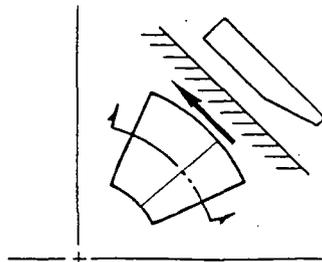
- Contact Face Seals
- Radial Step
- Radial Taper
- Hydrodynamic Step
- Hydrodynamic Taper
- Hydrostatic
- Spiral Groove
- Multi-pad



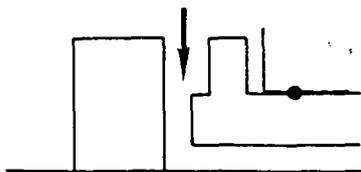
Hydrostatic



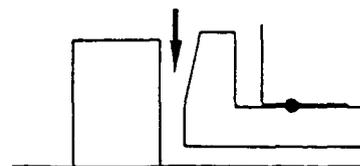
Circumferential Rayleigh Step



Circumferential Tapered Land

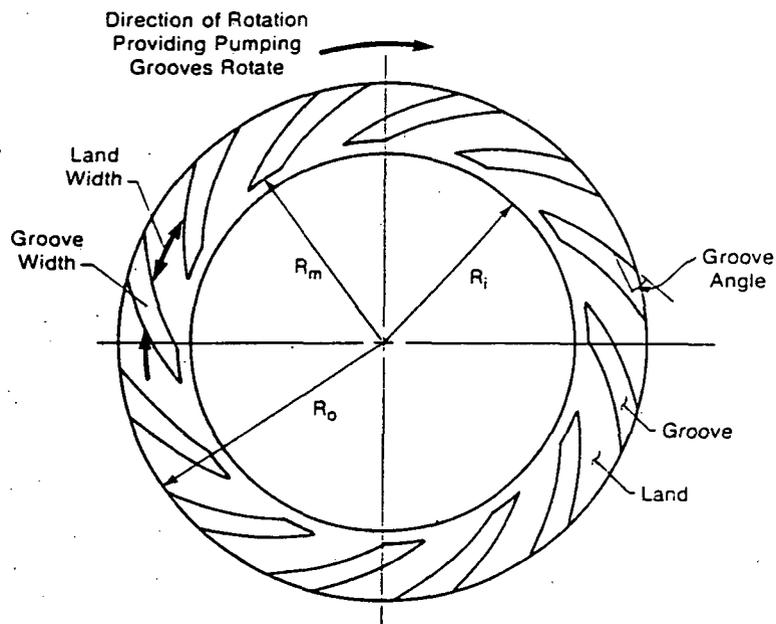


Radial Rayleigh Step



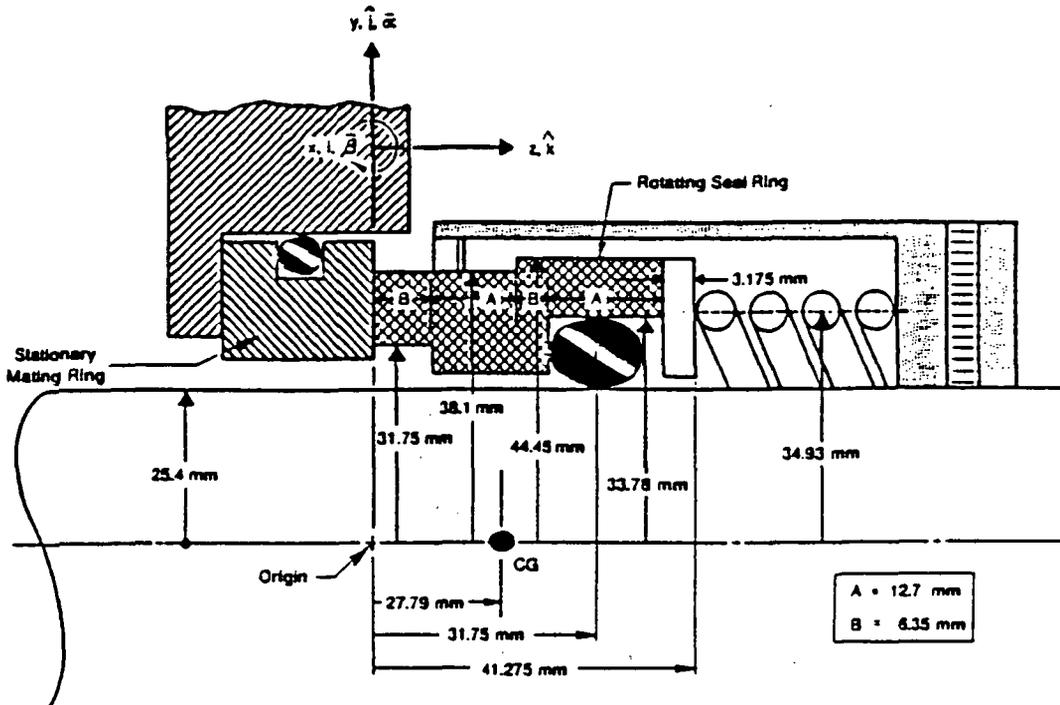
Radial Tapered Land

GFACE Configurations



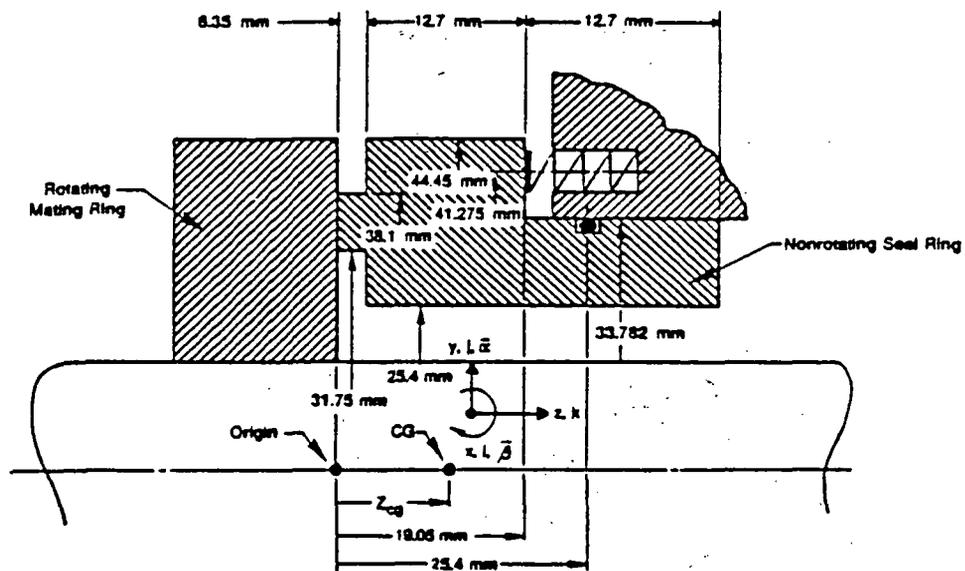
Groove Angle = α
 Groove Depth = GD
 Land Width/Groove Width = γ

SPIRAL GROOVE PARAMETERS



831853-1

CONTACT FACE SEAL WITH ROTATING SEAL RING



831834-1

CONTACT FACE SEAL WITH NON-ROTATING SEAL RING

(Dimensions in mm Unless Otherwise Noted)

Brush Seals

Labyrinth Seals

- Straight
- Stepped
- Abradable
- Angled

Electro-Fluids Seals

Smart Seals

Effect of Bristle Overhang

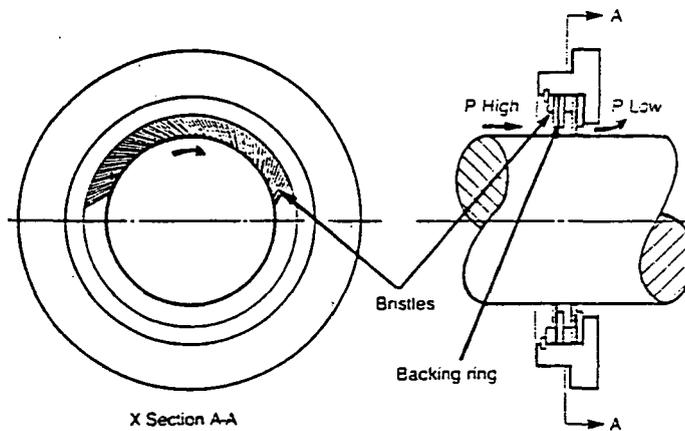
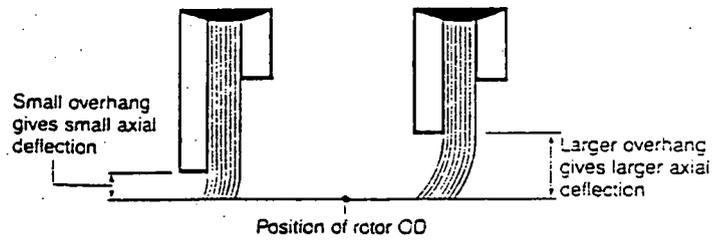
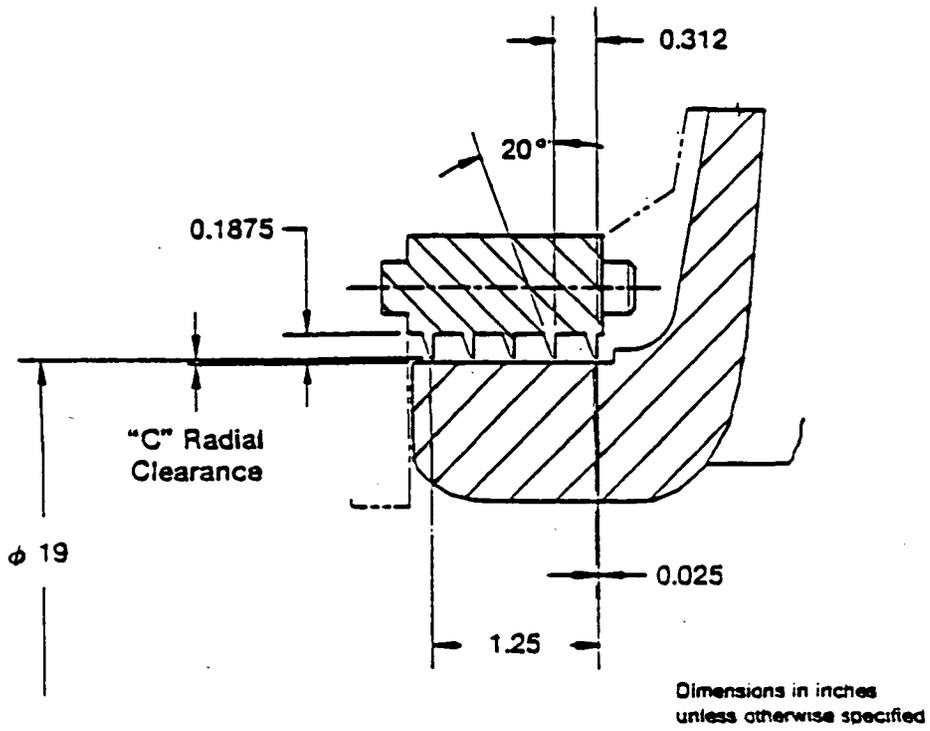
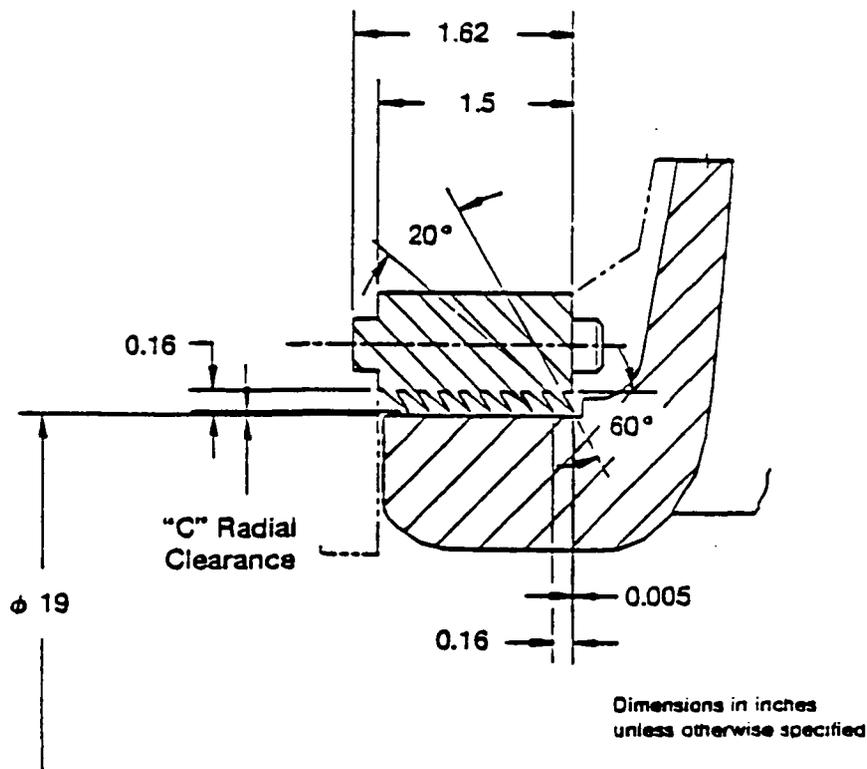


DIAGRAM SHOWING TYPICAL BRUSH SEAL ARRANGEMENT



881815

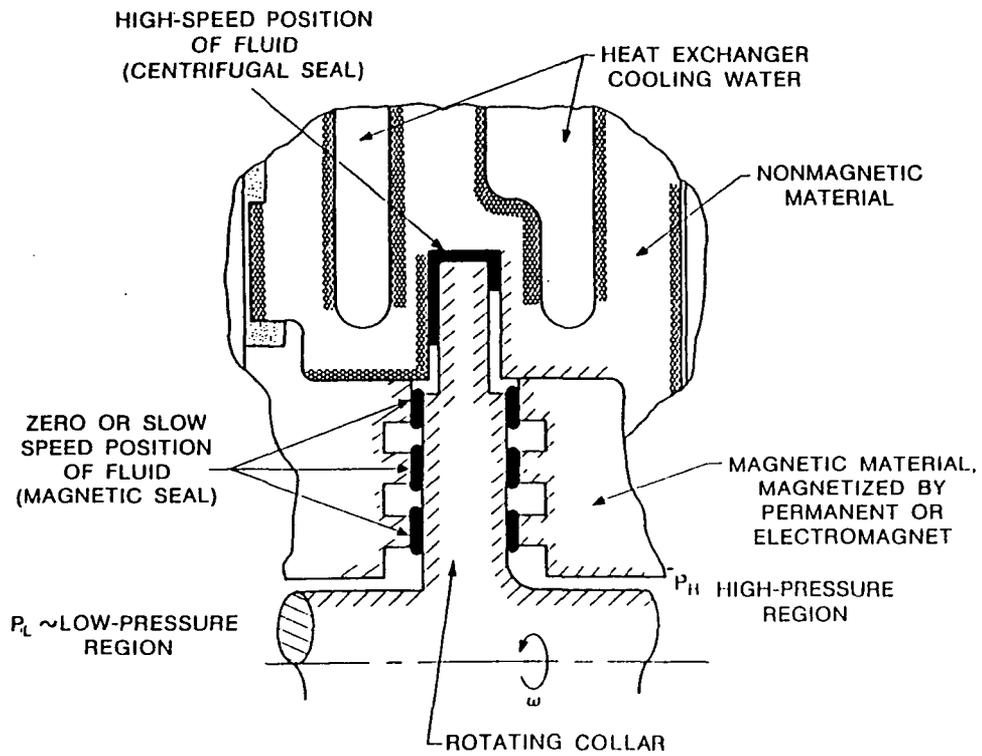
ORIGINAL INLET SEAL



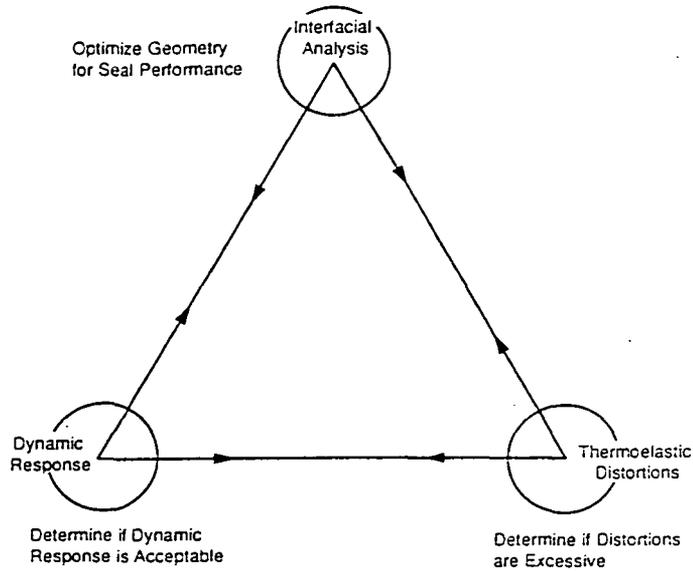
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OPTIMIZED STRAIGHT INLET SEAL

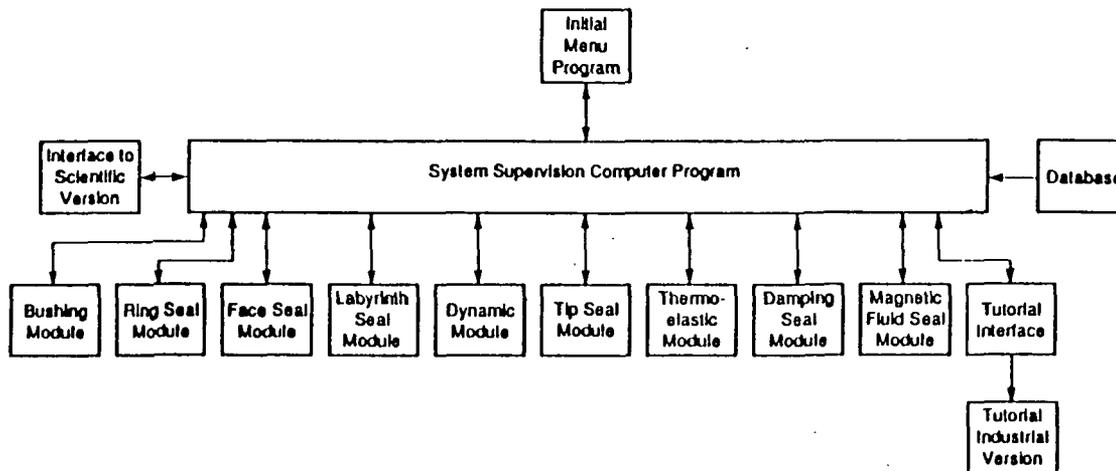
MAGNETIC FLUID SEAL



FUNDAMENTAL SEAL CONFIGURATION



ANALYTICAL TRIAD



Code Deliverables

<u>Code Module</u>	<u>Approximate Delivery Date</u>
GCYL (Gas Cylindrical)	02/01/91 ←
ICYL (Incompressible Cylindrical)	03/01/91 ←
SPIRALG (Gas Spiral Groove)	04/01/91 ←
CFD Cylindrical Code	02/01/92
IFACE (Incompressible Face)	02/01/92
GFACE (Gas Face)	03/01/92
SPIRALI (Incompressible-Spiral Groove)	04/01/92
FACEDY (Face-Dynamics)	02/01/93
RINGDY (Ring-Dynamics)	03/01/93
LABYRINTH (Gas)	04/01/93
Augmented CFD Cylindrical Module	02/01/94
FACECON (Face Contact)	02/01/94
DISTORTION (Thermo Elastic Distortion)	04/01/94
Additional Codes	04/01/95
• Brush	
• Damping Seal	
CFD Code, Face, Wave, Groove Module	09/01/95
Industrial KBS	04/01/96 ←
Scientific KBS	04/01/96
CFD, Tip, Contact, Non-Continuous Module	09/01/96

PLANNED ACTIVITY

- **Code unification and completion**
 - Unified Grid Generator
 - On-line Help

- **Code documentation**
 - Consistent with KBS usage

- **Additional problems and checkout**

- **Annual report**

DEVELOPMENT OF A CFD CODE FOR ANALYSIS OF
FLUID DYNAMIC FORCES IN SEALSCFD Research Corporation
M.M. Athavale, A.J. Przekwas and A.K. Singhal

This presentation is a status report for Task I of the Seals Flow Code project. The aim of this task is to develop a 3D CFD code for the analysis of fluid flow in cylindrical seals and evaluation of the dynamic forces on the seals. This code is expected to serve as a scientific tool for detailed flow analysis as well as a check for the accuracy of the 2D industrial codes

The features necessary in the CFD code are outlined. These include general considerations such as code accuracy, efficiency, and robustness and other specific features such as rotating coordinate frames, steady and time-accurate solutions, inclusion of non-isotropic wall roughness, effects of phase-change and cavitation, and integration with KBS.

The approach and initial focus of the task is discussed next. The initial focus of the task was to develop or modify and implement new techniques and physical models. These include collocated grid formulation, rotating coordinate frames and moving grid formulation. Other advanced numerical techniques include higher-order spatial and temporal differencing and efficient linear equation solver.

These techniques were implemented in a 2D flow solver for initial testing. Several benchmark test cases were computed using the 2D code and the results of these are compared with analytical solutions or experimental data to check the accuracy. Tests presented here include planar wedge flow, flow due to an enclosed rotor and flow in a 2D seal with a whirling rotor. Comparisons between numerical and experimental results for an annular seal and a 7 cavity labyrinth seal are also included.

The presentation is closed with plans for the second and final year of Task I. This involves completion of modifications in the 3D base code, and incorporation in the 3D code of the physical models to treat turbulence, non-isotropic wall roughness, phase-change and cavitation, brush-seal model, and calculation of dynamic coefficients.

OBJECTIVES

- **Develop Verified CFD Code for Analyzing Seals**
- **Required Features Include:**
 - **Applicability to a Wide Variety of Seal Configurations, such as: Cylindrical, Labyrinth, Face, Tip and Brush Seals**
 - **Accuracy of Predicted Flow Fields and Dynamic Forces**
 - **Efficiency (Economy) of Numerical Solutions**
 - **Reliability (Verification) of Solutions**
 - **Ease-of-Use of the Code (Documentation, Training)**
 - **Integration with KBS**

CFD CODE REQUIRED CAPABILITIES

- **Solve 2-D and 3-D Navier-Stokes Equations with Provisions for:**
 - **Complex Geometries (Body Fitted Coordinates, High Aspect Ratio Cells, Skewed Grids, *etc.*)**
 - **Stationary and Rotating Coordinates**
 - **Steady-State and Transient Analysis**
 - **Turbulence, Surface Roughness**
 - **Compressibility, Viscous Dissipation**
 - **Heat Transfer, Phase Change, Cavitation**
 - **Electromagnetic Effects, *etc.***

CFD SEALS CODE DEVELOP. - APPROACH

- Use state-of-the art techniques and latest relevant physical models
- Starting Point: REFLEQS-2D and 3D codes
- 2D code used as a base for efficient evaluation of latest numerical techniques
- Optimum procedure and programming practice tested in 2D code (computer memory vs. computational speed dilemma)
- Fast turnaround time
- Several benchmark-quality validation experiments available for 2D and only few for 3D
- Verified 2D code used as a checkout test bed for 3D code

INITIAL FOCUS OF TASK 1

- Study, Implement and Test:
 - a) Non-Staggered Grid Formulation
 - b) Rotating Coordinates
 - c) Transient Solution Algorithm
- Physical Model Modifications for:
 - a) Turbulence in Rotating Flows
 - b) Non-Isotropic Wall Roughness
 - c) Compressibility and Viscous Dissipation
 - d) Two-Phase Flows (Phase Cavitation, *etc.*)
- Calculation of Dynamic Forces and Coefficients

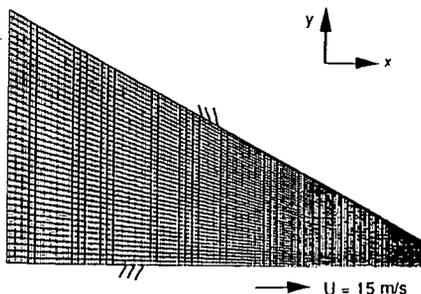
ADVANCED NUMERICAL TECHNIQUES - STATUS

- Colocated Grid Formulation for BFC Grids
- Strong Conservative Formulation of Momentum Equations with Cartesian Components
- Choice of SIMPLE, Modified SIMPLEC and Noniterative PISO
- Higher Order Accurate Temporal Differencing
- Higher Order (2nd, 3rd) Spatial Discretizations Available
- Rotating Grid System for Stator-Rotor Configurations
- Moving Grid option for Arbitrary Rotor Whirling Analysis
- Efficient Multigrid Solver

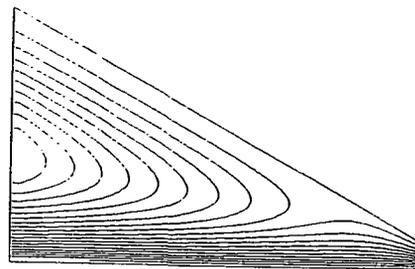
PLANAR WEDGE FLOW

Length = 0.1, Heights: Minimum = 3×10^{-5} m,
Maximum = 3×10^{-4} m, y scale enlarged 200 times

192 x 40 Grid



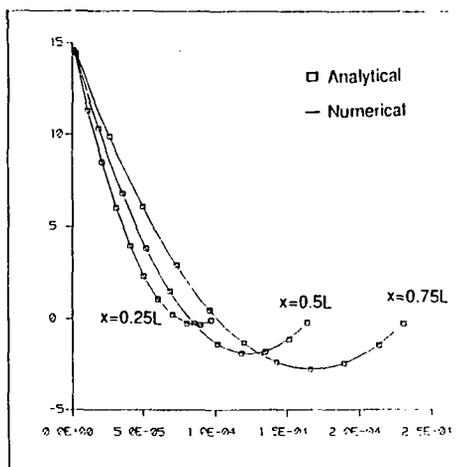
Streamlines



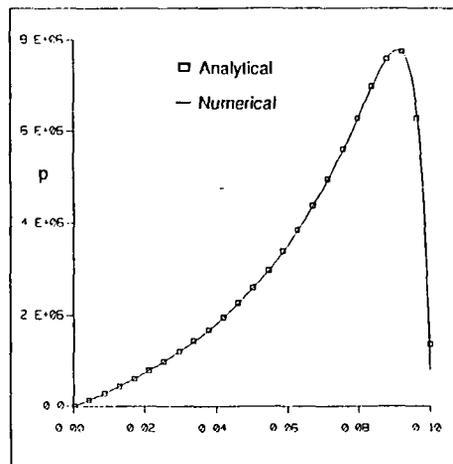
```
STR1  CONTOURS
FMIN  5 051E-03
FMAX  7 027E-01
CONTOUR LEVELS
1  5 052E-03
2  4 459E-02
3  0 353E-02
4  1 224E-01
5  1 512E-01
6  2 001E-01
7  2 389E-01
8  2 777E-01
9  3 166E-01
10 3 554E-01
11 3 943E-01
12 4 331E-01
13 4 719E-01
14 5 109E-01
15 5 499E-01
21 7 029E-01
```

PLANAR WEDGE FLOW

u Velocity

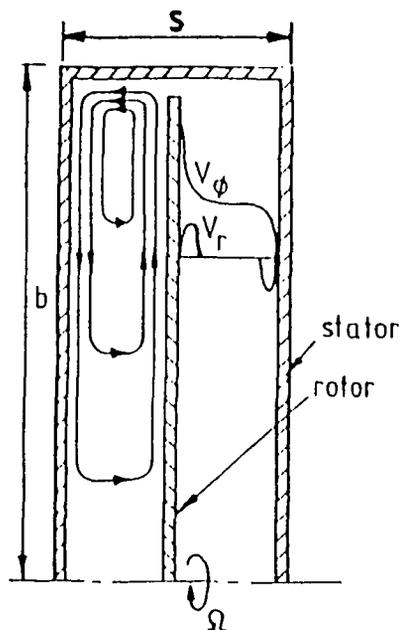


Pressure



ENCLOSED ROTOR

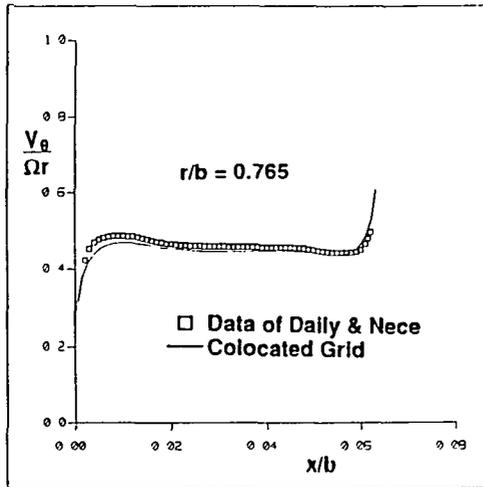
Daily & Nece (1960)



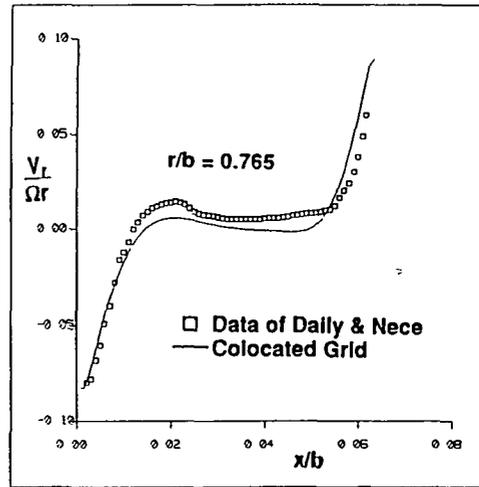
ENCLOSED ROTOR

Daily and Nece

Tangential Velocity



Radial Velocity

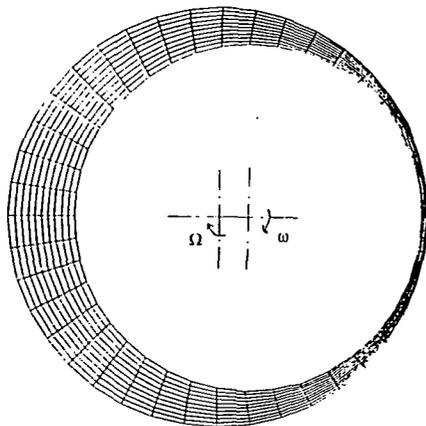


WHIRLING ROTOR IN AN ANNULAR SEAL

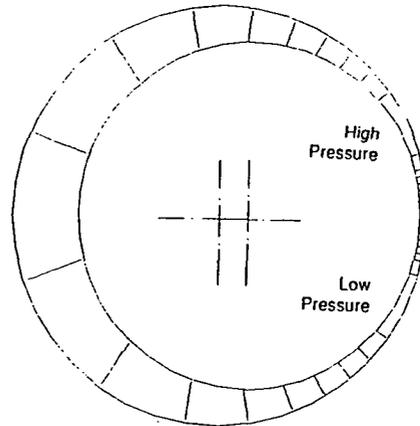
Stator radius = $50.1478 \times 10^{-3} \text{m}$,

Clearance = $495 \mu\text{m}$, $\epsilon = 0.8 \times \text{clearance}$,

Shaft Speed $\omega = 5085 \text{rpm}$



40 x 10 Computational Grid

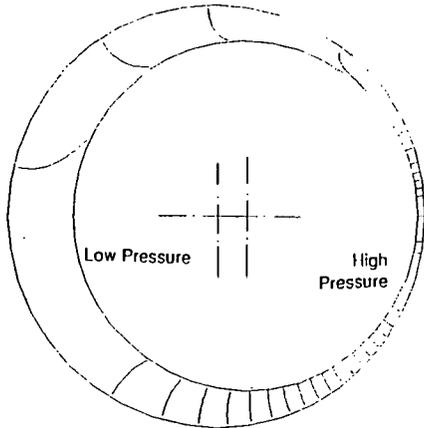


**Pressure Contours
Synchronous Whirl, $\Omega = \omega$**

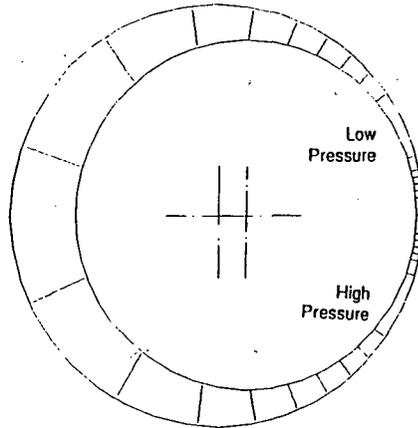
```

PRES CONTOURS
FMIN -3 003E+06
FMAX 6 197E+06
CONTIN LEVELS
1 -3 003E+06
2 -2 515E+06
3 -2 035E+06
4 -1 551E+06
5 -1 066E+06
6 -5 022E+05
7 -9 792E+04
8 3 653E+05
9 8 706E+05
10 1 355E+06
11 1 035E+06
12 2 323E+06
13 2 020E+06
14 3 292E+06
15 3 775E+06
20 6 197E+06
    
```

WHIRLING ROTOR IN AN ANNULAR SEAL



PPES	CONTOURS
FMIN	-1.322E+05
FMAX	2.324E+04
CONTOUR LEVELS	
1	-1.322E+05
2	-1.240E+05
3	-1.150E+05
4	-1.076E+05
5	-9.945E+04
6	-9.127E+04
7	-8.302E+04
8	-7.491E+04
9	-6.673E+04
10	-5.855E+04
11	-5.037E+04
12	-4.215E+04
13	-3.401E+04
14	-2.583E+04
15	-1.765E+04
20	2.324E+04



PPES	CONTOURS
FMIN	-5.040E+06
FMAX	3.027E+06
CONTOUR LEVELS	
1	-5.040E+06
2	-5.562E+06
3	-5.065E+06
4	-4.606E+06
5	-4.131E+06
6	-3.654E+06
7	-3.176E+06
8	-2.693E+06
9	-2.222E+06
10	-1.743E+06
11	-1.265E+06
12	-7.86E+05
13	-3.134E+05
14	1.630E+05
15	6.410E+05
20	3.027E+06

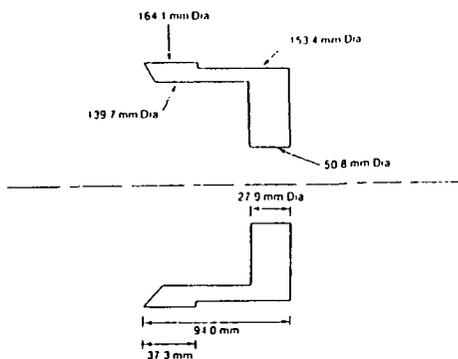
Pressure Contours
Subsynchronous Whirl, $\Omega = 0.5\omega$

Pressure Contours
Subsynchronous Whirl, $\Omega = 0.01\omega$

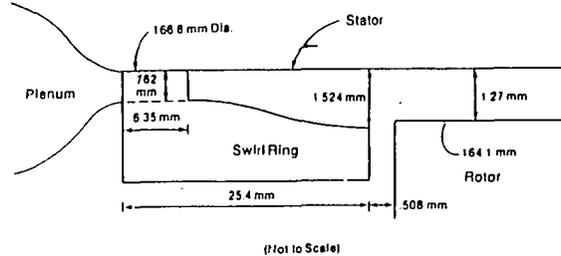
ANNULAR SEAL

Morrison, et. al
Re = 27000, $T_a = 6600$, L/C = 29.4

Annular Rotor



Seal Geometry



ORIGINAL PAGE IS
OF POOR QUALITY

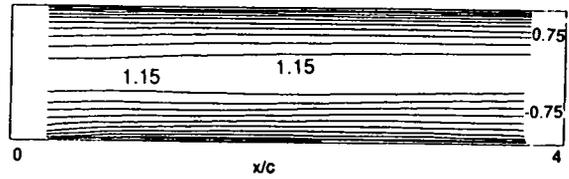
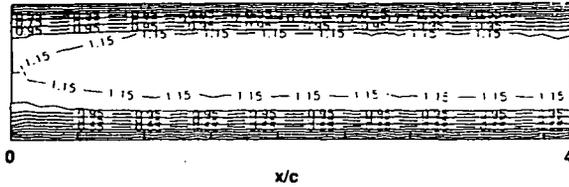
ANNULAR SEAL

u_x/\bar{U} contours

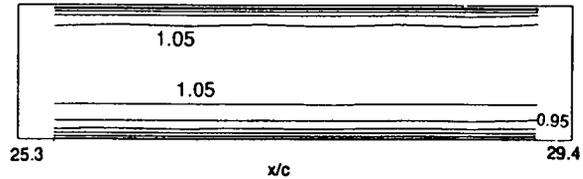
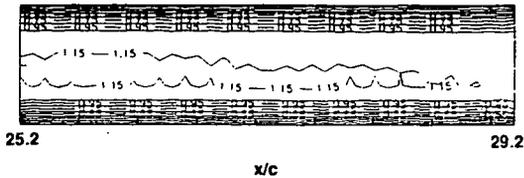
Experimental

Numerical

Inlet



Outlet



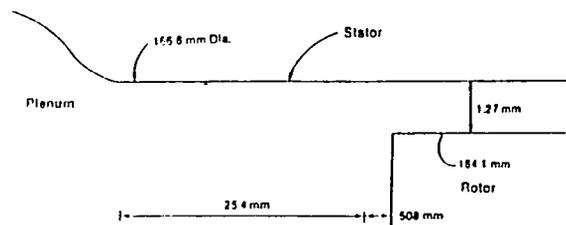
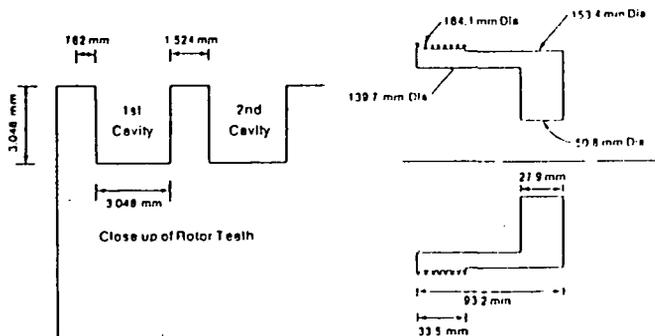
SEVEN CAVITY LABYRINTH SEAL

Morrison, *et. al.*

$Re = 28000$ $Ta = 7000$

Labyrinth Rotor

Inlet Geometry

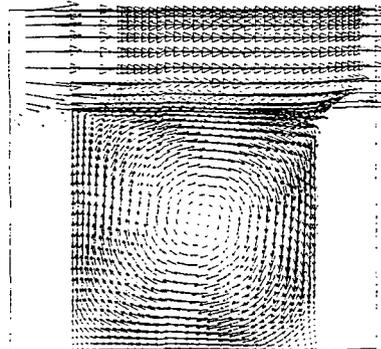
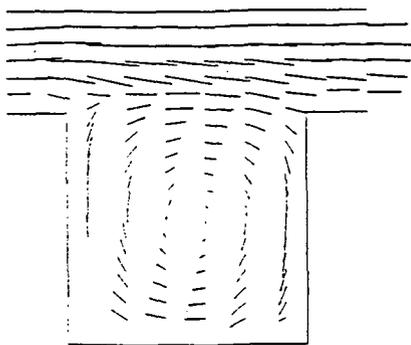


SEVEN CAVITY LABYRINTH SEAL
Velocity Vector Plot

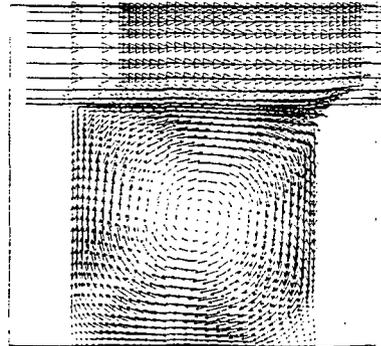
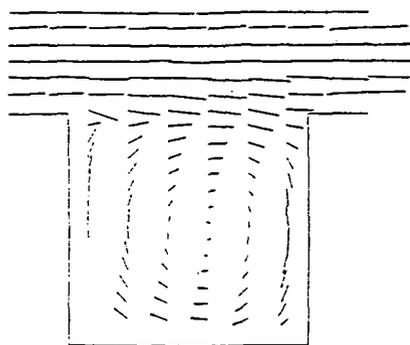
Experimental

Numerical

First Cavity



Third Cavity



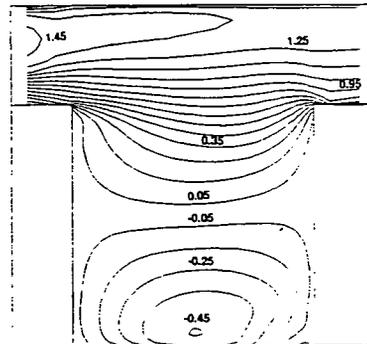
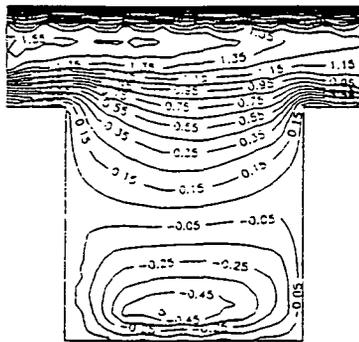
SEVEN CAVITY LABYRINTH SEAL

u_x/\bar{U} contours

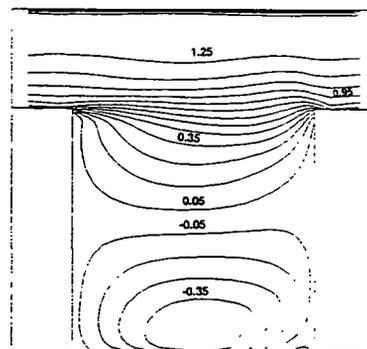
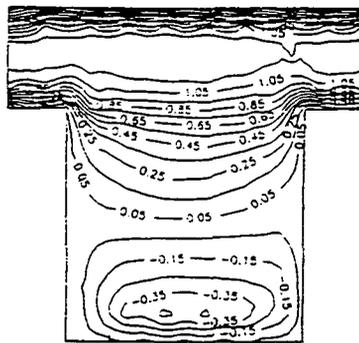
Experimental

Numerical

First Cavity



Third Cavity



TASK 1 COMPLETION PLAN (DEC 91)

- **Complete Advanced Numerical Techniques Implementation**
- **3D Code Modifications**
- **Incorporation of Advanced Physical Models**
 - **Turbulence Models**
 - **Non-Isotropic Wall Roughness**
 - **Compressibility and Viscous Dissipation**
 - **Two-Phase (Phase Change)**
 - **Cavitation**
 - **Brush Seal Model**
- **Incorporation of Dynamic Forces and Coefficients**

N92-15085

KBS DEVELOPMENT

Bharat Aggarwal
Mechanical Technology Inc.

The KBS has two main objectives: 1) Provide easy access to all the industrial and scientific codes through an executive program. The executive provides common services such as browsing and printing, direct access to a specific code by clicking a button or selecting from a menu, and expert help and guidance for seal analysis and design using expert systems to assist the user. Other features of the KBS include online help and access to a database of test cases for the analysis codes. 2) Provide an easy to use user interface for the analysis codes. The user interface is designed to minimize the effort expended in dealing with the mechanics of using a computer, allowing the user to concentrate on seal design and analysis.

The KBS is implemented using the OS/2 Operating System with the Presentation Manager (PM) graphical user interface. The PM environment provides support for windows, menus, buttons, etc. to enable design of a friendly user interface. In addition, a rich set of functions are provided to support the development of interactive graphics applications. This facility will be used to provide capabilities such as interactive seal layout and grid generation to reduce the volume of numeric input required by the programs. OS/2 currently runs on IBM PC compatibles using Intel 80286, 80386, or 80486 processors. IBM and Microsoft plan to port the system to run on some of the RISC platforms by the end of 1992. The OS/2 Extended Edition from IBM also provides integrated communications and database support. These facilities will be used extensively when the scientific codes are integrated into the KBS.

The user interface is designed to reduce the mechanics of using a computer to simple operations such as menu selections, clicking buttons, etc. The basic operations and menu items are consistent for all the programs to reduce the learning time and to make the user feel comfortable when using the various programs. Context sensitive help is provided at all times and the user is protected from making obvious errors. The data entry procedures are designed using engineering terminology rather than computer jargon. The interactive portions of the input are being designed to conform to the level of abstraction used in the theoretical model so that the user does not waste time and effort translating information on the screen into the concepts used to build the analytical model. The end result will be to have the interface recede into the background, leaving the user free to concentrate on seal design and analysis.

○ Objectives

- Develop 3-D CFD Scientific Codes (CFDRC)
 - Highly accurate
 - Standards for 2-D codes
- Generate 2-D Industrial Codes
 - Expeditious analysis
- Develop Knowledge-based System (KBS)
 - Integrate all analysis codes and modules
 - Design guidance
 - An upgradable database
 - User friendly input and output procedures

○ Hardware and Software Configuration

- IBM PS/2 Model 80-A31
 - 25 Mhz 80386 processor
 - 25 Mhz 80387 math coprocessor
 - 8 Mb RAM
 - 320 Mb high speed hard disk
 - 1.44 Mb 3.5 inch floppy drive
 - SCSI adapter with cache
- IBM High Resolution (VGA) Color Monitor
- Microsoft Serial PS/2 Mouse
- IBM OS/2 Extended Edition (V 1.2)
 - OS/2 Standard Edition
 - Communication Manager
 - Database Manager
- IBM OS/2 Programming Tools and Information Kit (V 1.2)
- Microsoft C Compiler (V 6)
- Microsoft FORTRAN (V 5)
- Kedit for OS/2
- Asymmetrix Toolbook for OS/2
- Nexpert Object for OS/2

○ **Design Philosophy for KBS**

- A consistent user interface
 - Reduce learning time and make the user feel at ease
 - Appearance of windows, input screens, etc. will be the same in all modules
 - All modules will use similar procedures for standard operations such as opening or closing files, printing reports, selecting items from menus, etc.
 - Names of menu items will be standardized as much as possible
 - Context sensitive help available at every stage
 - Provide facilities to recover from errors
- The user has complete control
 - The user can perform functions in any order
 - The program will warn user if the information needed to do the job is not available

○ **KBS: Analysis Definition**

- Analysis Types
 - Interfacial (2-D and 3-D)
 - Dynamic response
 - Thermoelastic distortion
- Direct Selection by the User
 - User selects analysis type from a menu
- KBS Assistance
 - User provides information relative to the application
 - A knowledge base to analyze the information and recommend analysis type and the analysis codes to be used

○ **KBS: Design Guidance and Optimization**

□ Guide iterative analysis

- Optimization is an iterative process involving interfacial analysis, dynamic analysis, and thermoelastic analysis
- Analyze output data to determine if iterations should continue
- Recommend the analysis to run in the next iteration
- Recommend the parameters to be changed in the next iteration

○ **KBS: Databases**

□ Data to be Archived

- User Input data sets
- User Output data sets
- Data sets used in code validation

□ Database Procedures

- OS/2 Extended Edition Database Manager used for storing and retrieving data
- Networked database support provided through OS/2 facilities
- Data entry and retrieval screens will be designed using the Query Manager and SQL compatible commands
- Password protection will be provided to prevent unauthorized access

○ **KBS: Help and Guidance**

□ **Implementation**

- Hypertext capabilities of Toolbook and the Information Presentation Facility (IPF) included with OS/2 will be used to design the help system
- Graphics and text will be mixed as needed
- Context sensitive help

□ **Help: General**

- User Interface

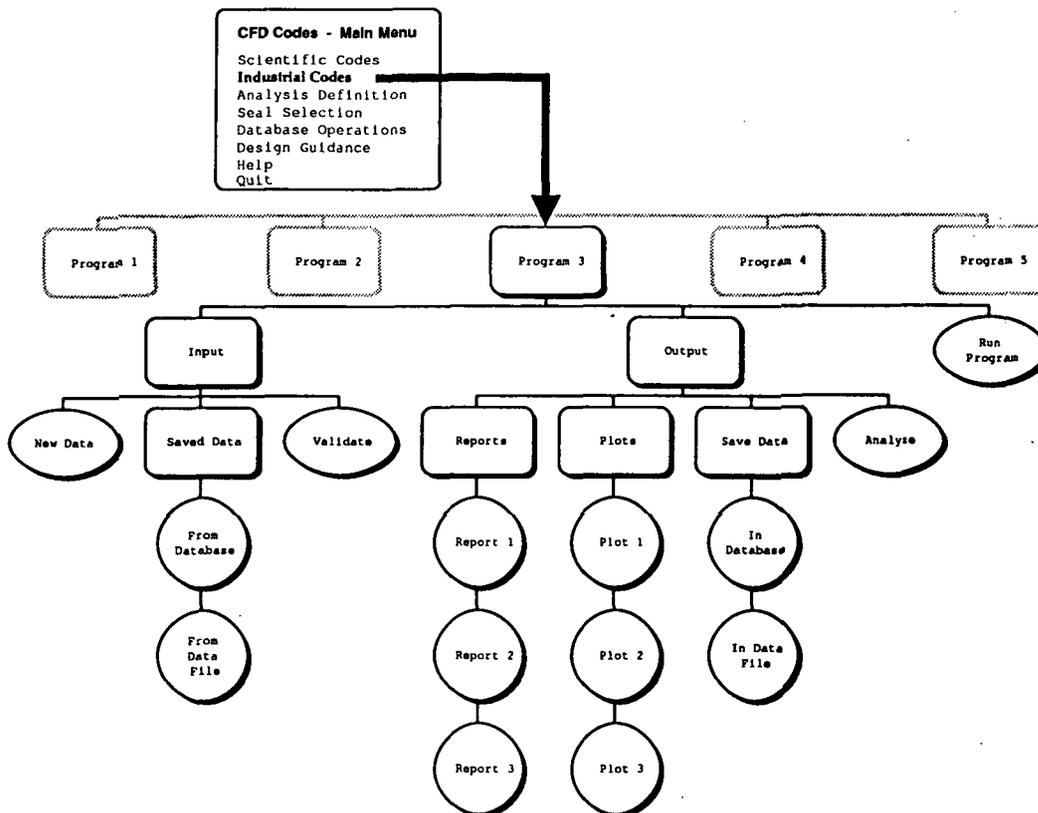
□ **Help: Each Analysis Module**

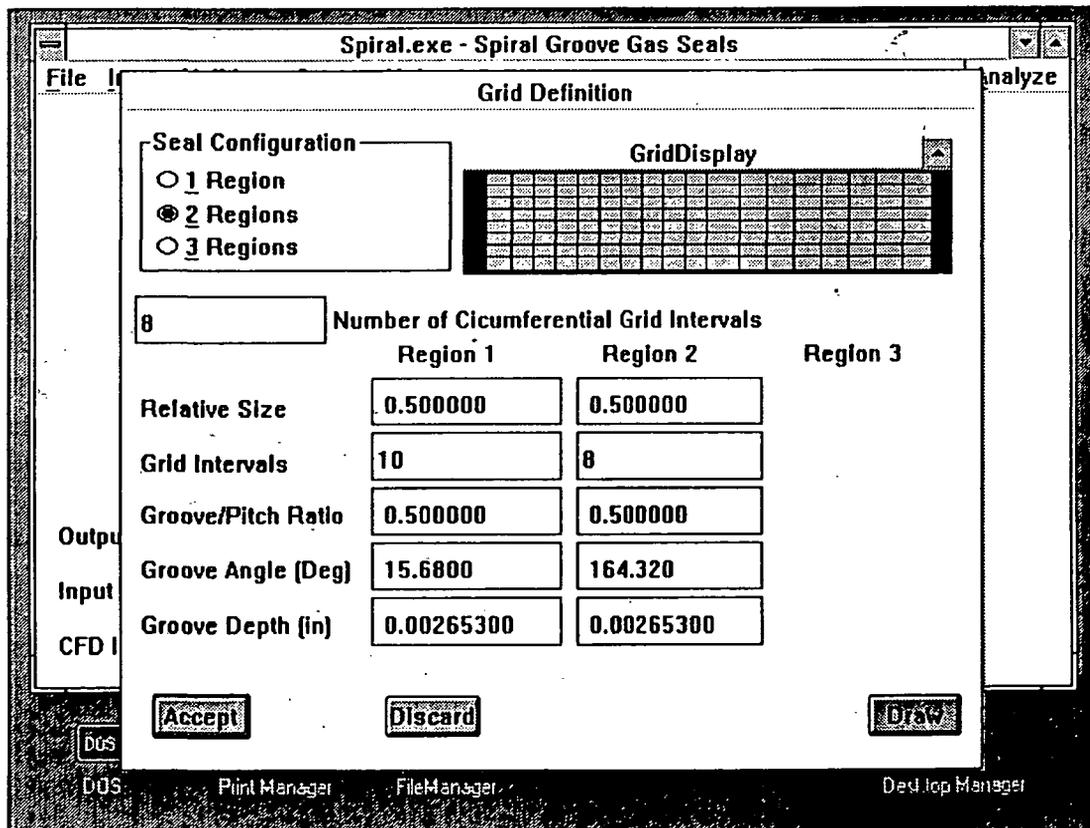
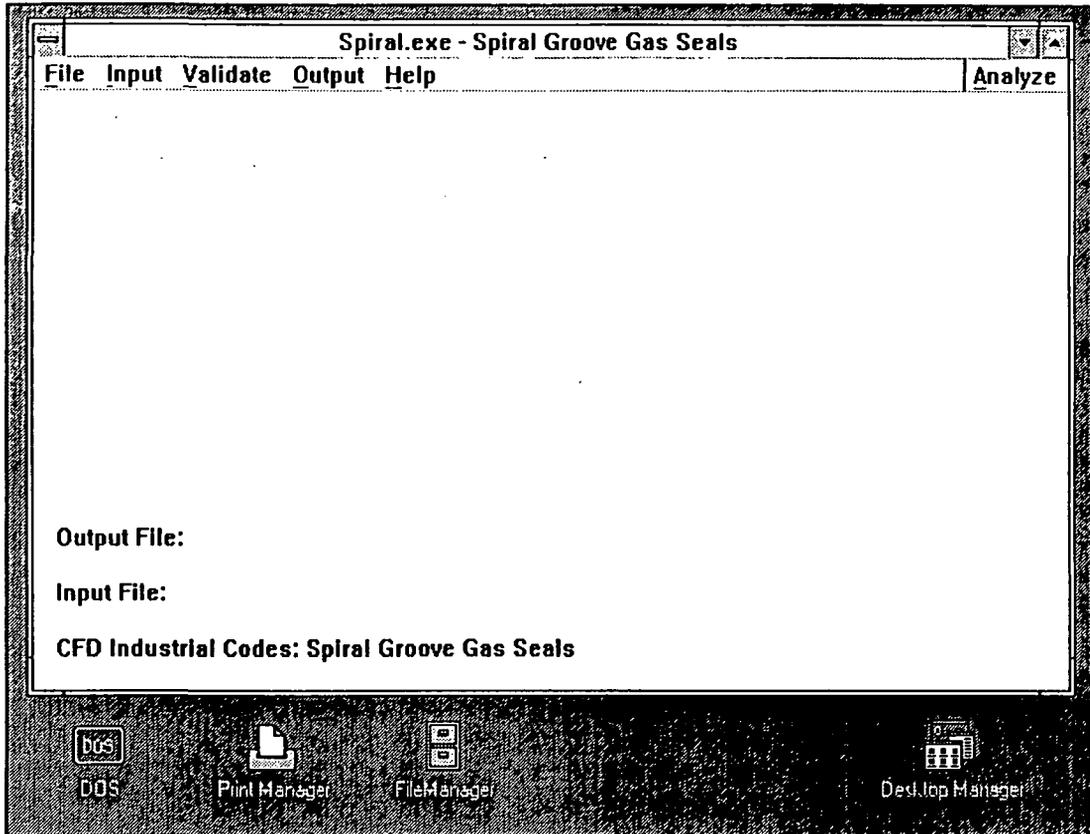
- Purpose
- Capabilities and limitations
- Theoretical background
- References
- Code validation procedures
- Description of input and output variables
- Example problems with sample input and output

□ **Guidance**

- Design procedures
- Seal type recommendations

○ **KBS: Menu Structure**





KBS Demonstration
B. Aggarwal, A. Artiles, and W. Shapiro
Mechanical Technology, Inc.

The demonstration included five different items; the executive program, three of the industrial codes, and graphical data display capability using current MTI MS-DOS programs. The graphics capability included two- and three-dimensional plots viewed from different angles. This capability will be ported to OS/2 and made an integral part of the KBS executive program.

The executive program has a button for each industrial code and facilities to print and browse input and output files generated by the analysis codes. The plotting capability will be added in the future. The user can start any of the codes by clicking on the button for the code. The number of codes running simultaneously is limited only by the amount of memory available on the machine. Multitasking capabilities of OS/2 are exploited to perform printing, browsing and analysis functions in parallel.

The three codes demonstrated included Spiral Groove Gas Seals (SPIRAL), Gas Cylindrical Seals (GCYL) and Incompressible Seals (ICYL). SPIRAL and GCYL interface has the standard PM interface while ICYL interface was designed using ToolBook.

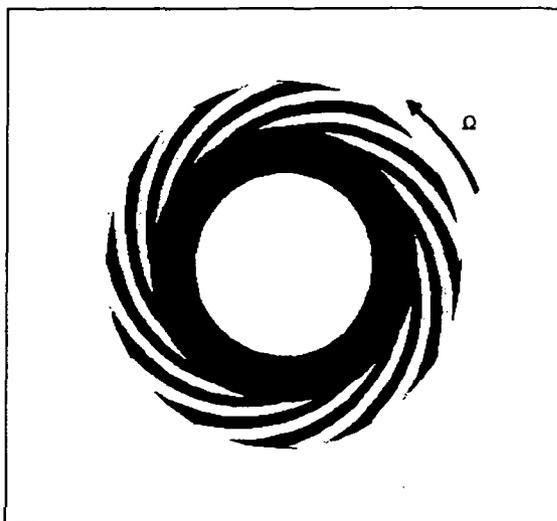
SPIRAL and GCYL have pull down menus to access input screens. The names of the menu items are the same in both programs. Program options are chosen using radio buttons and check boxes instead of entering numbers. Entry fields for numeric information have built in checks to ensure that the numbers are within acceptable ranges. Context sensitive help is provided for all input. When the input is complete, the user may start the analysis by clicking on the analyze button in the menu bar. The output is stored in a user specified output file. The user may also elect to save the input data as a file for future use.

Interactive graphics have been used to ease the input process. In SPIRAL, the user can get immediate feedback during analysis grid specification by clicking on the DRAW button. The program will display the grid as currently specified. In GCYL, the layout of features such as Rayleigh Steps, Recesses, fluid sources, etc. on seal pads is done interactively. The components are laid out on the specified grid using the mouse. This provides a visual representation of the seal pad and avoids having to input a large volume of numerical data. This capability will be extended to include variable grid specification.

ICYL interface shows an alternative approach. The menu items are laid out on the screen in the traditional manner. Submenus appear cascaded on the same screen when a menu item is selected by clicking on it. The concept is similar to the pulldown menus of the standard PM interface. Direct access is provided to any input screen from any other input screen. Menu item names are the same as in SPIRAL and GCYL. Program options and numeric data input procedures are the same as in SPIRAL and GCYL. Arrays of numbers are input using scrollable entry fields. This capability will be added to SPIRAL and GCYL.

SPIRAL-GROOVE CODE

Dr. Jed Walowit



Stator for Spiral Grooved Face Seal

Spiral Grooved Gas Seal Computer Codes

- **Shaft seals and face seals**
- **Compressible flow**
- **Finite eccentricity and misalignment**
- **Four degrees of freedom for shaft seals (three for face seals)**
- **Frequency dependent dynamic coefficients**
- **Arbitrary end pressures**
- **Predicts load, flow, power loss, dynamic coefficients, shaft displacements and minimum film thickness**

ICYL (Incompressible Cylindrical Seals) Code

Dr. Antonio Artiles

MTI

=====

PROGRAM ICYL

=====

CAPABILITIES

- 2-D incompressible isoviscous flow in cylindrical geometry
- Rotation of both rotor and housing
- Roughness of both rotor and housing
- Arbitrary film thickness distribution, including:
 - Steps, pockets, tapers
 - Preloaded arcs
- Rotor position and velocity is described by four degrees of freedom (translational and rotational)
- External forces and moments may be prescribed to find rotor position
- Pocket pressures or orifice size are prescribed
- Laminar or turbulent flow
- Cavitation
- Inertia pressure drop at inlets to fluid film
 - From ends of seal
 - From pressurized pockets

Computer Code GCYL
(Gas Cylindrical Code)

Wilbur Shapiro

MTI

Computer Code GCYL

The general capabilities of the GCYL include:

- Varying geometries
- Variable or constant grid (30 x 74)
- Shaft eccentricity and misalignment
- Specified boundary pressures and periodic boundary conditions
- Symmetry in axial direction
- Determining load (function of displacement) or seal position to satisfy given load
- Choice of English or SI units.

The output of the program include:

- Clearance distribution
- Pressure distribution
- Leakage at specified flow paths
- Load and load angle
- Righting moments
- Viscous dissipation
- Cross-coupled, frequency-dependent, stiffness and damping coefficients
- Plotting routines (pressure and clearance distribution)

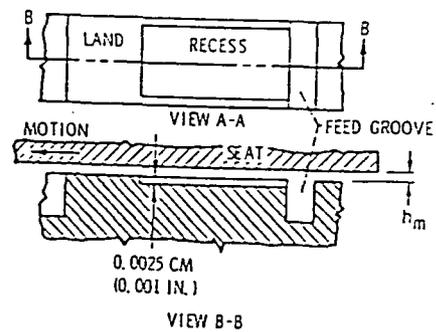
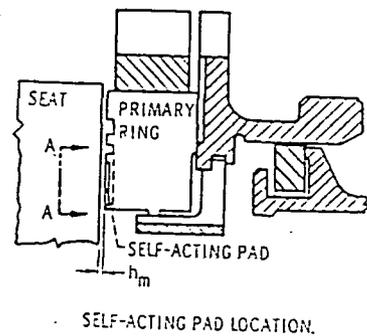
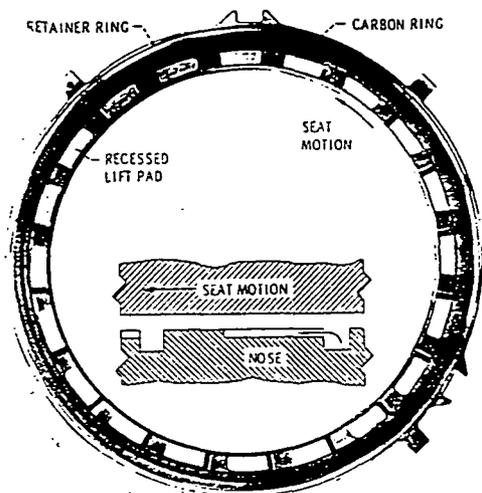
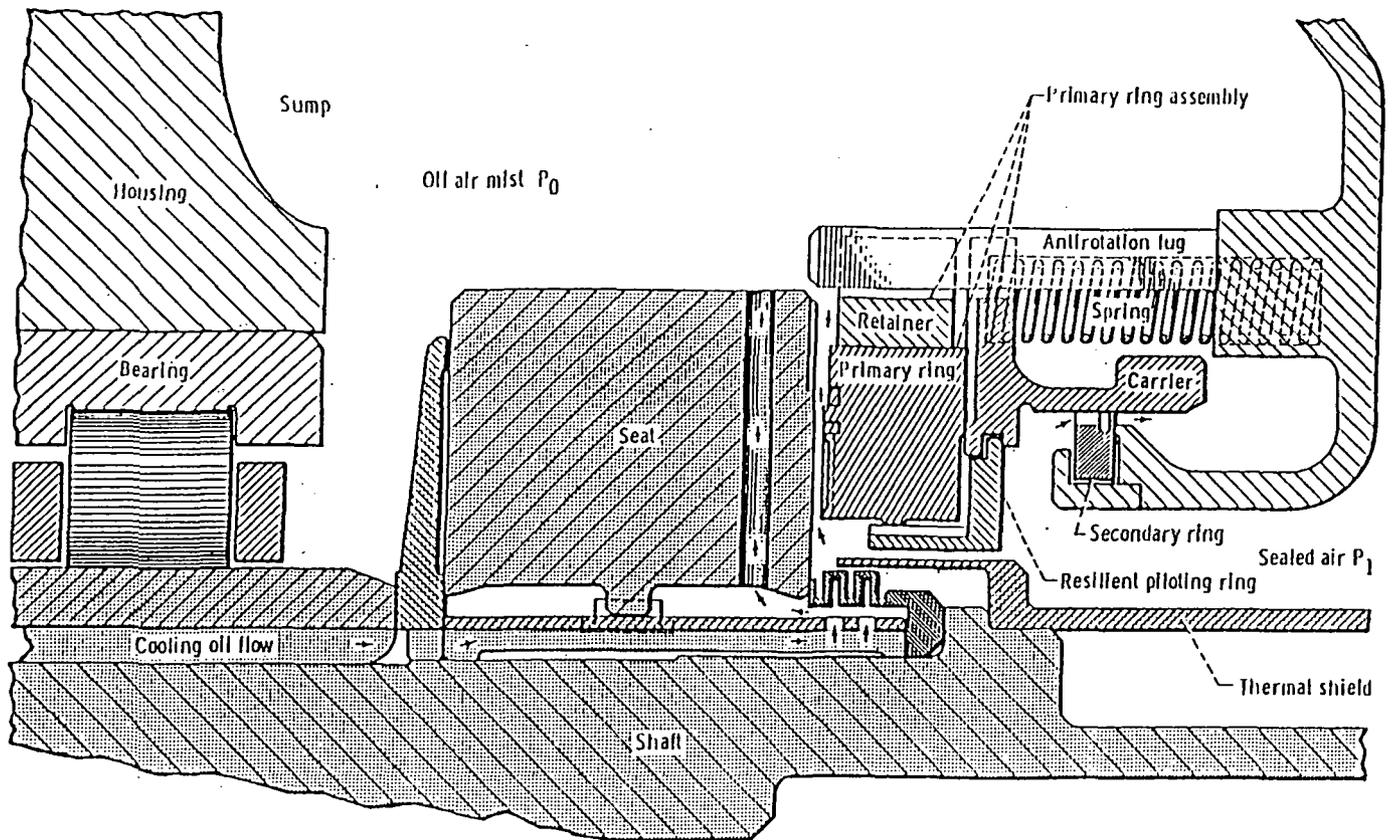
SEALS RELATED RESEARCH AT LEWIS RESEARCH CENTER

R. C. Hendricks
NASA Lewis Research Center
Cleveland, Ohio

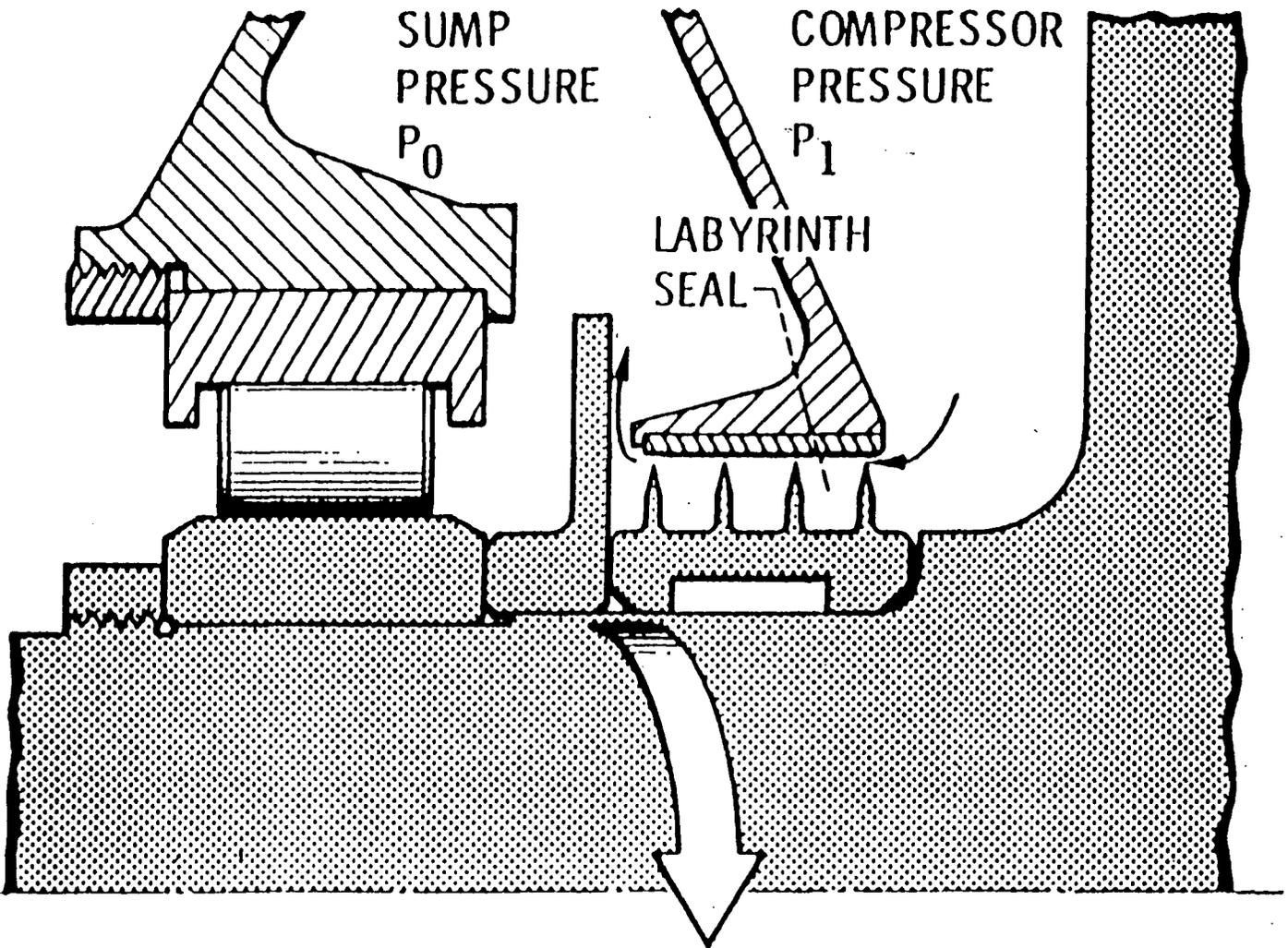
Lewis Research Center has a strong history supporting seals, and seal dynamics, research design, design, fabrication and test. Some efforts include spiral groove, self energized configurations, Rayleigh lift pads, conical, labyrinth, bore, honeycomb, face, tip, support for two-phase work, stepped configurations for SSME, near critical expansion, visualization, dynamic analyses, and materials.

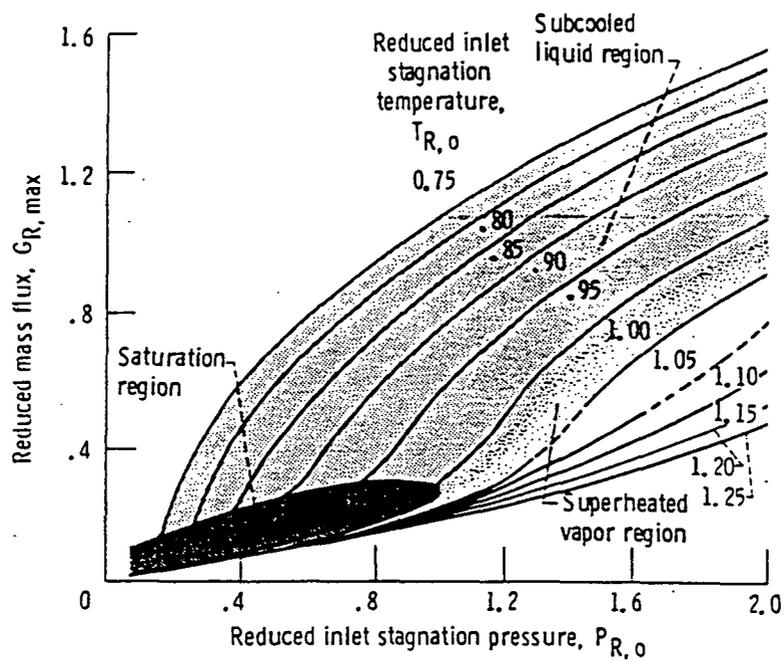
Some researchers on these topics include: Larry Ludwig and Bob Johnson's various seal designs and application; John Zuk's cavity analysis and seals codes; Tom Strom's face and spiral groove seals; Dave Fleming's various configurations including conical seals and dynamic stability predictions; Bob Bill's abradable and ceramic configurations; Bill Hughes' two-phase flow analyses; Hal Sliney's materials work; Gordon Alen, Bill Loomis, El-Dirusso and Bill Hady's test data comparisons and analyses; Isaac Etsion's analyses of a variety of configurations; Allen Lubeck's face and shaft seal analyses; Hendricks' shuttle seal and multiple aperture configuration research; Glen McDonald and Hendricks' ceramic shroud seal; and the Texas A&M program to cite some of LeRC's efforts.

Some current efforts include: Bruce Steinetz and Paul Sirocky's self sealing linear segmented ceramic configurations; George Bobula, Bob Bill and Hendricks' T700 brush seal engine test; flow and duration characteristics of brush seals and other configurations with Margaret Proctor and Julie Schlumberger; cryogenic hydrogen brush seal tests at Rocketdyne with Joe Scharrer; Teledyne brush seal tester with USAF; and support for contracts and grants.

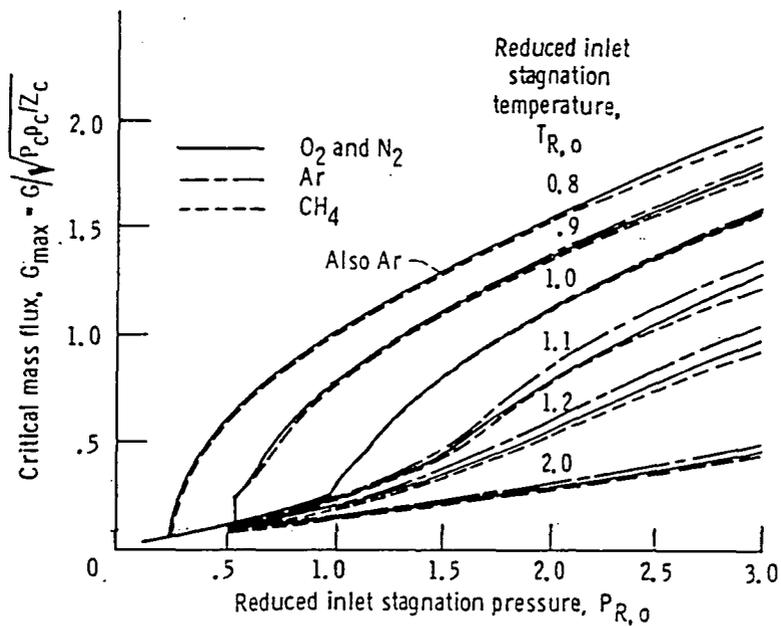


LABYRINTH SEAL

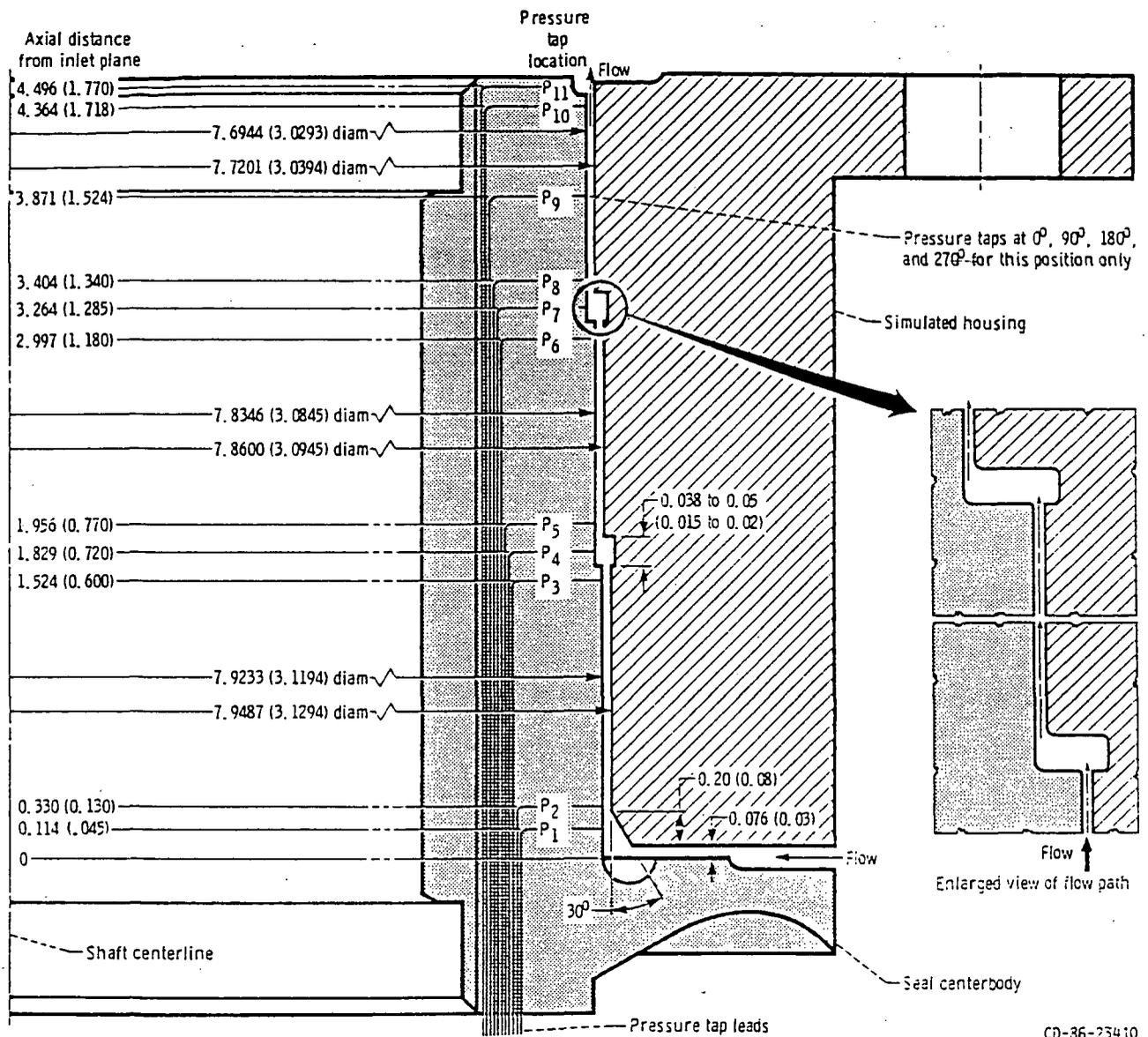




Reduced choked mass flux based on homogeneous isentropic equilibrium model.



Critical mass fluxes of oxygen, nitrogen, argon, and methane computed by isentropic equilibrium expansion using corresponding-states principles.

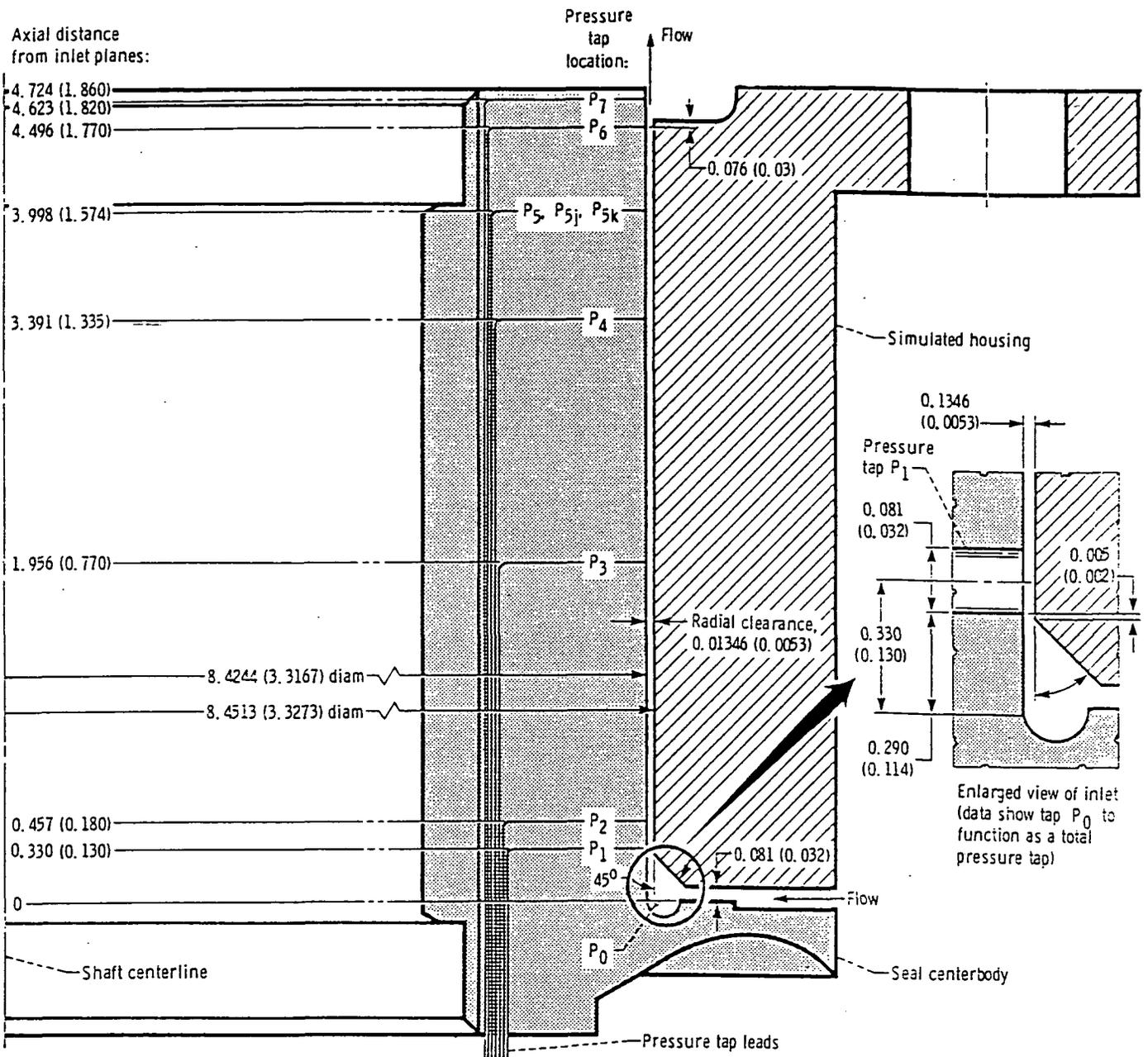


CD-86-23410

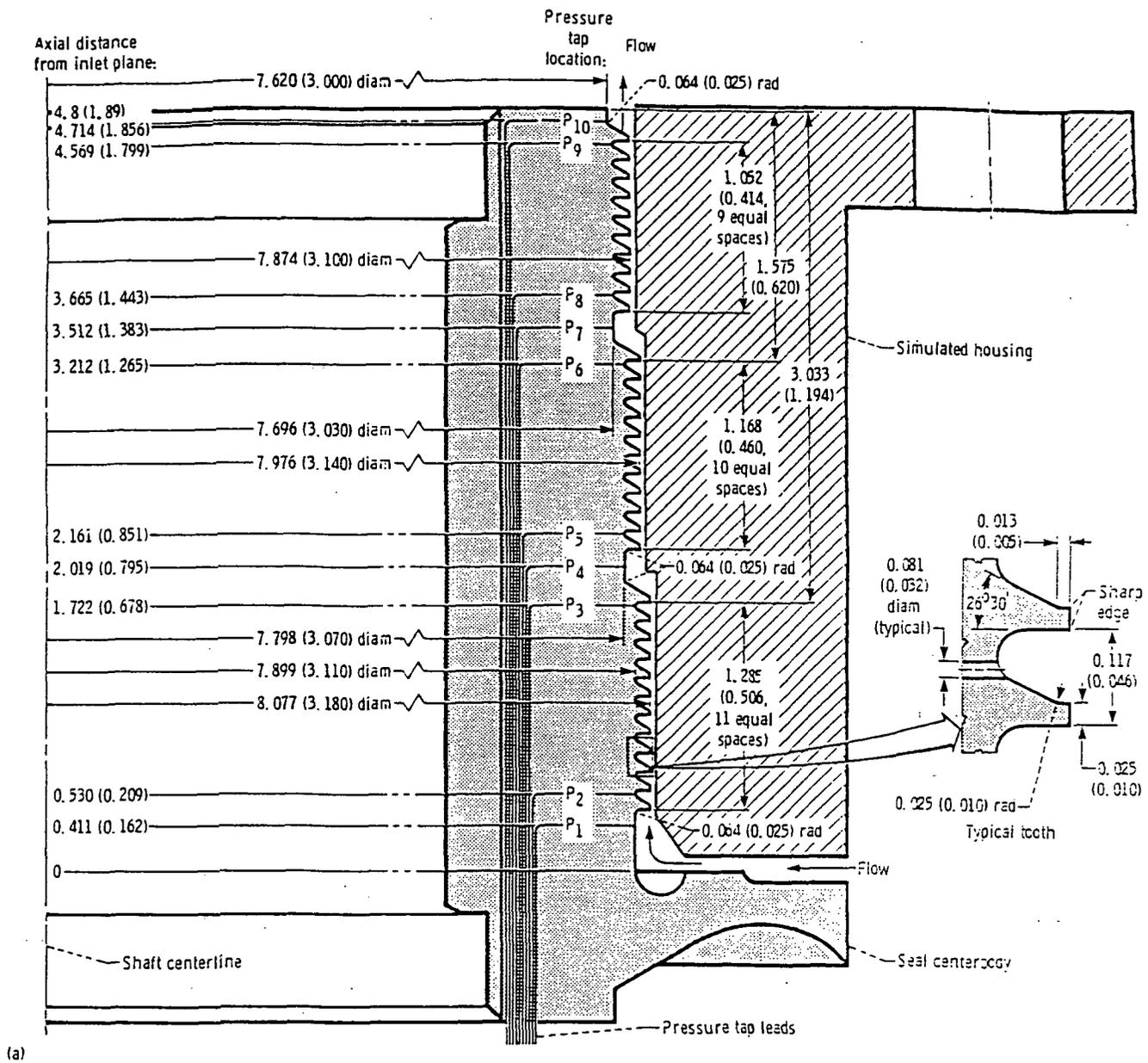
(a) Pressure taps.

(b) Step geometry.

Schematic of three-step flow path and pressure tap locations. (Linear dimensions are in centimeters (inches).)

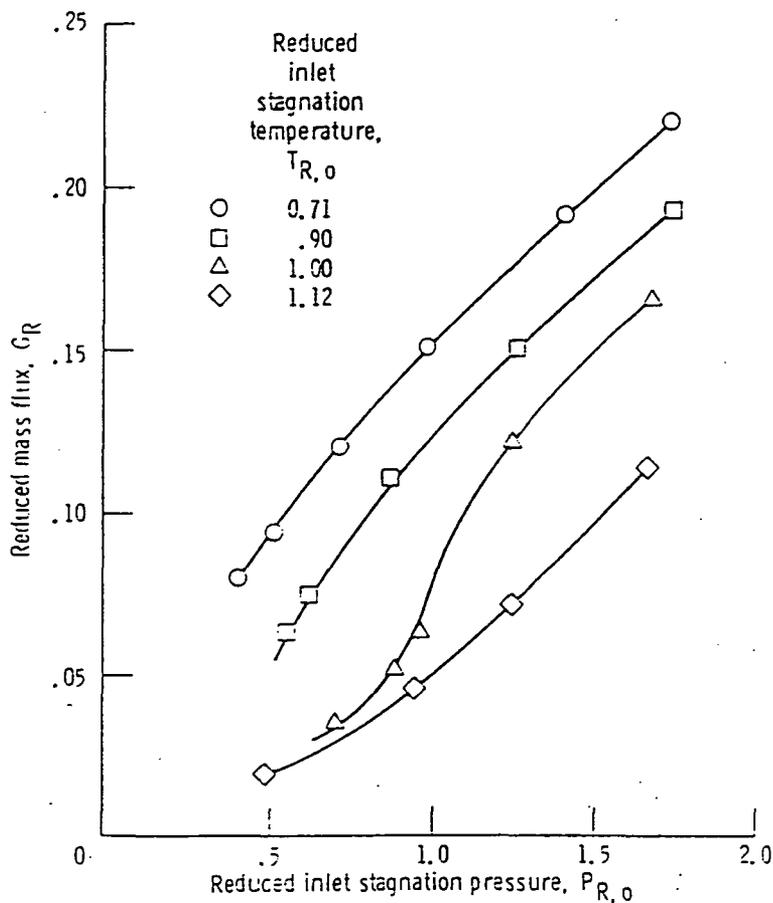


Overview of pressure taps and geometry for straight cylindrical seal. (Linear dimensions are in centimeters (inches).)

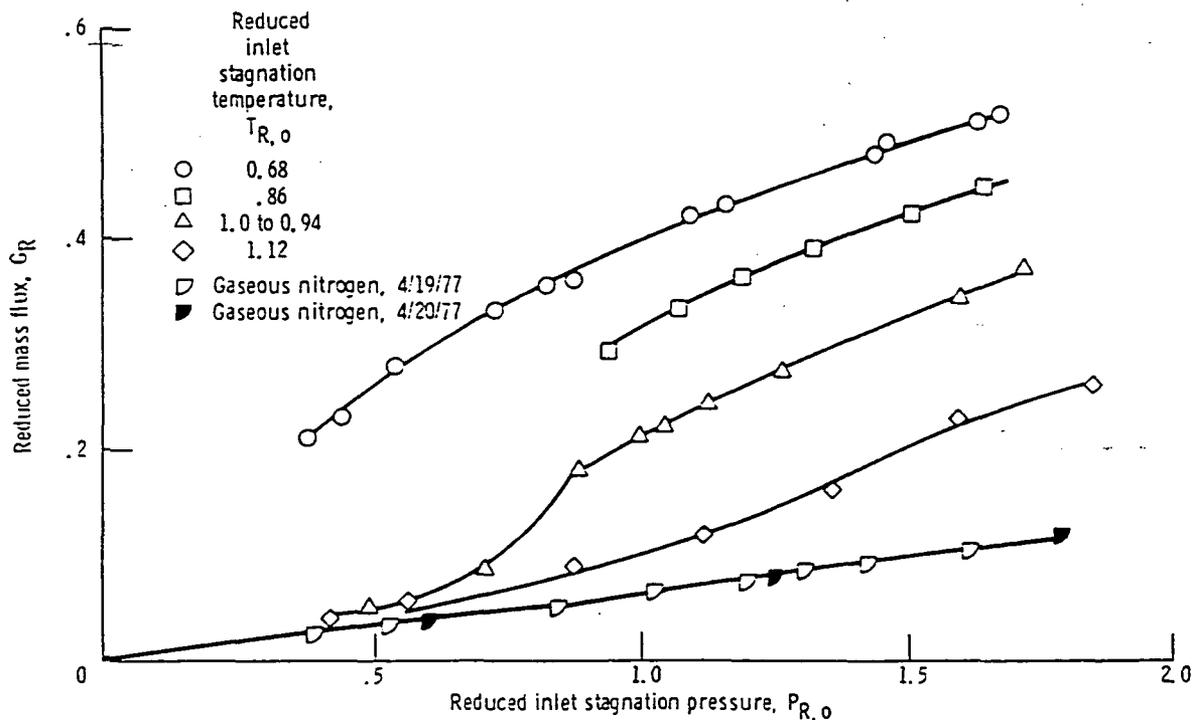


(a) Pressure taps.

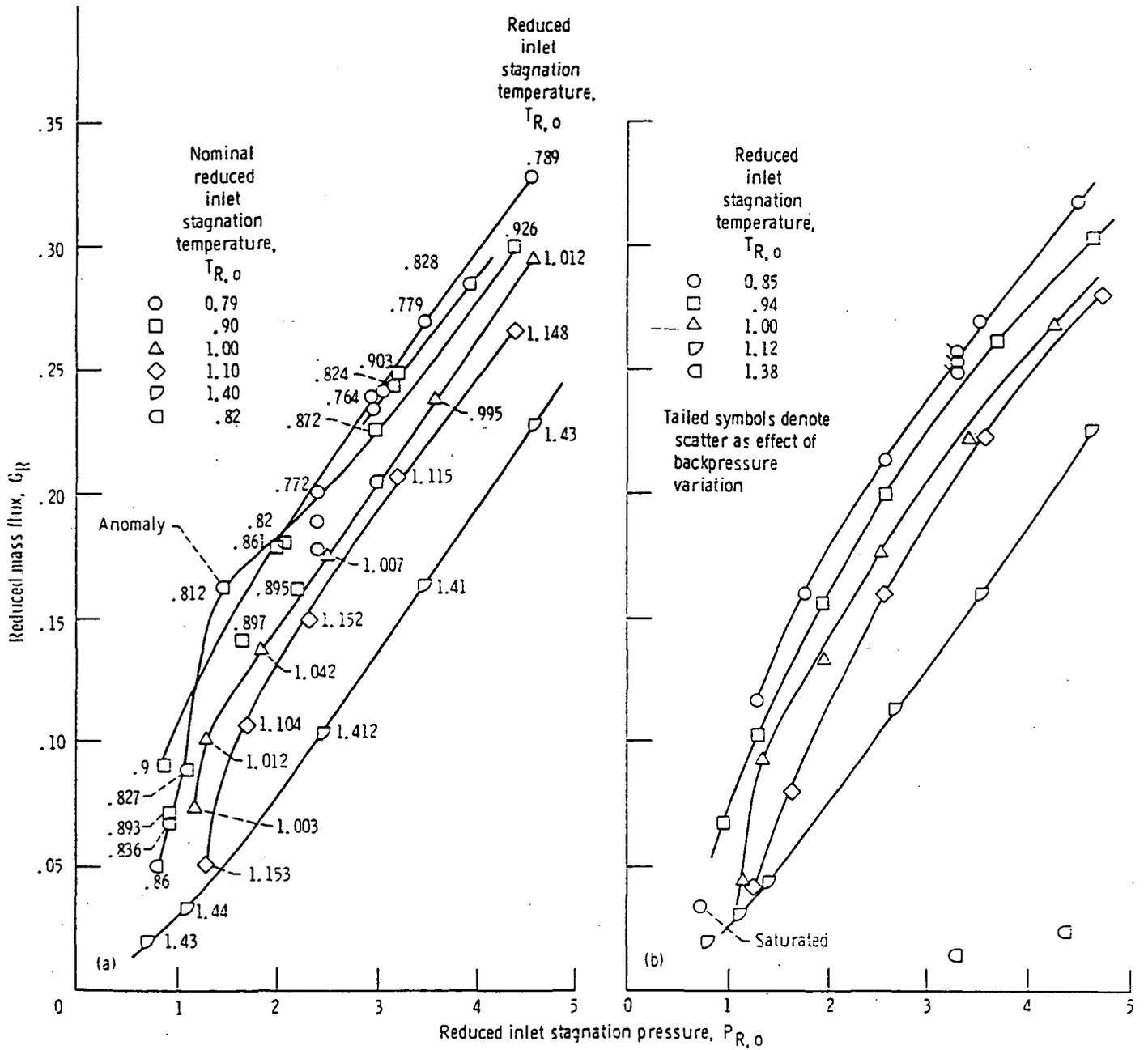
Overview of pressure taps and geometry for three-step labyrinth seal. (Linear dimensions are in centimeters (inches), and surface finish on all machined surfaces is 32.)



Reduced mass flux of fluid nitrogen through three-step labyrinth seal in concentric position, as function of reduced inlet stagnation pressure.

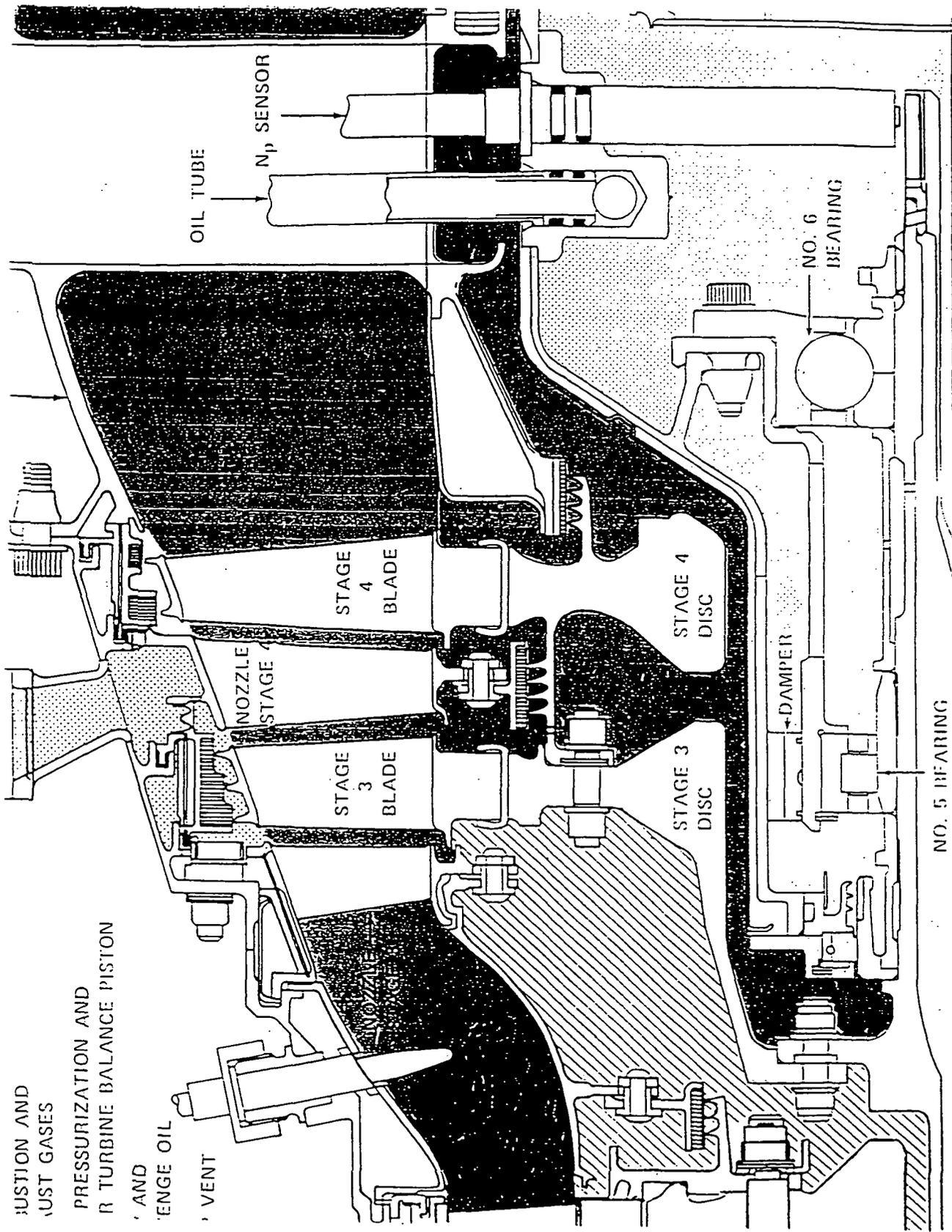


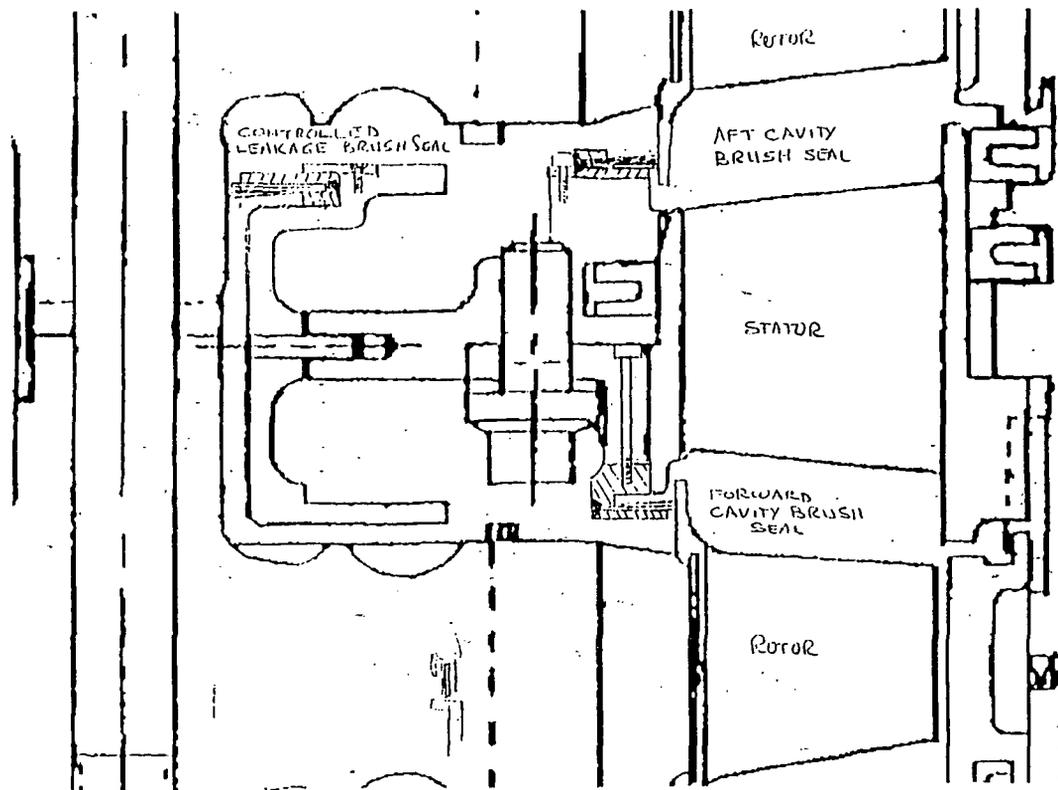
Reduced mass flux of fluid nitrogen through three-step cylindrical seal in fully eccentric position, as function of reduced inlet stagnation pressure.



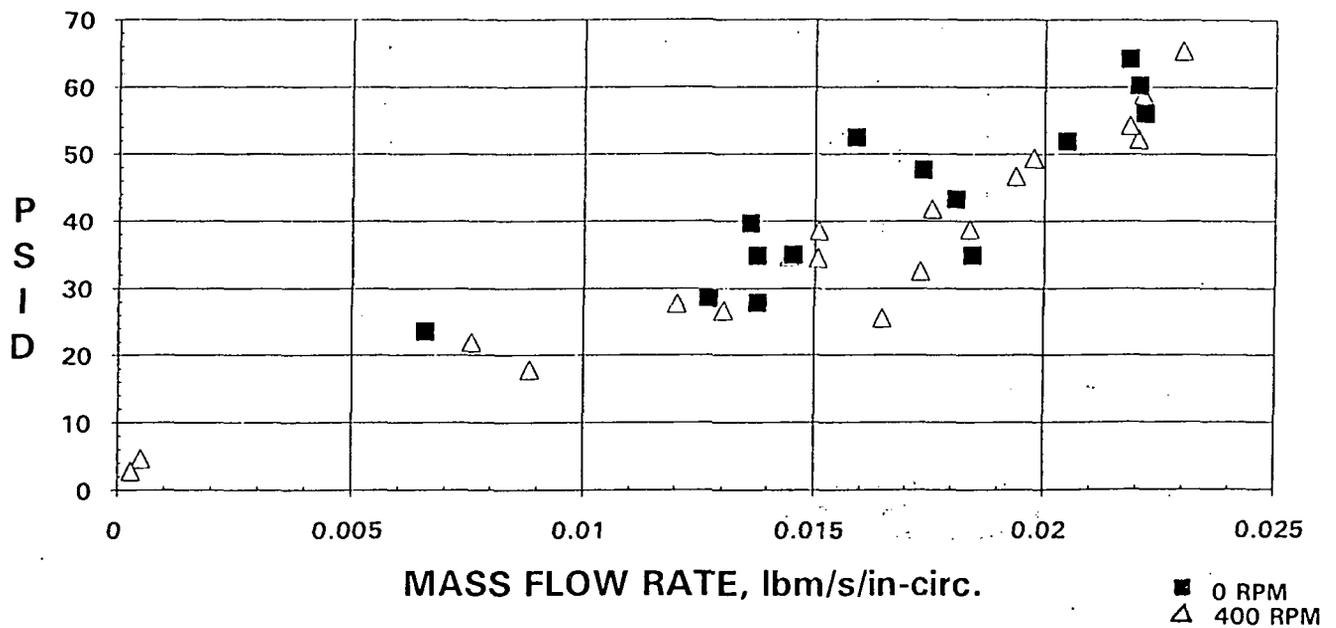
(a) Fluid hydrogen with an anomaly.
 (b) Fluid hydrogen with backpressure control.

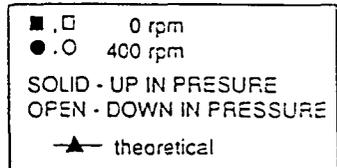
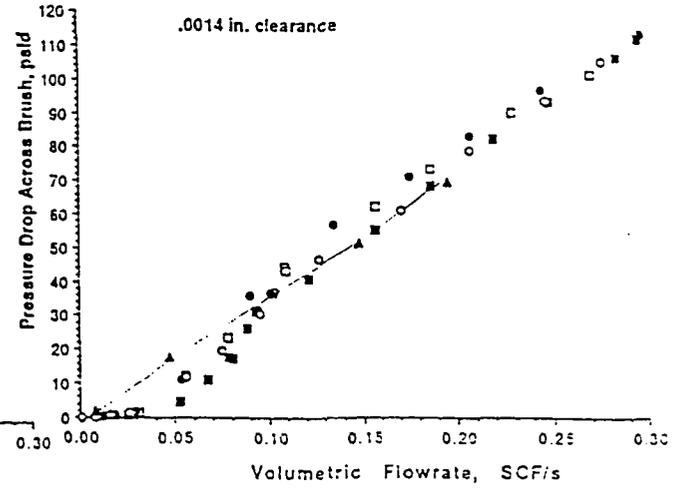
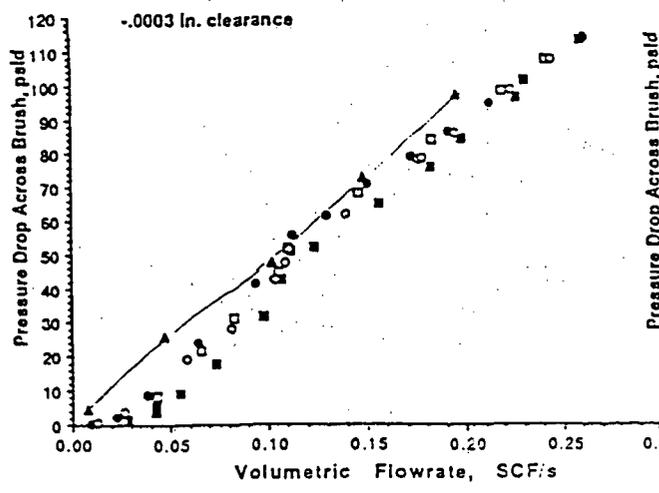
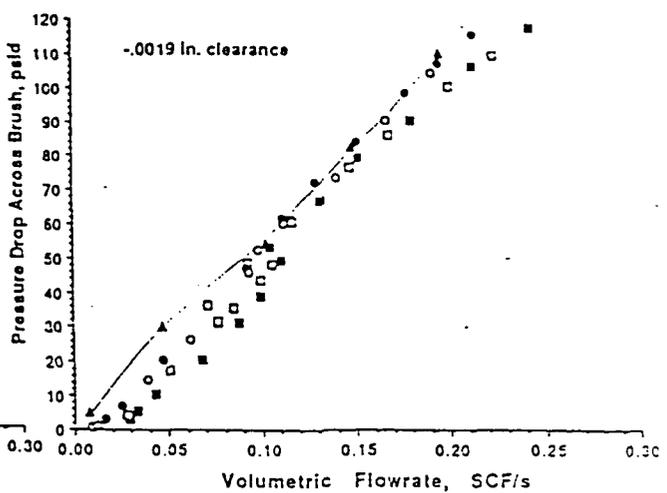
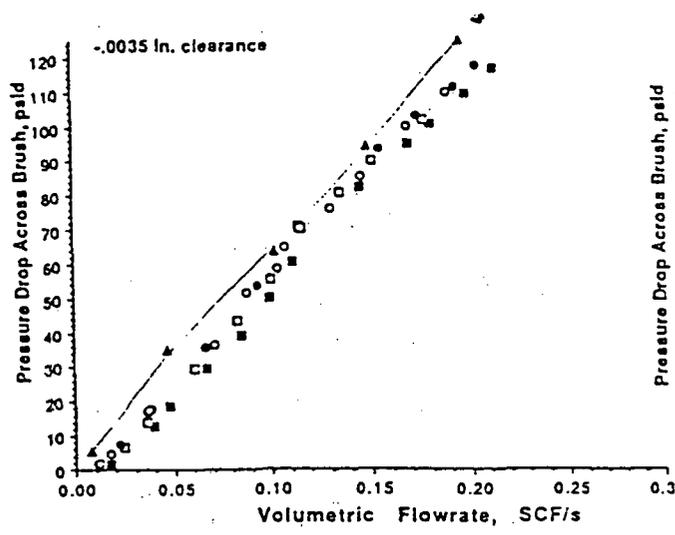
Reduced mass flux of fluid hydrogen through three-step labyrinth seal in concentric position, as function of reduced inlet stagnation pressure.





PRESSURE DROP ACROSS BRUSH VERSUS MASS FLOW RATE
(IN LIQUID NITROGEN)





COMPARISON OF DATA AT 0 AND 400 RPM WITHOUT FLOW STRAIGHTENER

MSFC HYDROSTATIC BEARING ACTIVITIES

Theodore G. Benjamin
Computational Fluid Dynamics Branch
Aerophysics Division
Structures and Dynamics Laboratory
George C. Marshall Space Flight Center

The basic approach for analyzing hydrostatic bearing flows at MSFC is three pronged. First, the Hydrostatic Bearing Team has responsibility for assessing and evaluating flow codes, evaluating friction, ignition, and galling effects, evaluating wear, and performing tests. Secondly, the Office of Aerospace and Exploration Technology Turbomachinery Seals Tasks consist of tests and analyses. Thirdly, MSFC in-house analyses utilize one-dimensional bulk-flow codes; computational fluid dynamics (CFD) analysis is used to enhance understanding of bearing flow physics or to perform parametric analyses that are outside the bulk-flow data base. As long as the bulk-flow codes are accurate enough for most needs, they will be utilized accordingly and will be supported by CFD analysis on an as-needed basis.

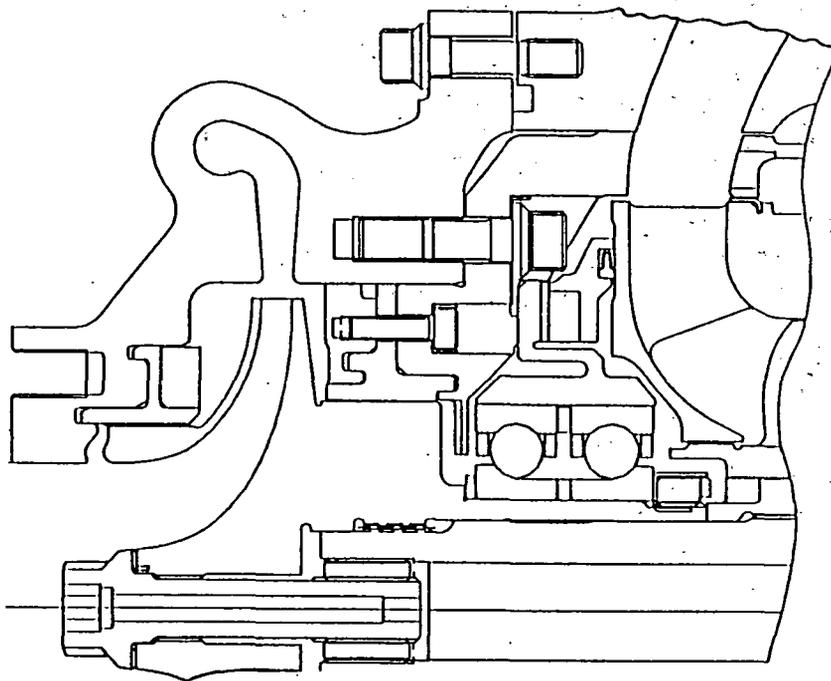
Overview

- **Hydrostatic Bearing Team formed 02/16/90**
 - Assess and validate flow codes
 - Evaluate friction and ignition effects
 - Evaluate wear and galling effects
 - Verify design by HPOTP pump-end test (Rocketdyne IRAD)
 - TTB in October / November timeframe
- **OAET Turbomachinery Seals Tasks**
 - Three tasks in place - - E3b, E4e, and LSVT13
 - One task pending - - LSVT8 (NRA)
- **In-house CFD analyses**
 - Baseline damping seal
 - Code validation
 - Rotordynamic coefficients
 - Baseline hydrostatic seal
 - Flow cavity parameters
 - Flow visualization

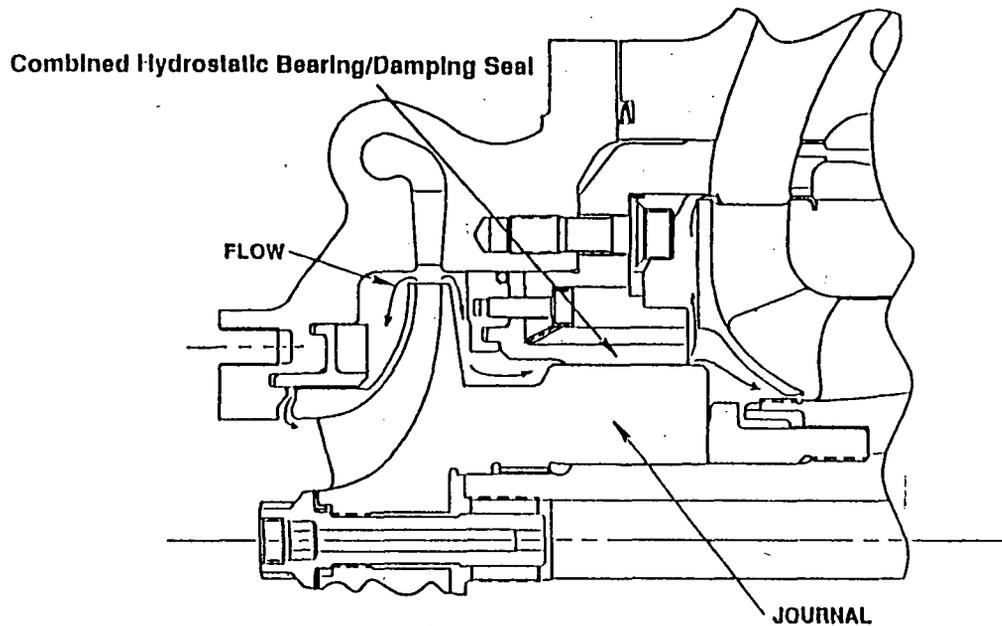
MSFC Turbomachinery Working Group Summary

Work Element Title	Prior	89	90	91	92	93	94	Product
E3e. Damping Seal Rotor Support		[Bar spanning 89-94]						Design criteria for rolling element/damping seal assemblies for high side loads; Results led to current TTB validation for HPOTP
E4e. Damping Seals for Turbomachinery		[Bar spanning 89-94]						Test verification of dynamic properties of damping seals; Wyle tester; measures rotordynamic coefficient density; Test in progress
LSVT8. Verification of Damping Seal Modeling Techniques				[Bar spanning 91-93]				Hydrostatic bearing data base for code validation; NRA contractor TBD
LSVT13. Experimental Verification of Rotordynamic Analysis				[Bar spanning 91-92]				Hydrostatic damping bearing data for rotordynamic coefficients; Internally and externally fed HPOTP turbine end configuration

Flight Configuration HPOTP Phase II Preburner Pump Bearing Package



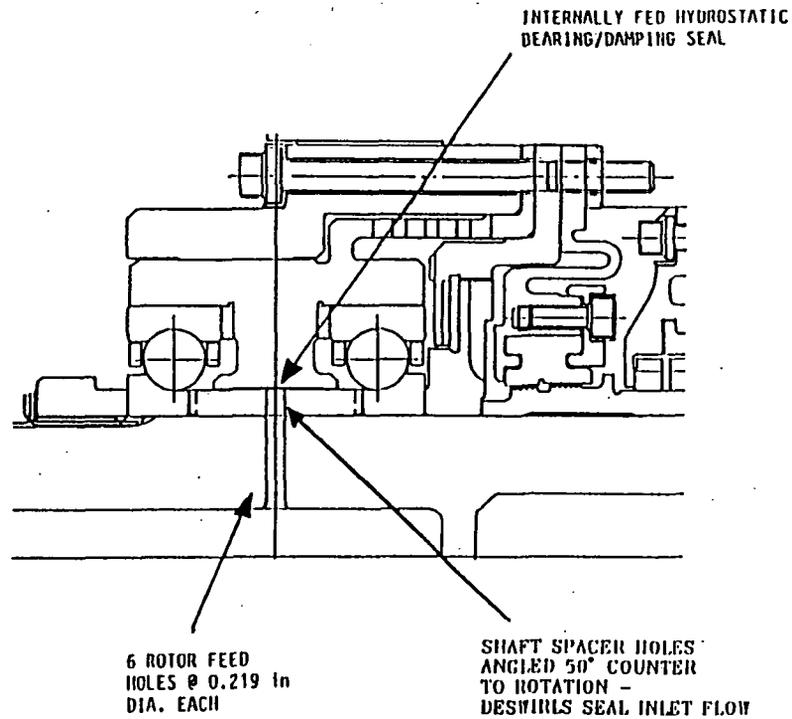
HPOTP Pump End Retrofit Annular Hydrostatic Bearing Axially Fed



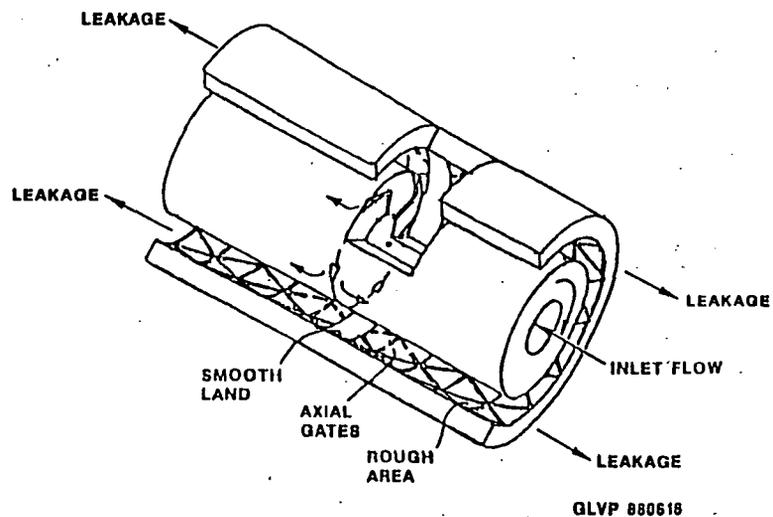
Experimental Verification of Rotordynamic Analysis MSFC Program Status

- Complementary Damping bearing development initiated in October
 - Verifies rotordynamic coefficient calculations for hydrostatic bearings
- Test four hydrostatic bearings in modified long life tester
 - HCFC test fluid
 - Two bearings internally fed through the shaft
 - Conventional and damping designs TBD
 - Two bearings internally fed through the stator
 - Conventional and damping designs TBD
- Extracts all rotordynamic coefficients
 - Measures leakage and frictional torque
- Conceptually designs new HPOTP turbine end package
 - Includes lowest whirl ratio bearing tested
 - Provides manufacturing estimate

Potential HPOTP Turbine End Hybrid Bearing Retrofit

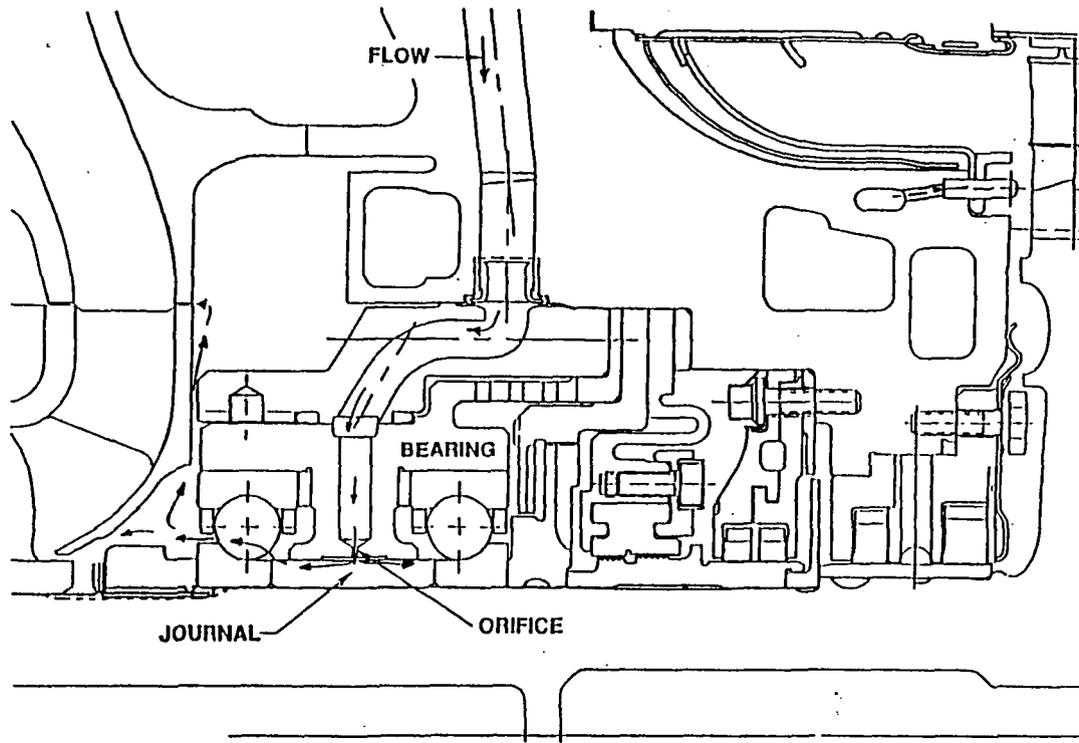


Internally Fed Damping Bearing



- George Von Pragenau, NASA-MSFC, Design Concept

Potential HPOTP Turbine End Hybrid Bearing Retrofit



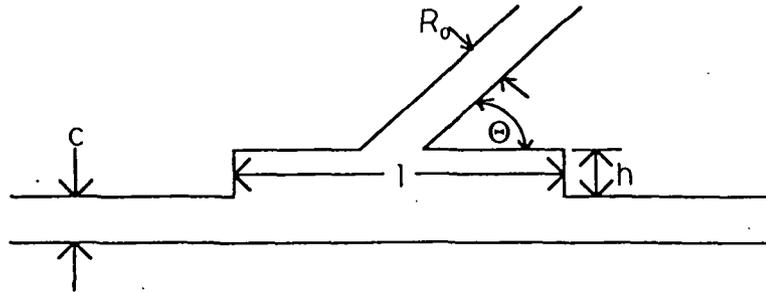
In-house CFD Analysis

- 3-D analysis; 60° slice of bearing
- Single-phase incompressible Navier-Stokes analysis; constant γH_2
- Rotational Reynolds number based on annulus width $\sim 4.8 \times 10^4$
- Multi-block solution in progress with FDNS3D code
 - 3-dimensional pressure-based finite-difference Navier-Stokes solver
 - PISO algorithm with modified Stone's solver
 - Convection term differencing
 - Central
 - 3rd-order upwind
 - 2nd-order upwind
- K- ϵ turbulence model
 - Two high-Reynolds-number models
 - Four low-Reynolds-number models

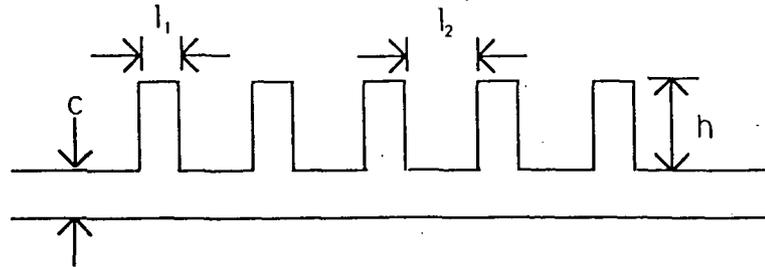
In-House CFD Analysis

Configuration

Baseline Hydrostatic Seal

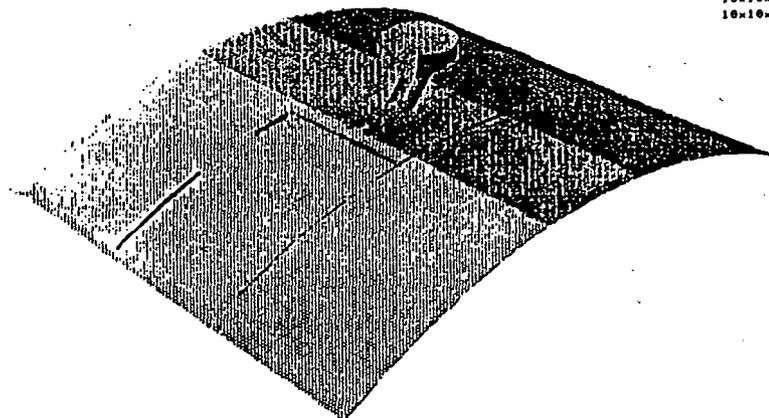


Baseline Damping Seal



In-House CFD Analysis

Typical Grid



96x106x7	GRID 1
68x58x12	GRID 2
10x10x15	GRID 3
10x10x7	GRID 4
10x10x12	GRID 5

Summary

- **Hydrostatic Bearing Team meeting regularly with Rocketdyne design organization**
 - TTB validation for HPOTP set for October/November 1991 timeframe
- **OAET tasks defined**
 - Data bases for determining rotordynamic coefficients and flow physics are evolving
- **Bulk-flow computer design codes are in place and being extended**
 - CFD being applied to support bulk-flow code development for assessing secondary flows in damping seal pockets
- **In-house analysis initiated to assess generic flows related to hydrostatic bearings**

ARMY RESEARCH CONCERNS IN ENGINE SEALING

Robert C. Bill
U.S. Army Propulsion Systems Directorate
Lewis Research Center

The Army Propulsion Directorate is primarily concerned with small engine technology, where sealing performance is most critical. Tip leakage and secondary flow losses have a much greater performance impact on small engine aero-components than on large engines. A brief survey and critique of presently employed sealing concepts is presented. Some recent new research thrusts that show promise for substantial improvement are discussed. An especially promising approach for small engine applications is brush seals. Brush seal concepts are being considered for outer air seal and secondary airflow system seal locations.

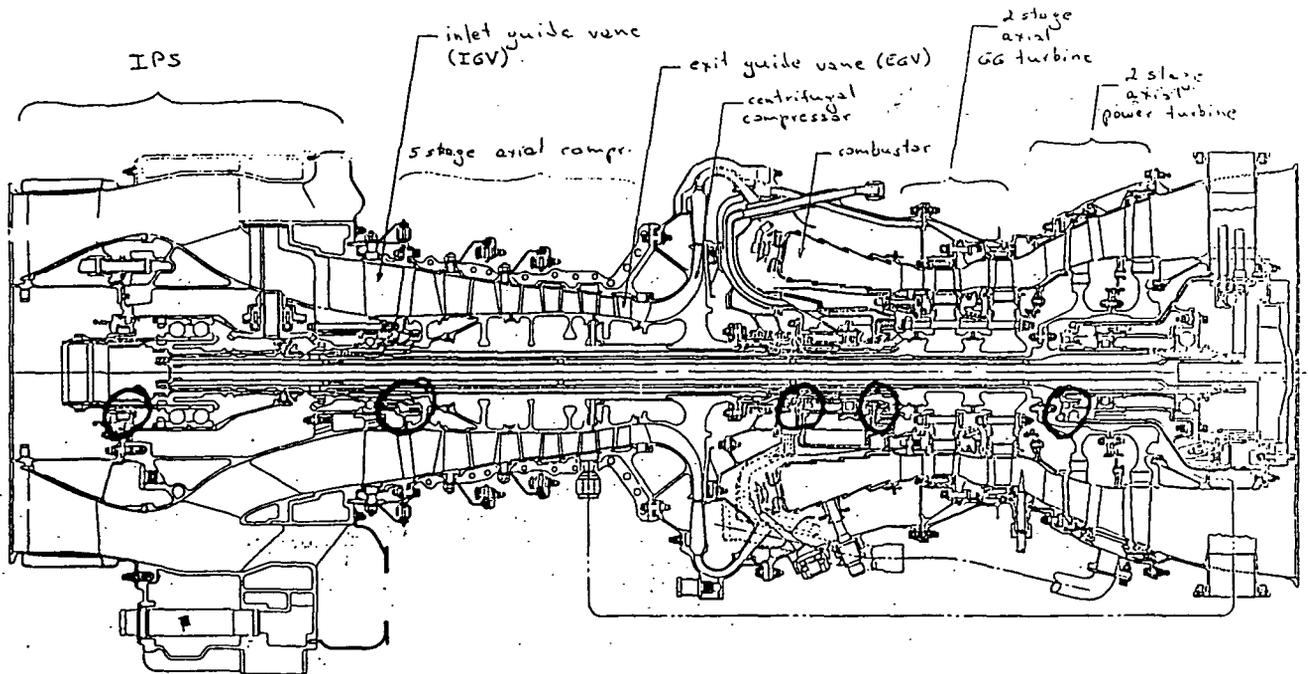
PRIMARY FUNCTIONS OF ENGINE SEALING

- ISOLATE BEARING COMPARTMENTS FROM ENGINE E
- REDUCE EFFICIENCY LOSSES CAUSED BY LEAKAGE
- CONTROL SECONDARY AIRFLOW SYSTEM
 - COOLING
 - PURGE
 - BUFFER
 - PRESSURE BALANCE

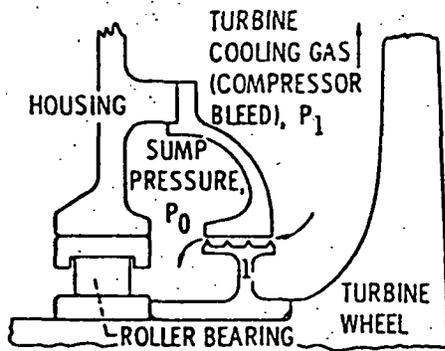
SHAFT SEALS

- ISOLATE BEARING CAVITIES FROM ENGINE ENVIRONMENT
- PREVENT LOSS OF LUBRICANT

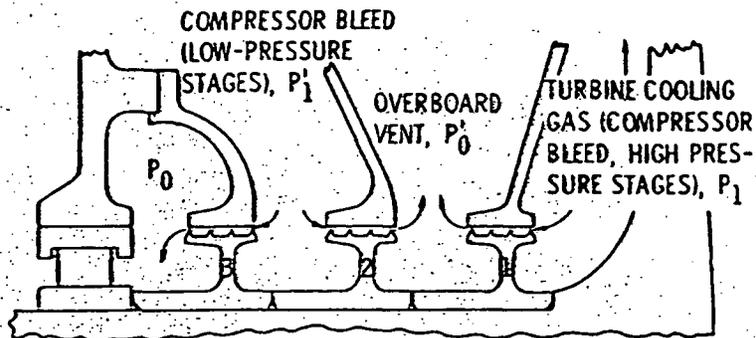
T700 Turboshaft Engine



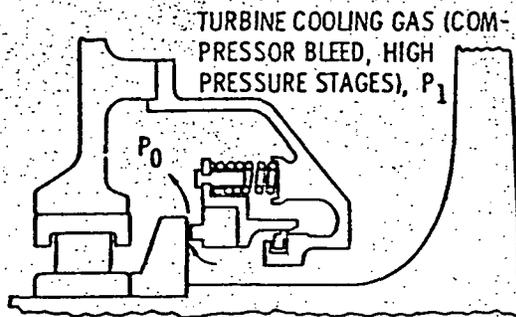
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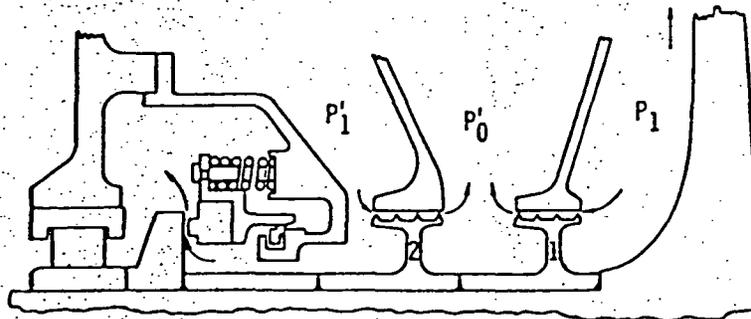
(a) SINGLE LABYRINTH, EARLY ENGINES.



(b) MULTIPLE LABYRINTH FOR HIGH-TEMPERATURE HIGH-PRESSURE TURBINE COOLING GAS.



(c) CONVENTIONAL FACE SEAL



(d) CONVENTIONAL FACE SEAL WITH LABYRINTH SEAL FOR HIGH-TEMPERATURE, HIGH-PRESSURE COOLING GAS.

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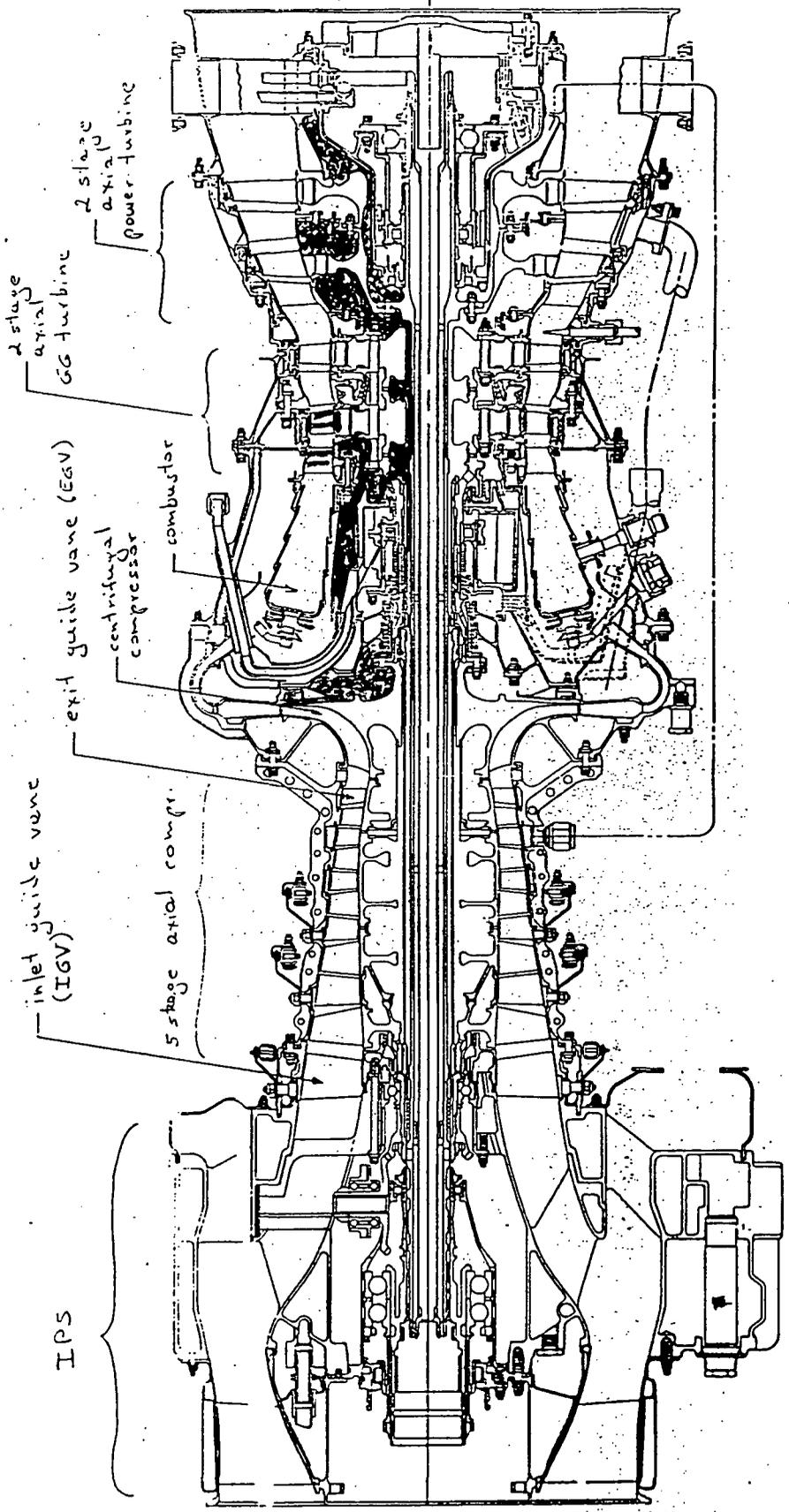
SUMMARY - SHAFT SEALS

- MUST FUNCTION AS SEALS - NOT FLOW RESTRICTORS
- RUB CAPABILITY AND TEMPERATURE CAPABILITY OF MATERIALS ARE TECHNICAL BARRIERS
- NEW CONCEPTS BEING EXAMINED
 - "BRUSH" SEALS
 - FLUIDIC SEALS

INNER AIR SEALS CONTROL SECONDARY AIRFLOW SYSTEM

- COOLING AIR TO HOT SECTION COMPONENTS
- DISK CAVITY PURGE AIR
- PRESSURE BALANCE SYSTEM
- SHAFT SEAL BUFFER AIR

T700 Turboshaft Engine



IPS

inlet guide vane (IGV)

5 stage axial comp.

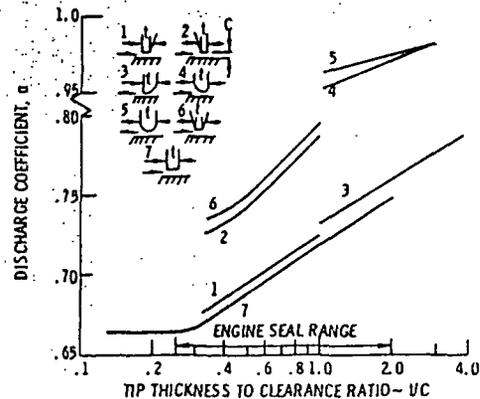
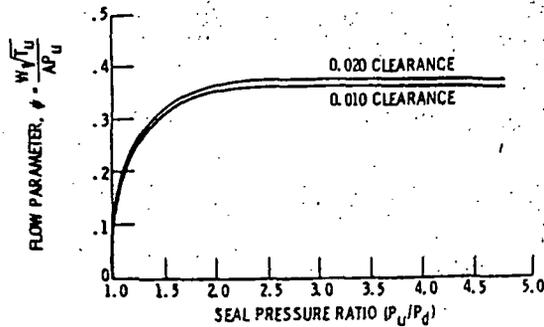
exit guide vane (EGV)
centrifugal compressor

combustor

2 stage axial compressor
2 stage axial power turbine

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**MAINTAINING MINIMUM CLEARANCE AND KNIFE-EDGE
GEOMETRY ARE CRITICAL TO LABYRINTH
SEAL PERFORMANCE.**

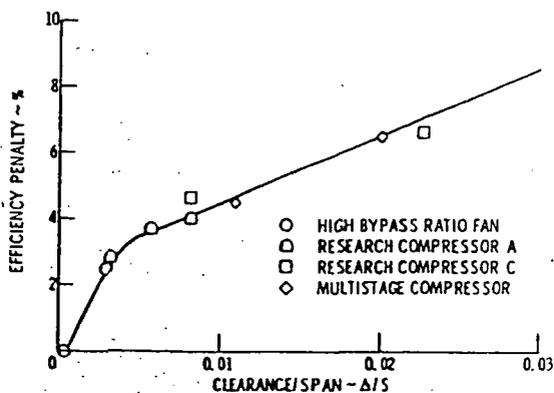


SUMMARY - IAS

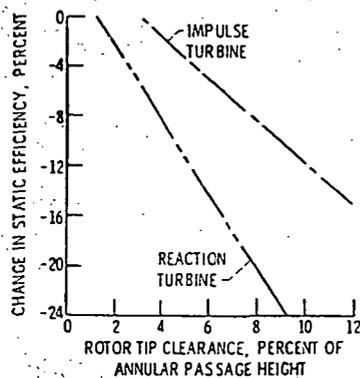
- CLEARANCE PREDICTION AND CONTROL ARE CRITICAL TO RELIABLE FUNCTION OF IAS SYSTEM
- EXISTING FLOW MODELS ARE CRUDE, SEMI-EMPERICAL
- MATERIAL REQUIREMENTS SIMILAR TO THOSE FOR OAS
- STRUCTURAL STABILITY CONCERNS AND GUIDELINES EXIST
 - AEROELASTIC INSTABILITIES
 - THERMOELASTIC INSTABILITIES

OUTER AIR SEALS REDUCE BLADE TIP LOSSES

- OVER THE TIP LEAKAGE
- INDUCED SECONDARY FLOW LOSSES



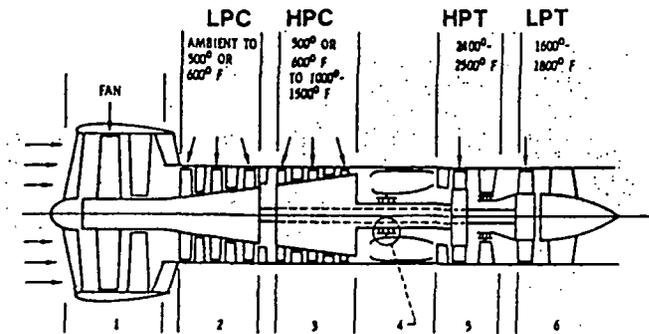
- Typical compressor efficiency penalty as a function of blade clearance-to-span ratio



- Effect of rotor tip clearance on performance for various turbines

OAS MATERIAL REQUIREMENTS

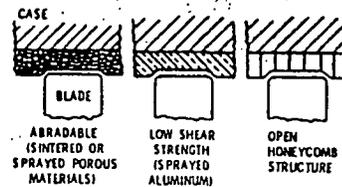
- ABRADABILITY
- EROSION RESISTANCE
- CAPACITY TO SURVIVE IN ENGINE ENVIRONMENT



TYPICAL SEAL MATLS:

- 1 SILICONE RUBBER; Al HONEYCOMB; EPOXY
- 2 SPRAYED Al; SPRAYED NICKEL-GRAPHITE; SILICONE RUBBER; FIBERMETAL
- 3 HASTELLOY-X; FIBERMETAL; SPRAYED NICKEL-GRAPHITE; SPRAYED NICHROME WITH ADDITIVES
- 4 LABYRINTH SEALS; Ag BRAZE; FIBERMETAL; HONEYCOMB
- 5 CAST SUPERALLOY (COOLED); SINTERED HIGH TEMP METALS; CERAMICS (EXPERIMENTAL)
- 6 SUPERALLOY HONEYCOMB

GENERAL CLASSES OF ABRADABLE MATERIALS



SUMMARY - OAS

- RETENTION OF MINIMUM TIP CLEARANCES IS CRITICAL TO THE EFFICIENCY OF AERO-COMPONENTS
- OAS SYSTEM MUST MEET CONFLICTING DEMANDS OF:
 - ABRADABILITY
 - EROSION RESISTANCE
 - DURABILITY
- OAS TECHNOLOGY HAS FOCUSED HEAVILY ON MATERIAL APPROACHES

SEALS RESEARCH AT TEXAS A&M UNIVERSITY

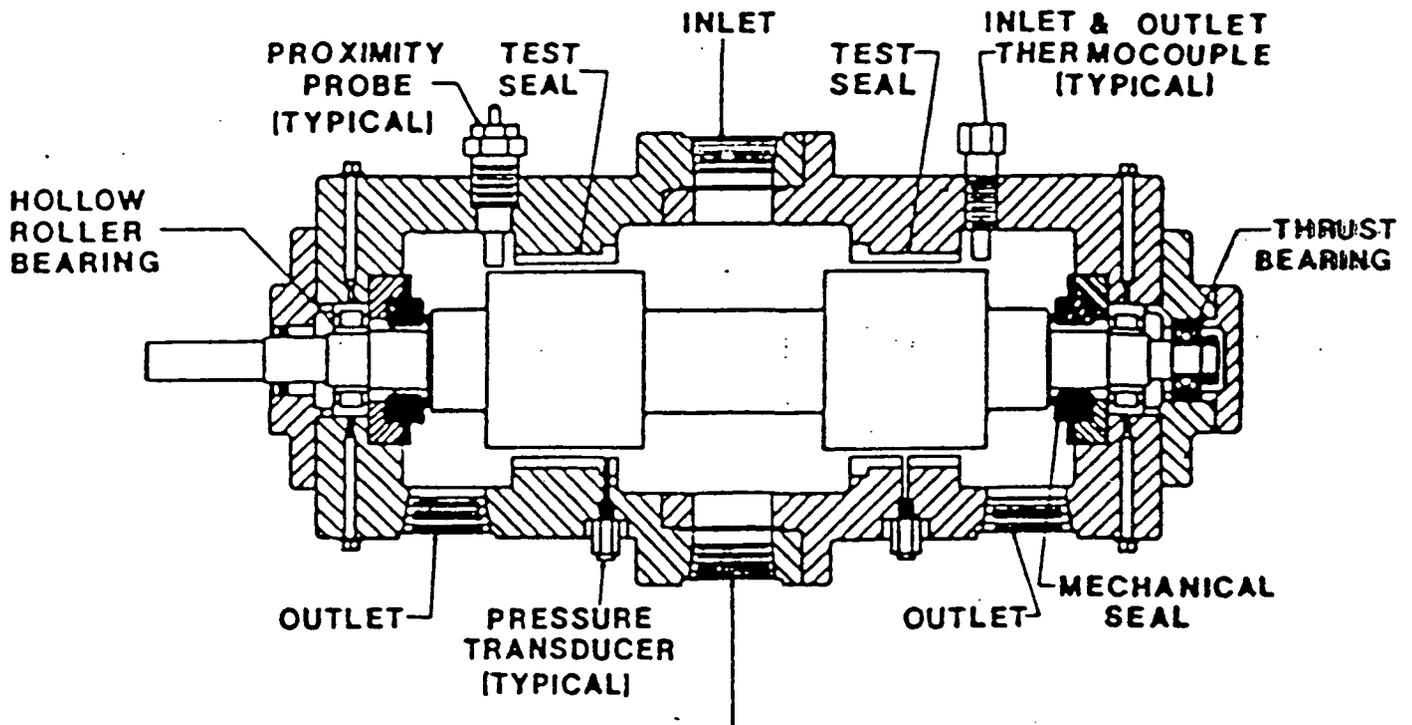
Gerald L. Morrison
Turbomachinery Laboratory
Texas A&M University

The Turbomachinery Laboratory at Texas A&M University has been providing experimental data and computational codes for the design seals for many years. Dr. Dara Childs began the program with the development of a Halon based seal test rig. This facility provided information about the effective stiffness and damping in whirling seals. The Halon effectively simulated cryogenic fluids. Dr. Childs then developed another test facility (using air as the working fluid) where the stiffness and damping matrices can be determined. This data has been used to develop bulk flow models of the seal's effect upon rotating machinery. In conjunction with Dr. Child's research. Dr. Luis San Andres has developed a bulk flow model for calculation of performance and rotordynamic coefficients of annular pressure seals of arbitrary non-uniform clearance for barotropic fluids such as LH2, LOX, LN2, and CH4. This program is very efficient (fast) and converges for very large eccentricities. Dr. Childs is now working on a bulk flow analysis of the effects of the impeller-shroud interaction upon the stability of pumps.

Dr. Gerald Morrison designed and used this data along with data from other researchers to develop an empirical leakage prediction code for NASA Marshall. He is presently studying, in detail, the flow field inside labyrinth and annular seals. Dr. Morrison is using an advanced 3-D laser Doppler anemometer system to measure the mean velocity and entire Reynolds stress tensor distribution throughout the seals. Concentric and statically eccentric seals have been studied. He is presently studying whirling seals. The data obtained are providing valuable information about the flow phenomena occurring inside the seals, as well as a data base for comparison with numerical predictions and for turbulence model development.

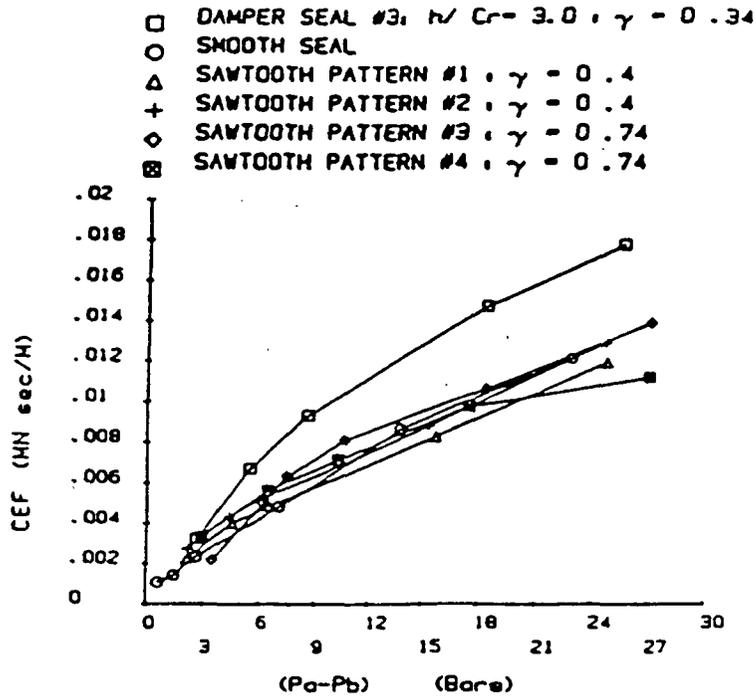
Dr. David Rhode has developed a finite difference computer code for solving the Reynolds averaged Navier Stokes equations inside labyrinth seals. He is currently evaluating a multi-scale k-e turbulence model. Using his computer code, Dr. Rhode designed and patented a new seal geometry. Dr. Rhode is also developing a large scale, 2-D seal flow visualization facility.

HIGH REYNOLDS NUMBER SEAL TEST SECTION

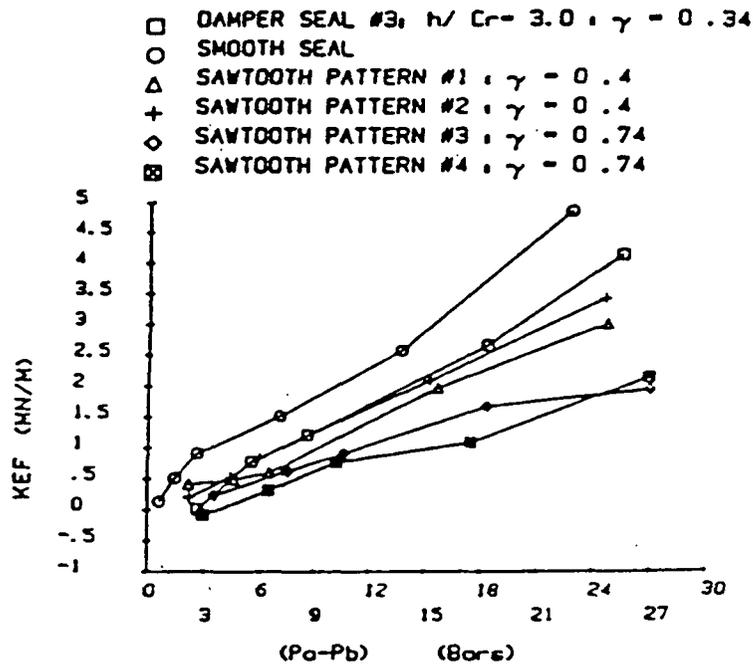


High-Reynolds-number seal test section

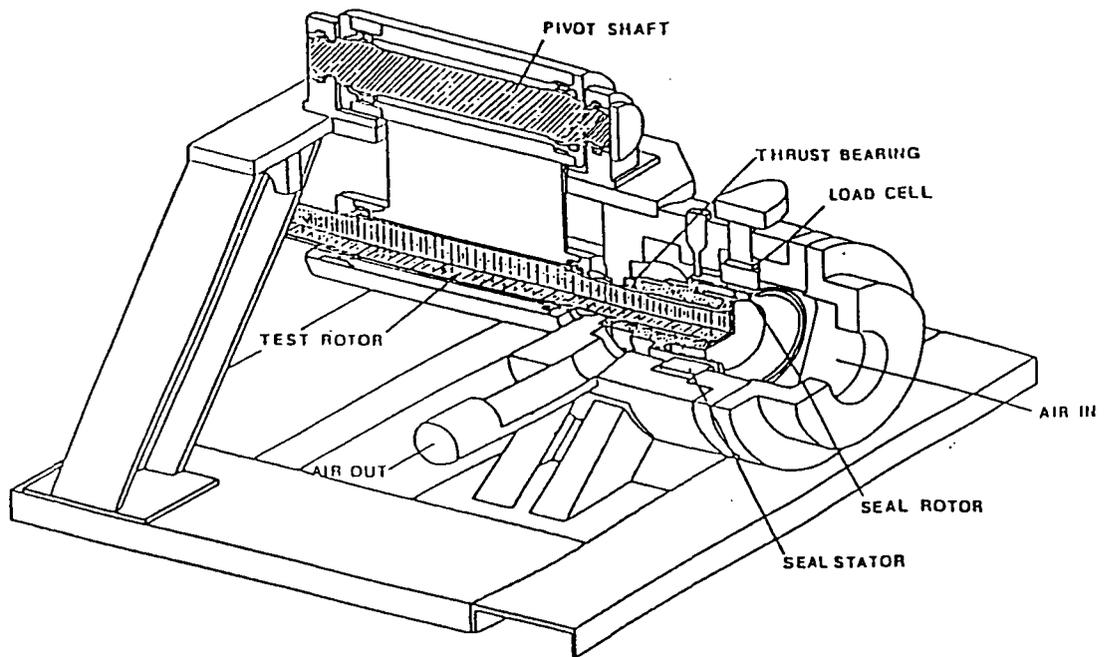
$$\begin{aligned}
 - \begin{Bmatrix} F_x \\ F_y \end{Bmatrix} &= \begin{bmatrix} K & k \\ -k & K \end{bmatrix} \begin{Bmatrix} X \\ Y \end{Bmatrix} \\
 &+ \begin{bmatrix} C & c \\ -c & C \end{bmatrix} \begin{Bmatrix} \dot{X} \\ \dot{Y} \end{Bmatrix} + M \begin{Bmatrix} \ddot{X} \\ \ddot{Y} \end{Bmatrix}
 \end{aligned}$$



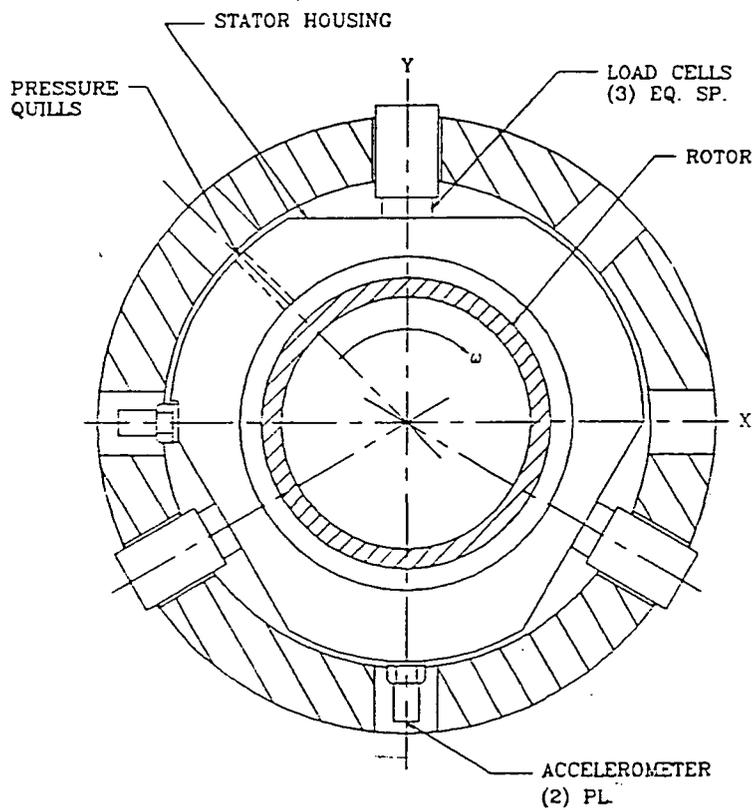
C_{ef} versus ΔP for sawtooth stators 1 through 4 ($h/C_r = 4.8$), a smooth stator, and the optimum-damping round-hole pattern stator



K_{ef} versus ΔP for sawtooth stators 1 through 4 ($h/C_r = 4.8$), a smooth stator, and the optimum-damping round-hole pattern stator



Test apparatus.



End view of the test-section showing stator instrumentation.

Research Objective

To obtain a better understanding of the flow field inside annular and labyrinth seals.

This information is important for:

1. Gaining insight into the turbulent flow fields, how they change with operating conditions, and how they effect leakage and stability.
2. Providing detailed flow field measurements for the purpose of comparing to and helping refine computational predictions of the flow field.

3-D LASER DOPPLER VELOCIMETER

Three Colors: Green, Blue, Violet

Three Bragg Cells: 40 MHz

8.5X and 3.75X Beam Expanders

450 mm Lenses

1 X 1 X 4 Mil Measurement Volume

Simultaneously Measures:

Mean Velocity Vector

U, V, W, with Flow Reversals

Entire Reynolds Stress Tensor

$u'u'$, $v'v'$, $w'w'$, $u'v'$, $u'w'$, $v'w'$

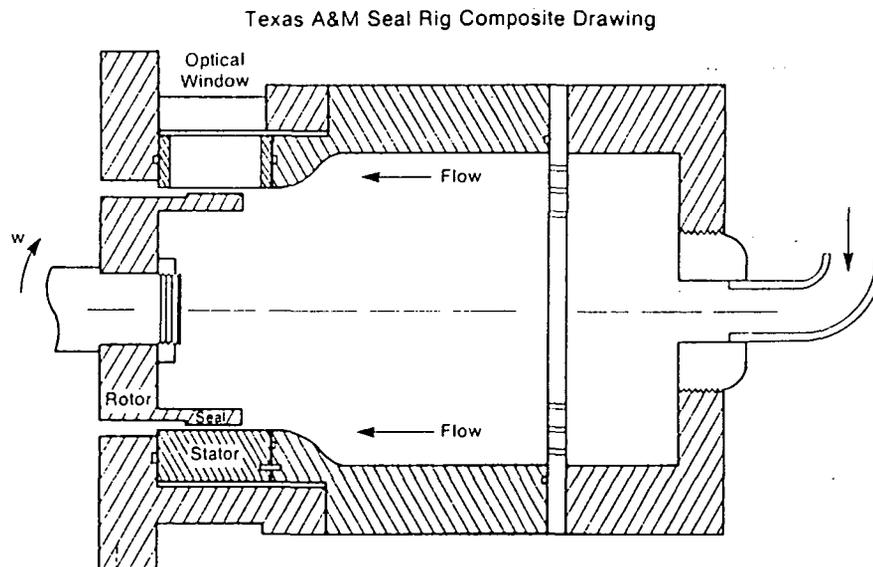
3-D Traverse System

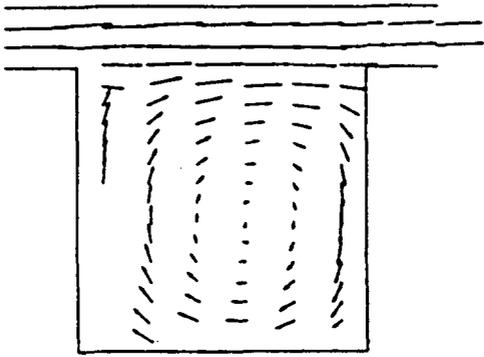
Rotary Encoding System for Periodic Flow Mapping

Integrated Data Acquisition, Analysis, and Traverse Control

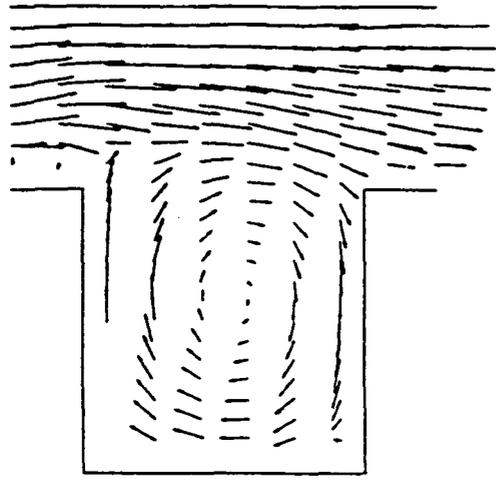
The 3-D LDA system is uniquely qualified for this study due to:

1. The small size of the probe volume (0.001" X 0.001" X 0.004").
2. The non-invasive nature of the measurement device.
3. The ability to measure the mean velocity and the entire Reynolds stress tensor.
4. Ensemble averaging capability for use on whirling rotors.
5. The ability to measure flow reversals.

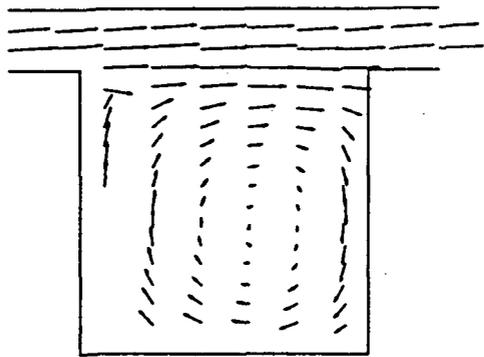




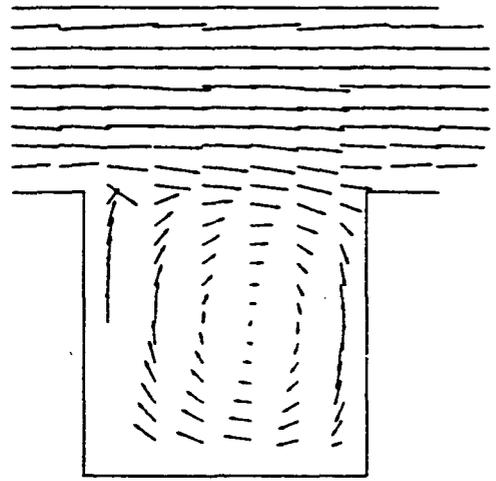
FIRST CAVITY



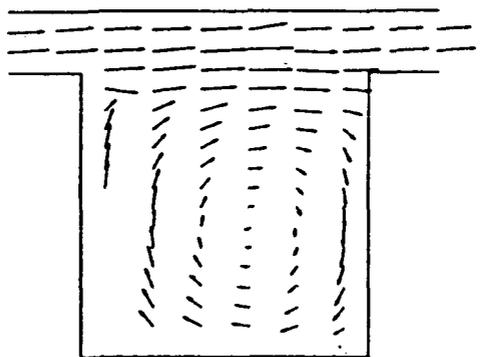
FIRST CAVITY



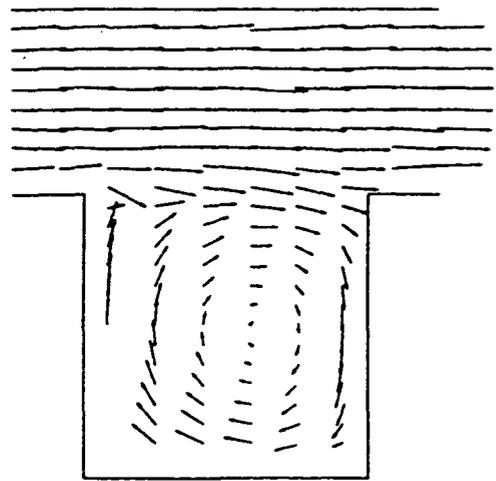
THIRD CAVITY



THIRD CAVITY

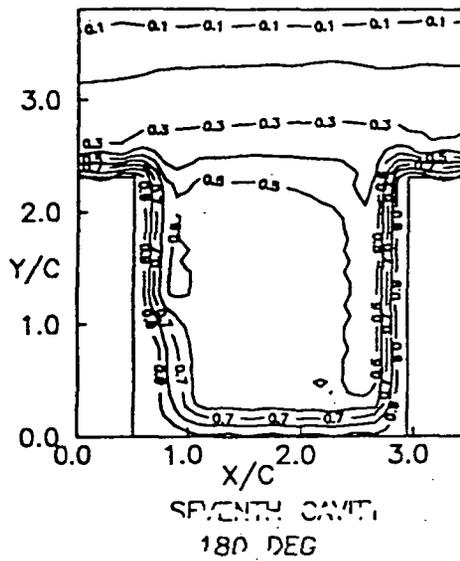
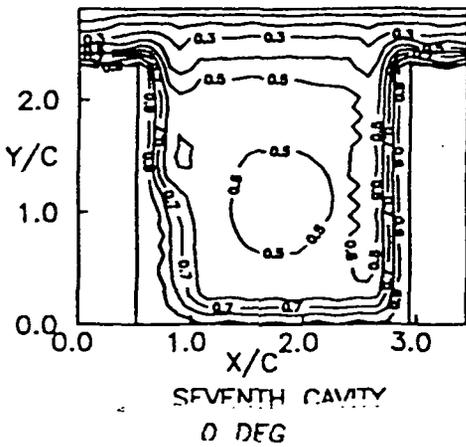
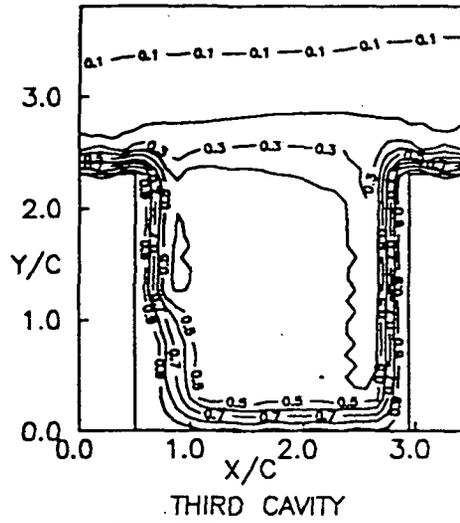
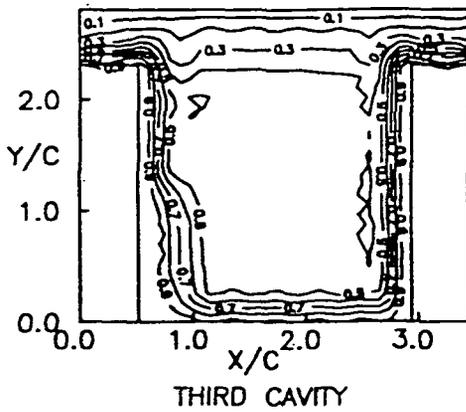
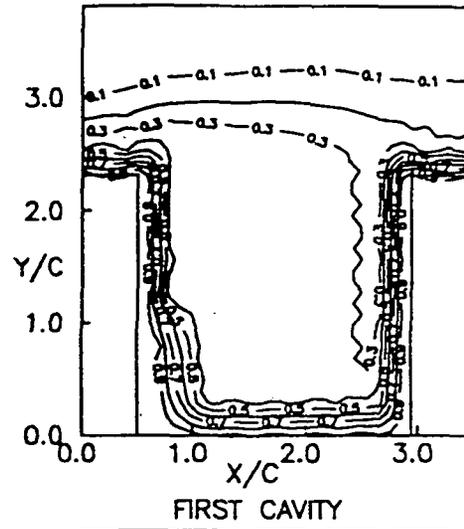
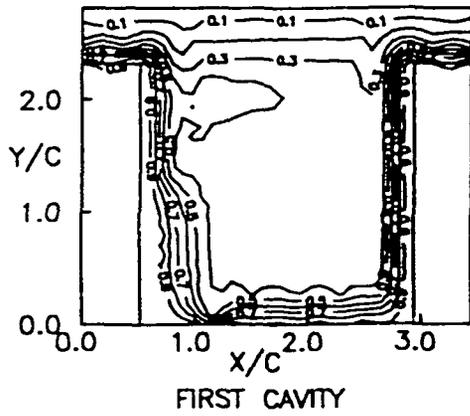


SEVENTH CAVITY
0 DEG

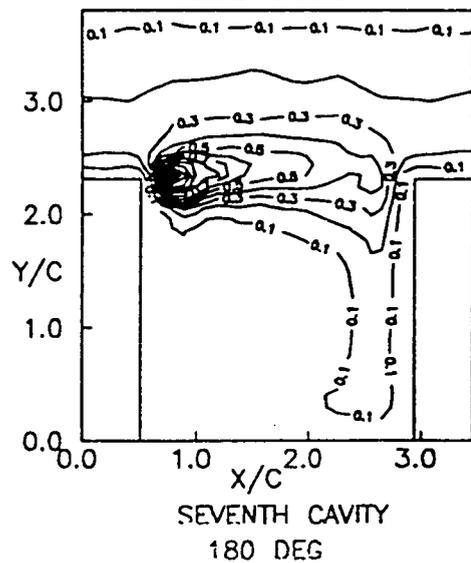
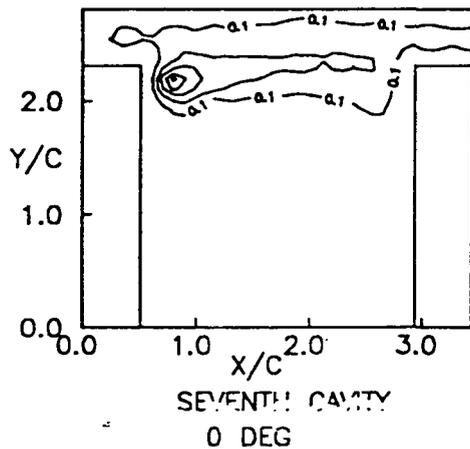
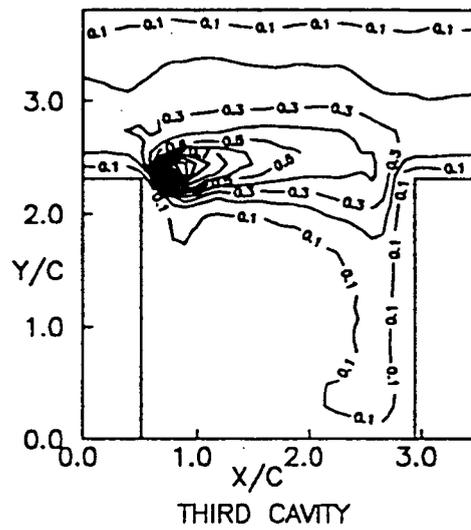
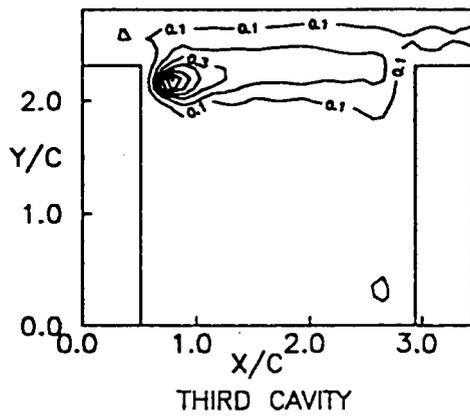
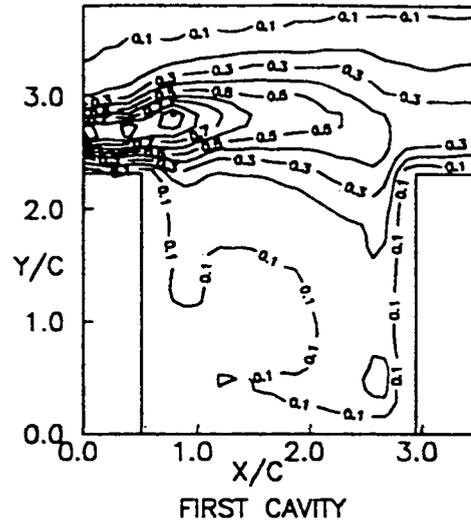
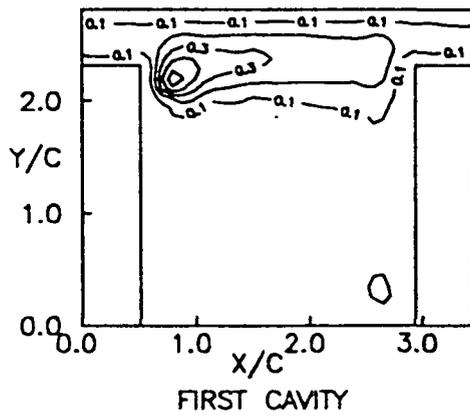


SEVENTH CAVITY
180 DEG

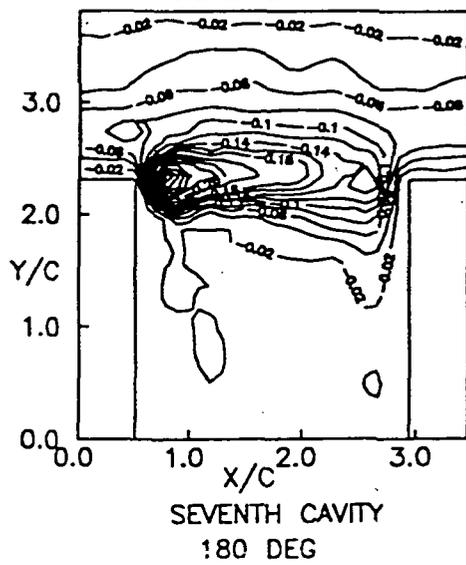
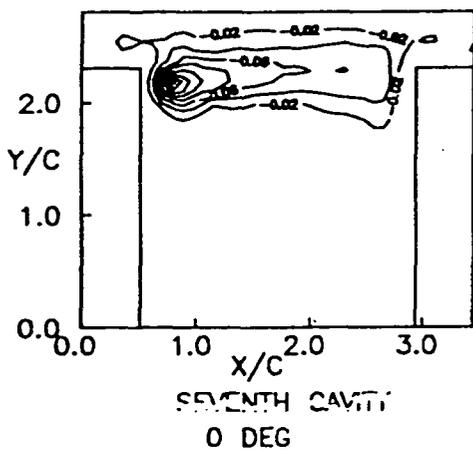
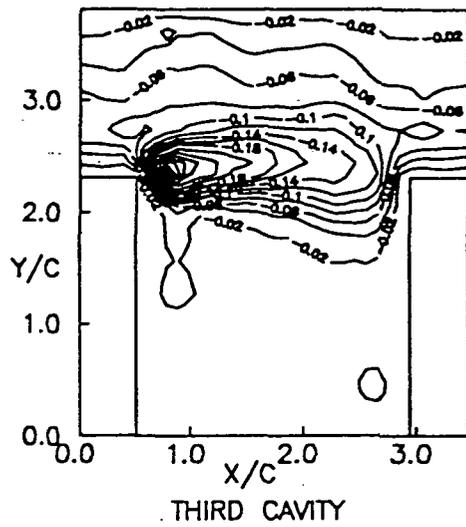
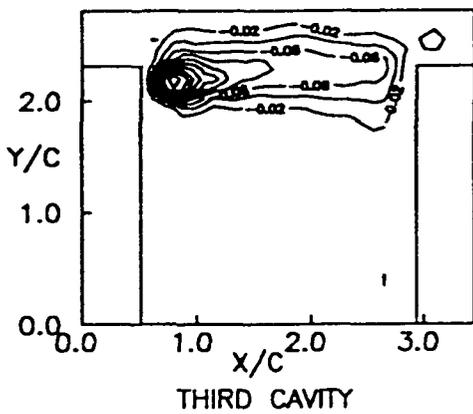
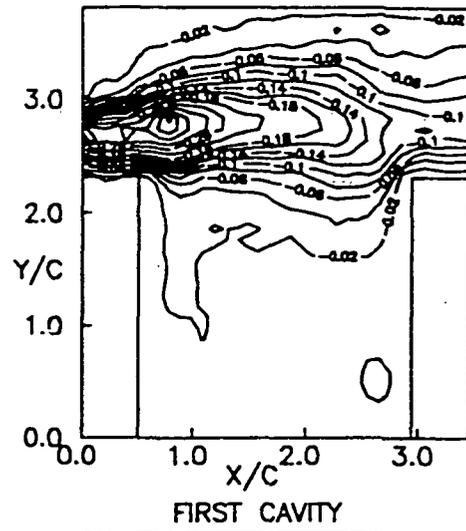
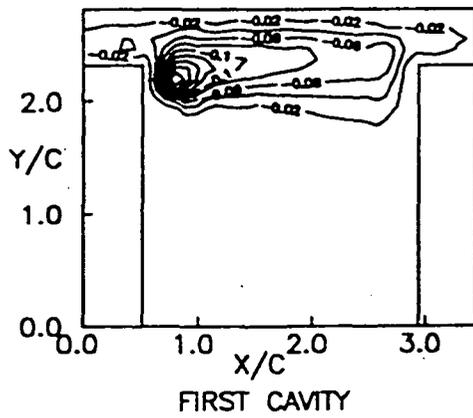
Mean Velocity Vector Fields, $\theta = 0^\circ$ and 180° .



Mean Azimuthal Velocity Contours, U_θ/W_{sh} , $\theta = 0^\circ$ and 180° .



Turbulent Kinetic Energy Contours, κ/U^2 , $\theta = 0^\circ$ and 180° .



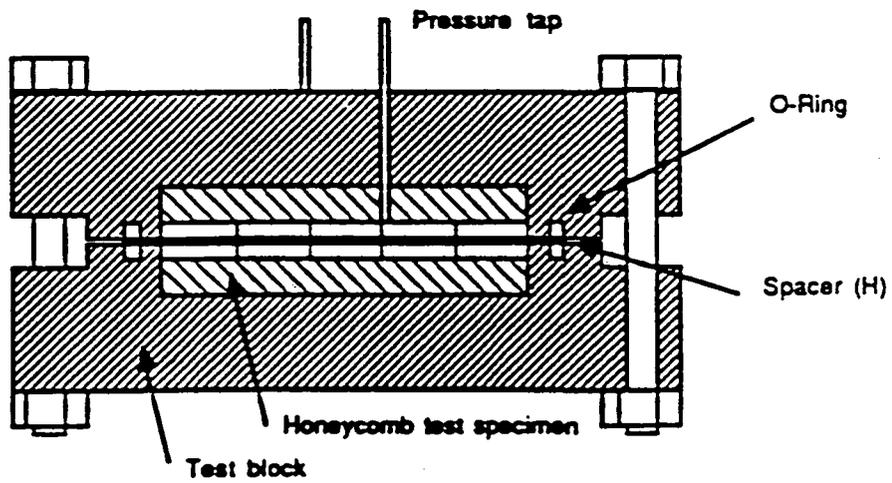
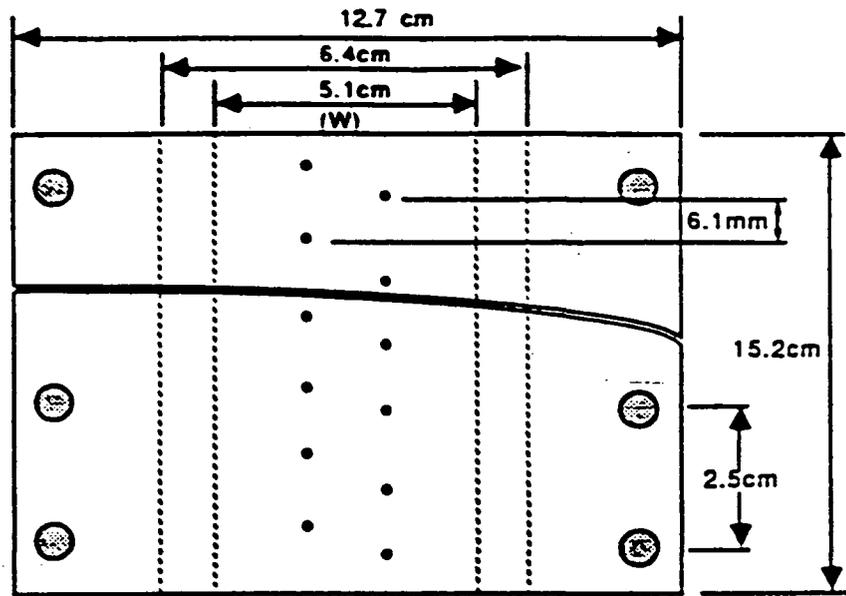
Reynolds Stress Contours, $u_x'u_y'/U^2$, $\theta = 0^\circ$ and 180° .

Measurements To Date:

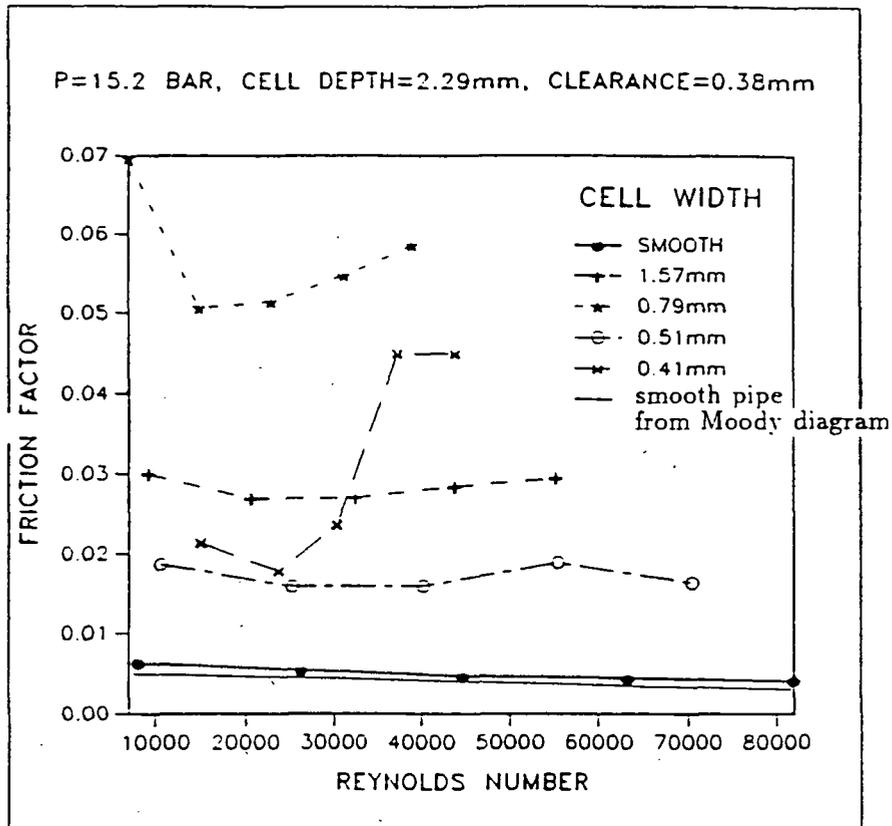
Type of Seal	Whirl	Eccentricity	RPM	Re	Ta	Swirl	Plug
Annular	None	0	3,600	28,000	7,000	None	Yes
Annular	None	0	0	28,000	0	None	Yes
Annular	None	0.5	3,600	28,000	7,000	None	Yes
Annular	None	0.5	3,600	28,000	7,000	+45°	Yes
Annular	None	0.5	3,600	28,000	7,000	-45°	Yes
Annular	None	0.5	500	0	970	NA	NA
Annular	None	0.5	1,500	0	2,900	NA	NA
Annular	None	0.5	3,000	0	5,800	NA	NA
Labyrinth	None	0.5	3,600	28,000	7,000	None	None
Labyrinth	None	0	3,600	28,000	7,000	None	None
Labyrinth	None	0	3,600	28,000	7,000	+45°	Yes
Labyrinth	None	0	3,600	28,000	7,000	-45°	Yes
Labyrinth	None	0	5,300	15,000	10,300	None	None

Measurements To Be Made This Year

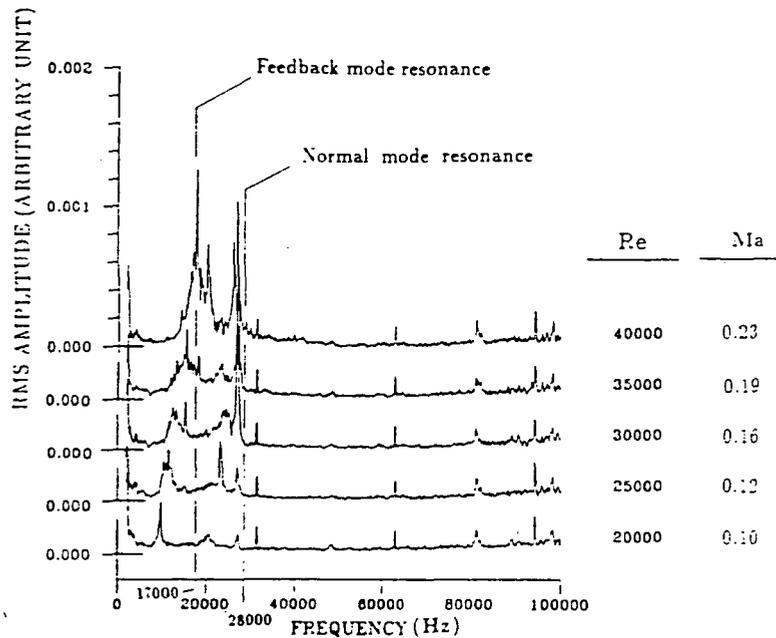
Type of Seal	Whirl Ratio	Eccentricity	RPM	Re	Ta	Swirl	Plug
Annular	1.0	0.5	3,600	28,000	7,000	None	Yes
Annular	1.0	0.5	5,300	15,000	10,300	None	Yes
Labyrinth	1.0	0.5	3,600	28,000	7,000	None	Yes
Labyrinth	1.0	0.5	5,300	15,000	10,300	None	Yes



Flat plate tester assembly.

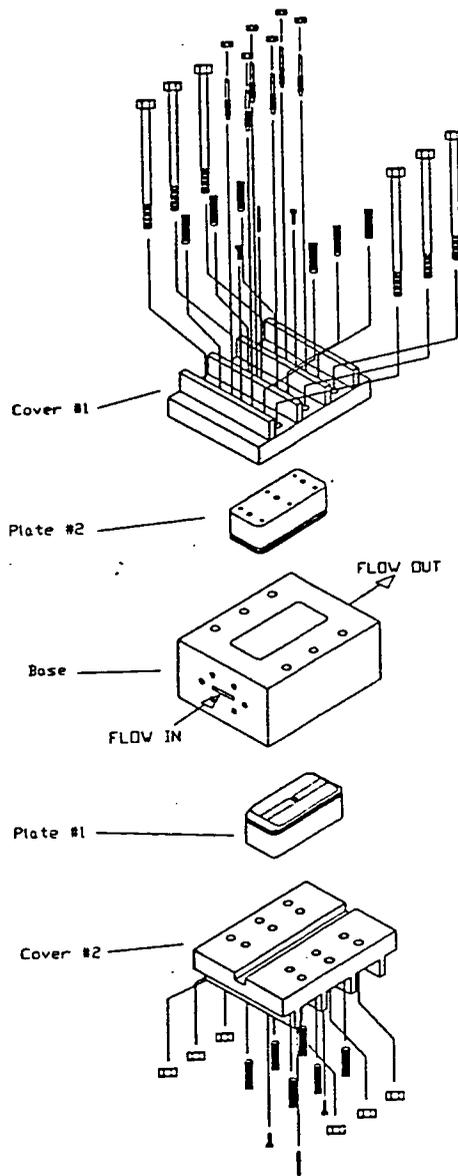


A typical friction-factor pattern.

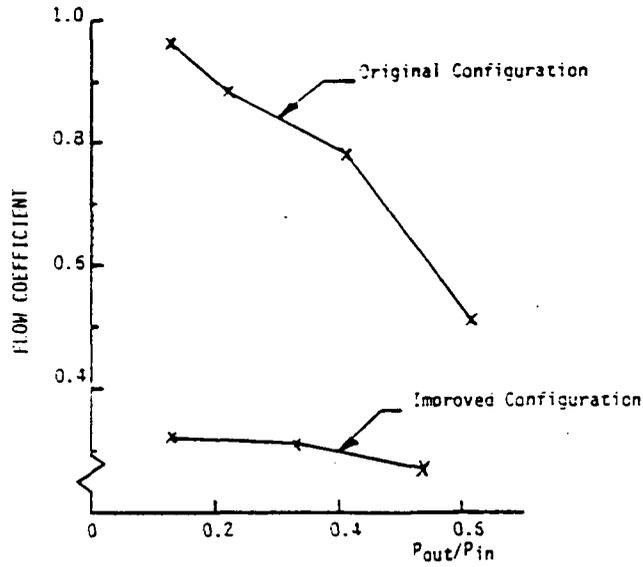


Frequency spectra for test number 7.

(b=1.57, d=3.05 and H=0.25mm)

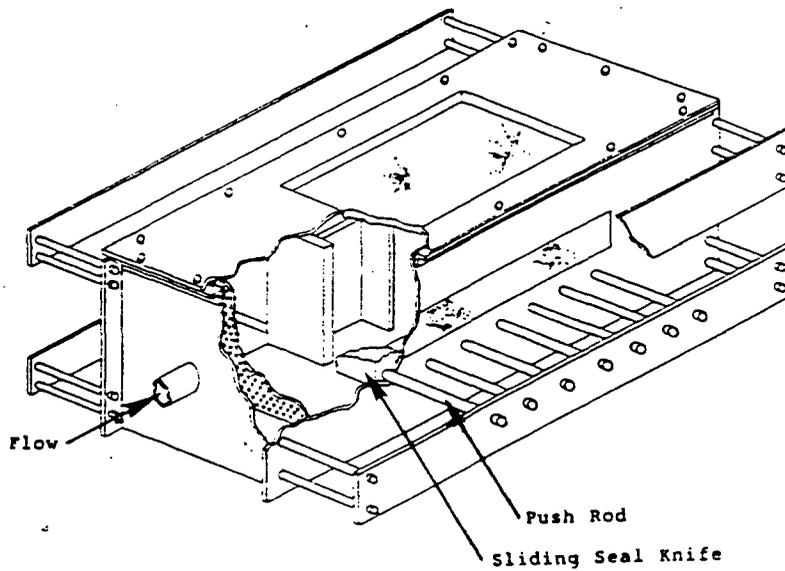


**MEASURED LABYRINTH LEAKAGE REDUCTION FROM
CFD DESIGN (Rhode, et al.)**



Measured leakage rate characteristic for the impeller inlet seal of the space shuttle fuel pump comparing the new CFD design with the current design.

**NEW, ADJUSTABLE-GEOMETRY LABYRINTH RIG :
LEAKAGE & FLOW VISUALIZATION**



Sketch of the quick-change geometry labyrinth seal water test rig

Correlate Large-Scale With Full-Scale Design Results

- A. Design and Construct Rig (Variable c and Rotor Position)
- B. Fabricate Several Advanced Land and Knifed Surfaces
- C. Obtain Scale Relationships for Limiting Cases:
 1. With and Without Rub Grooves
 2. Standard and Sharp Corners
 3. Standard and Advanced Knife Tip Shapes

Advanced Geometry Effects on \dot{m} and \dot{m} -Variation

- A. Standard Corners ($R=0.003$ in)

Obtain design data, including \dot{m} Variation with a change of: (a) clearance and (b) relative rotor position for:

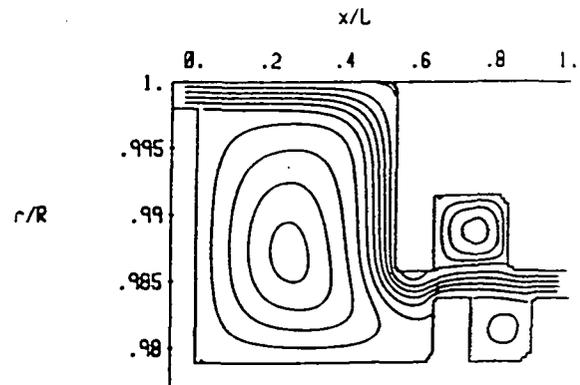
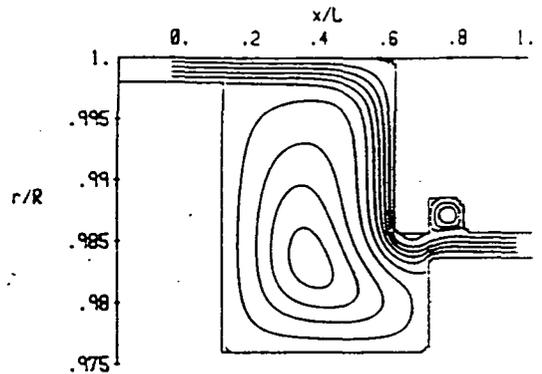
Record:

- | | |
|-----------------|--|
| \dot{m} | 1. Baseline geometry |
| VCR Movies | 2. Various annular grooves (stator and stator + rotor) |
| Photographs | 3. Various step heights s |
| F.D. Solution | 4. Various knife thickness t_2 |
| Five-Hole Pitot | 5. Various knife angles |

- B. Sharper Corners ($R=0.0015$ in) (Same as A)

Record:

- | | |
|-----------------|--|
| \dot{m} | 1. Baseline geometry |
| VCR Movies | 2. Various annular grooves (stator and stator + rotor) |
| Photographs | 3. Various step heights s |
| F.D. Solution | 4. Various knife thickness t_2 |
| Five-Hole Pitot | 5. Various knife angles |



Research Objectives on Annular Seals for 1991-92 at Texas A&M University.

P.I. Dr. L. San Andres

-  Analysis of thermal effects on the performance and dynamic force response of high pressure annular seals handling cryogenic liquids.
Adiabatic and Constant Surface Temps.
Important for LOX due to higher viscosity and lower specific heat than LH2.
-  Development of a unified theory for liquid, gas, and two-phase flow annular seals.
-  Calculation of dynamic force and moment coeffs. for displacements and angular motions.
-  Analysis of high pressure OIL SEAL RINGS for compressors: single and multi-land seals.
Calculation of lock-up forces and face friction factors.
-  Study of Damper Seals and Hydrostatic Bearings as support elements in cryogenic turbopumps.
-  Improved Seal Entrance Factors by CFM simulations

hseal.f

Analysis of Turbulent Flow
Annular Pressure Seals

Dr. L. SanAndres, Texas A&M University

- 2-D Bulk Flow Model for barotropic liquids
Surface roughness: Moody's friction factor
- Arbitrary Axial Clearance Distribution:
uniform, taper, step, wavy via spline, and
stator wear profile
- Arbitrary Static Eccentricity Ratio, $0 \leq e/c \leq 1$
- Realistic liquid properties for LH2, LN2, LOX, CH4

Program calculates:

Leakage, Fluid Film Forces, Torque, and
Rotordynamic Coefficients: K_{ij} , C_{ij} , M_{ij}

- Solution scheme based on efficient CFM methods
and improved approximate guesses for fast
convergence.
- Program can be used for flooded or grooved
journal bearings.
- Laminar and/or Turbulent Seals and Bearings

N92-15091

SEALS RESEARCH AT THE UNIVERSITY OF AKRON

M.J. Braun
University of Akron
Akron, Ohio

FLOW AND PRESSURE STUDIES ON BRUSH SEALS

The flow visualization effort aims at determining the flow regimes and the sealing mechanisms that are at work in the brush seal, regardless of whether the seal is linear or circular. A vision system coupled with an image processing system is used to analyze the nature of the flow.

Pressure measurements were made to study the effect of the number of brushes as well as the brush structure on the seal effectiveness.

NUMERICAL SIMULATION OF FLOW IN A HYDROSTATIC POCKET

This portion of the presentation will detail a numerical approach to flow simulation in one hydrostatic pocket. The effects of the jet, shaft velocity and clearance on the flow patterns and pressure generation will be described.

PROGRAMS AT WRIGHT PATTERSON AIR FORCE BASE
WL/POSL

Ron Dayton
Wright Patterson Air Force Base

The Lubrication Branch has two active programs that are developing gas turbine engine mainshaft air/oil seals. Both of these programs, one of which is with General Electric Aircraft Engines and the other with Pratt & Whitney Aircraft, are addressing counter-rotating intershaft applications which involve very high rubbing velocities. My presentation will briefly address the objectives and requirements of both of these efforts.

HIGH SPEED AIR/OIL SEAL DEVELOPMENT

CONTRACTOR: UNITED TECHNOLOGIES (PRATT & WHITNEY)

CONTRACT NUMBER: F33615-88-C-2822

START / DURATION: SEP 88 / 45 MONTHS

OBJECTIVE: CONDUCT A COMBINED ANALYTICAL AND EXPERIMENTAL PROGRAM TO DEVELOP AND ENDURANCE TEST COUNTER-ROTATING INTERSHAFT SEALS FOR RELIABLE OPERATION UP TO 1200 FT/SEC PITCH LINE VELOCITY

- GOALS:
- * 4000 HOUR SEAL LIFE
 - * 1200 FT/SEC PITCH LINE VELOCITY
 - * 50 LB/HR MAX AIR LEAKAGE @ 50 PSID & 750 F
 - * 500 LB/HR MAX AIR LEAKAGE AFTER PRIMARY SEAL MALFUNCTION
 - * MISALIGNMENT TOLERANCE

HIGH SPEED AIR/OIL SEAL DEVELOPMENT

APPROACH:

- * DEFINE THE SEAL APPLICATION AND ESTABLISH REQUIREMENTS
- * SELECT TWO SEAL CANDIDATES THROUGH AN ANALYTICAL ASSESSMENT OF PERFORMANCE POTENTIAL FROM A MINIMUM OF FIVE SEAL DESIGNS
- * FABRICATE AND EVALUATE THE PERFORMANCE CAPABILITIES OF BOTH SEAL DESIGNS
- * SELECT THE BETTER OF THE TWO SEAL DESIGNS FOR ENDURANCE TESTING
- * ENDURANCE TEST THIS SEAL FOR AN ADDITIONAL 80 HOURS
- * EVALUATE TEST RESULTS TO IDENTIFY IMPROVEMENTS NEEDED AND POSSIBILITY OF TRANSITION INTO THE JTDE PROGRAM

HIGH SPEED AIR/OIL SEAL DEVELOPMENT

STATUS:

- * SEAL DESIGN REQUIREMENTS WERE BASED ON AN ADVANCED FIGHTER-TYPE AIRCRAFT WITH A 60% INCREASE IN THE THRUST-TO-WEIGHT CAPABILITY OF CURRENT STATE-OF-THE-ART SYSTEMS
- * TWO SEAL DESIGNS, A CONTROLLED GAP SEAL CONCEPT AND A SEGMENTED HYDRODYNAMIC CIRCUMFERENTIAL SEAL, WERE SELECTED FROM 25 CANDIDATES
- * FABRICATION OF THE CONTROLLED GAP SEAL DESIGN IS IN PROGRESS
- * FABRICATION OF THE SEGMENTED SEAL IS COMPLETE
- * SHAKEDOWN TESTING OF THE EG&G SEALOL TEST RIG HAS BEEN COMPLETED

COUNTER-ROTATING INTERSHAFT SEAL DEVELOPMENT

CONTRACTOR: G.E. AIRCRAFT ENGINES

CONTRACTOR NUMBER: F33615-90-C-2000

START/DURATION: APR 90/29 MONTHS

OBJECTIVE: DEVELOP AN ADVANCED DESIGN INTERSHAFT SEAL FOR PHASE II IHPTET ENGINE CONFIGURATIONS THAT UTILIZE COUNTER-ROTATING TWIN SPOOLS

GOALS:

- 900 FT/SEC PITCH LINE VELOCITY
- ΔP UP TO 50 PSID
- 900°F SEAL AIR INLET TEMPERATURE

COUNTER-ROTATING INTERSHAFT SEAL DEVELOPMENT

APPROACH:

- ADVANCED DESIGN BASED ON AN AIR BEARING-SUPPORTED CONTINUOUS RING CONFIGURATION
- THREE MATERIAL APPROACHES FOR CRITICAL SEALING INTERFACE:
 - (1) CONCURRENTLY DEVELOPED ADVANCED HIGH STRENGTH CARBON ($> 100\text{KSI PER LB/IN}^3$)
 - (2) STATE-OF-THE-ART METALLIC MATERIALS
 - (3) INLAID ARRANGEMENTS OF CARBON, METAL, AND/OR CERAMICS

COUNTER-ROTATING INTERSHAFT SEAL DEVELOPMENT

APPROACH (CON'T):

- CONDUCT PHYSICAL AND TRIBOLOGICAL CHARACTERIZATION TESTS TO SELECT BEST MATERIAL APPROACH
- FOR SELECTED APPROACH, DESIGN AND FABRICATE FULL-SIZE PROTOTYPE SEAL
- CONDUCT SEAL TESTS IN TWO PHASES:
 - (1) PERFORMANCE MAPPING
 - (2) ENDURANCE FOR UP TO 200 HRS
- BASED ON TESTS, DESIGN SEAL FOR THE PH II DEMONSTRATOR ENGINE

COUNTER-ROTATING INTERSHAFT SEAL DEVELOPMENT

STATUS:

- MATERIAL CHARACTERIZATION TESTS UNDERWAY
- PROMISING RESULTS OBTAINED WITH ADVANCED CARBON MATERIALS
 - (1) HIGH STRENGTH
 - (2) GOOD OXIDATIVE RESISTANCE

SEAL DEVELOPMENT ACTIVITIES AT
ALLISON TURBINE DIVISION

John Munson

Brush Seals

Brush seals are being evaluated for potential near and far term gas turbine engine applications. Development is in the form of rig component testing, and engine testing. Allison has tested an engine with 20 individual brush seal positions. These seals were located throughout the engine. The emphasis of the current work is on obtaining long term performance data for brush seals. Very little of this data is available.

Film Riding Face Seals

Allison is presently developing film riding face seal technology to support future gas turbine engine applications. Face seal with an approximate 7" diameter has been successfully tested to 1000°F, 100 psid, and 650 ft/sec. Seal leakage remained below 1 scfm throughout the duration of the test. A model for the compressible gas film has been developed which separates the primary seal rings during operation. This model is based on the traditional Reynold's approach which is customarily applied to lubrication type problems. Because of the difficulty of experimentally verifying the program predictions, a commercial Navier-Stokes code was used in parallel. By comparing predictions for similar cases, it is expected that the limitations of the Reynold's model can be assessed as it applies to this particular seal.

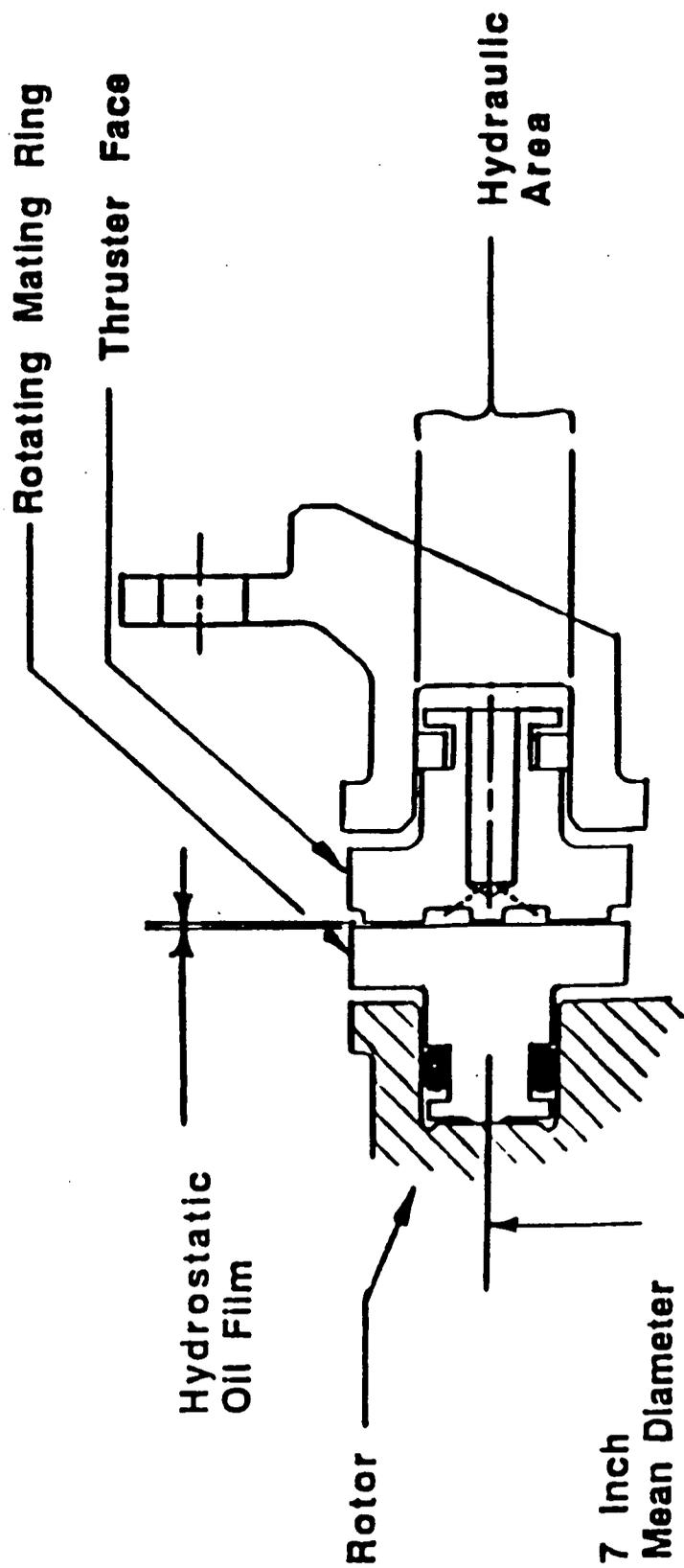
AREAS OF SEAL R&D AT GE
A. N. Pope
General Electric Company

About four years ago, work was completed on a 36 inch diameter gas to gas carbon ring seal used to buffer low pressure turbine air at the rim of the forward outer flowpath on the GE36 unducted fan (UDF) engine. This highly successful program demonstrated the ability to provide long life at a gas leakage rate equivalent to a .0018 inch clearance, or, conservatively estimating, a 20 to 1 reduction over a labyrinth, and an SFC reduction of at least 2.5%. Operating conditions were 1600 rpm (240 fps), 60 psid and 650 deg F. The seal design was based on the use of self-acting gas hydrostatic bearings.

At about the same time, we were working an AF/Navy contract for development of a long life counter-rotating intershaft air-oil seal of approximately 7.6 inch diameter for operation at 800 fps, 800 deg F and 50 psid. Although we were successful in meeting most program goals with a split ring seal of the axial bushing type, the seal with the greatest payoff in life and air leakage rates, bearing many features common with the GE36 seal, could not be successfully tested because of the structural weakness of the primary seal ring carbon material. This was a split ring seal using a hybrid combination of orifice compensated hydrostatic and shrouded hydrodynamic gas bearings. We are presently working an AF contract to develop this design in conjunction with high strength carbon materials being developed by Pure Carbon Co.

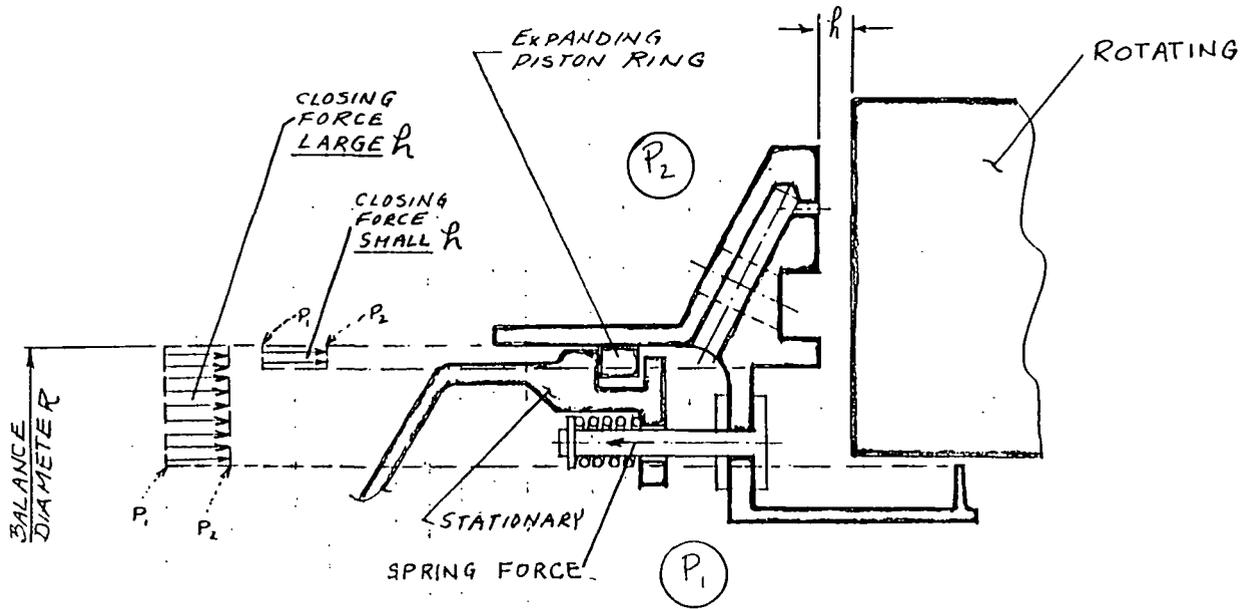
In the area of engine secondary gas flow path sealing for performance improvement, we are currently working with carbon and all metal face seals. Nine inch diameter hydrodynamic carbon face seals at 450 fps, 140 psid and 950 degrees F, have demonstrated long life at a flow reduction of approximately 96% (7.5 scfm) compared to a "best" labyrinth. A fifteen inch diameter all metal "aspirating" face seal, using self-acting hydrostatic bearings, has been successfully tested to 700 fps, 100 psid and 1000 deg F, demonstrating long life at a flow reduction of 86% compared to a "best" labyrinth. This seal will be developed through 1400 deg F, 900 fps and 350 psid. The seal "aspirates" closed at about idle speed pressure during engine start and reopens at engine shutdown.

A hydraulic thrust balance "seal", currently using orifice compensated hydrostatics, is under development. We have demonstrated long life operation for most large engine low pressure rotor applications (170 fps) with 30000 pounds control at 7 inches diameter and less than 3 gpm flow rate using Type 2 (23699) engine oil. We are now working high pressure rotor systems, to 450 fps. This program has two significant payoffs: 1) as much as 50 to 1 increase in thrust bearing fatigue life, 2) as much as 3% reduction in SFC and significant multipliers in turbine bucket life.

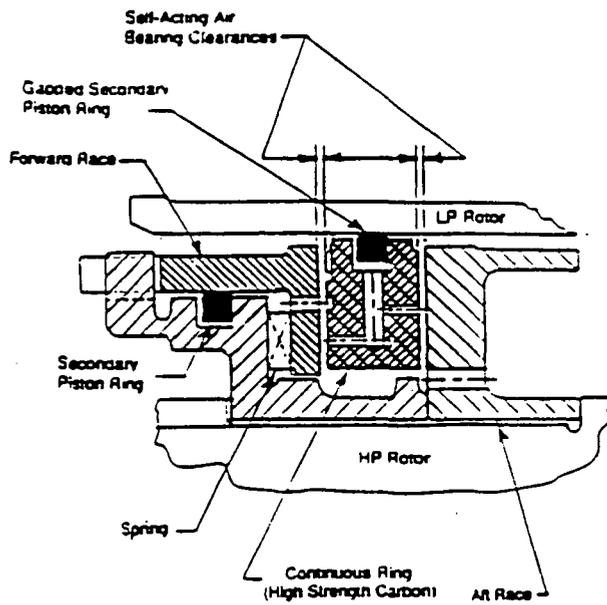


CROSS SECTION OF A 7 INCH HYDRAULIC THRUST CONTROL.

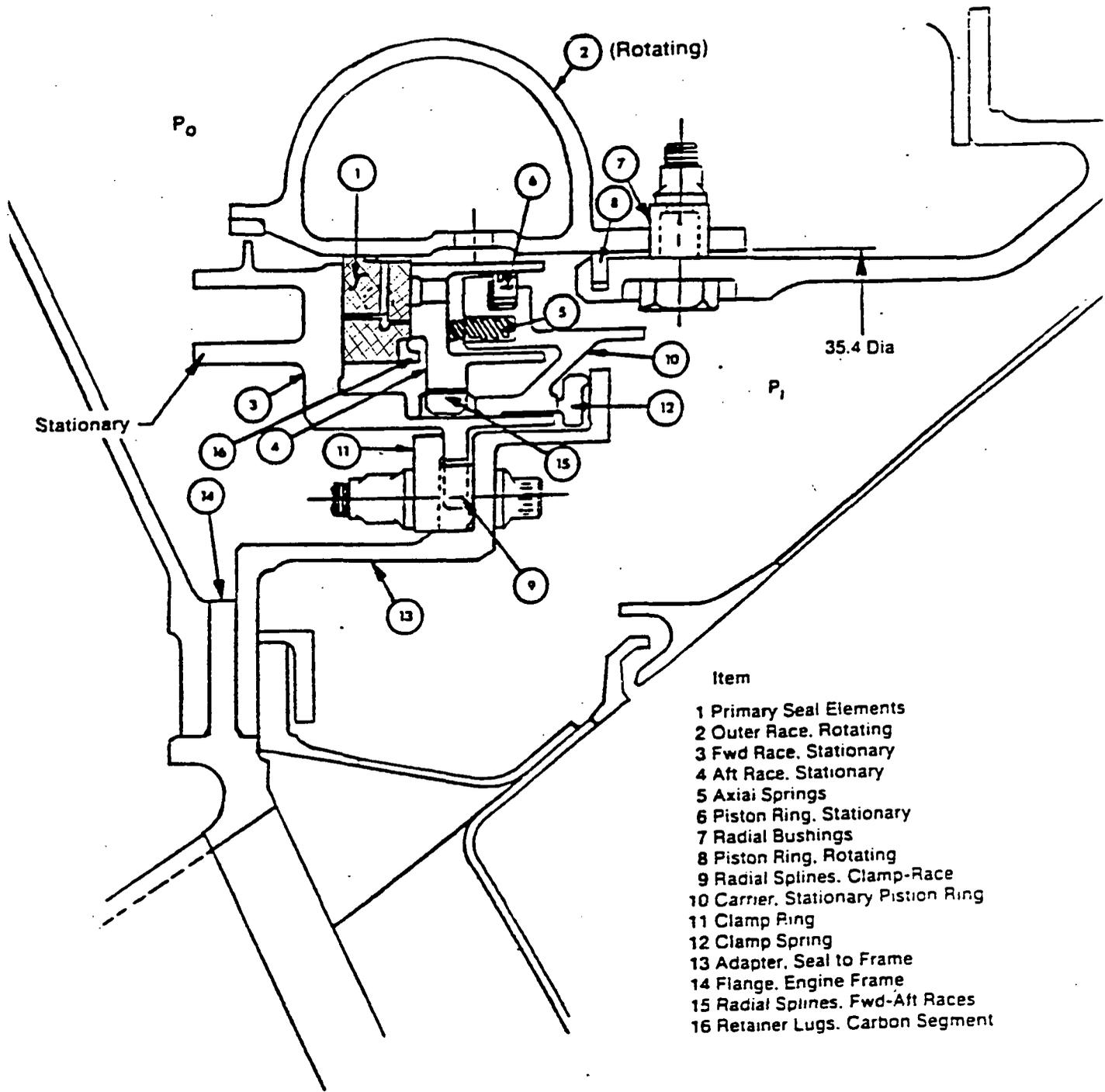
An axial force is transmitted to the engine rotor by applying oil under pressure to the hydraulic area of the thrust control mechanism.



ASPIRATING GAS BEARING FACE SEAL



CONTINUOUS RING SEAL DESIGN



LARGE DIAMETER HYDROSTATIC SEAL

SEAL RELATED DEVELOPMENT ACTIVITIES AT EG&G

H.F. Griner
Fluid Components Technology Group
EG&G

A brief introduction is made describing EG&G Fluid Components Technology Group and FCT Group R&D capabilities.

Seal related development activities, including modeling, analysis and performance testing are described for several current seal related projects. These include noncontacting, high speed, high pressure gas sealing systems for turbomachinery, brush seals for gas path sealing in gas turbines and tribological material evaluation for wear surfaces in sealing systems.

GROUP R & D

Staffed and equipped for:

- Material Characterization and Analysis
- Tribological Characteristics, Testing and Evaluation
- High Temperature, High Pressure and High Speed Testing of Seals and Sealing Systems
- Mechanical Design of Products and Specialized Testing Equipment
- Modeling of Systems and Components, Design Analysis and Performance Parameters
- Manufacturing Process Development

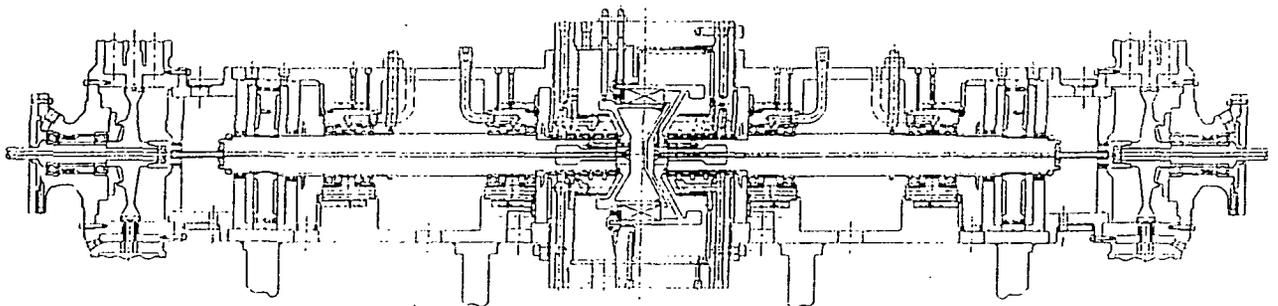
ADVANCED AEROSPACE TEST RIG

• Rig Capabilities (Counter Rotating Configuration)

- Spindle Speed/24,000 RPM each shaft
- Power/43 HP at 17,000 RPM, 32 HP at 26,000 RPM
- Temperature of Test Chamber/600° F
- Test Chamber Pressure/100 PSI
- Axial Travel/±.0625 inch each shaft

• Single Shaft (Brush Seal Testing)

- Spindle Speed/24,000 RPM
- Power/43 HP at 17,000 RPM, 32 HP at 26,000 RPM
- Temperature of Test Chamber/1000° F
- Test Chamber Pressure/ 100 PSI
- Axial Travel/±.0625 inches



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SEAL RELATED DEVELOPMENT ACTIVITIES

**BRUSH SEAL DEVELOPMENT PROGRAM
U. S. AIR FORCE PRDA-11
IN-HOUSE BRUSH SEAL TESTING**

**NON-CONTACTING GAS FILM SEALS
DEVELOPMENT AND TESTING**

**TRIBOLOGICAL MATERIAL EVALUATION
ANALYSIS AND TRIBOLOGICAL TESTING**

Brush Seal Development Program

U. S. Air Force

Integrated High Performance Turbine Engine Technology - IHPTET

PRDA - II

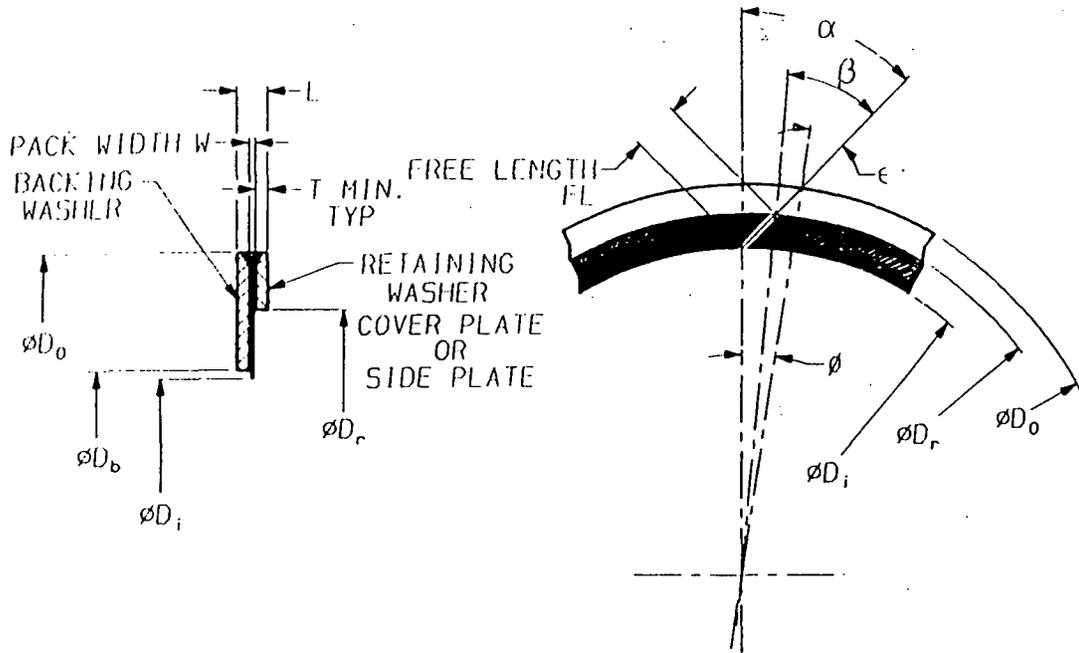
Objective: Develop a comprehensive design methodology for Brush Seals
using

1. Application requirements from engine manufacturer
2. Experimental characterization of seal design and tribological pairs

Goals: 1. Substantially lower leakage than laby seals
2. Seal life consistent with man-rated mission requirements
3. Achieve maximum pressure sealing capability with single or multiple stages

Provide: 1. Comprehensive seal design manual
2. Man-rated brush seal for test in an IHPTET engine

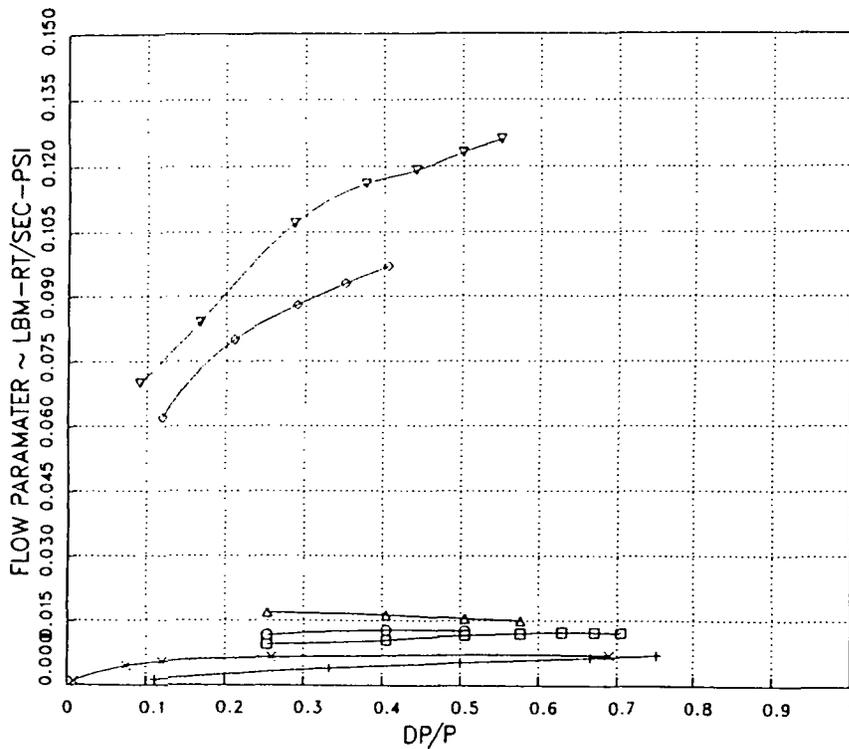
Project duration is two and one half years, started July 1990



WIRE DIAMETER- d
 TOTAL NUMBER OF BRISTLES- n_t
 WIRE DENSITY- ρ

BRUSH SEAL ASSY.

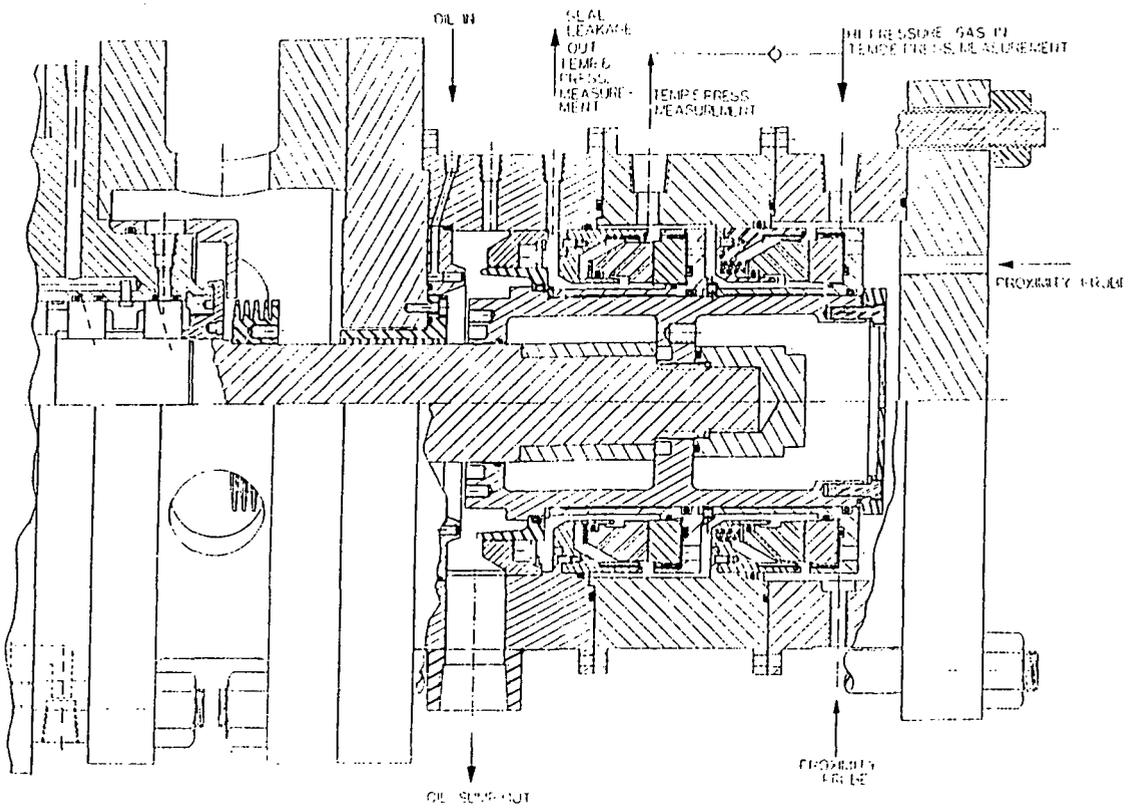
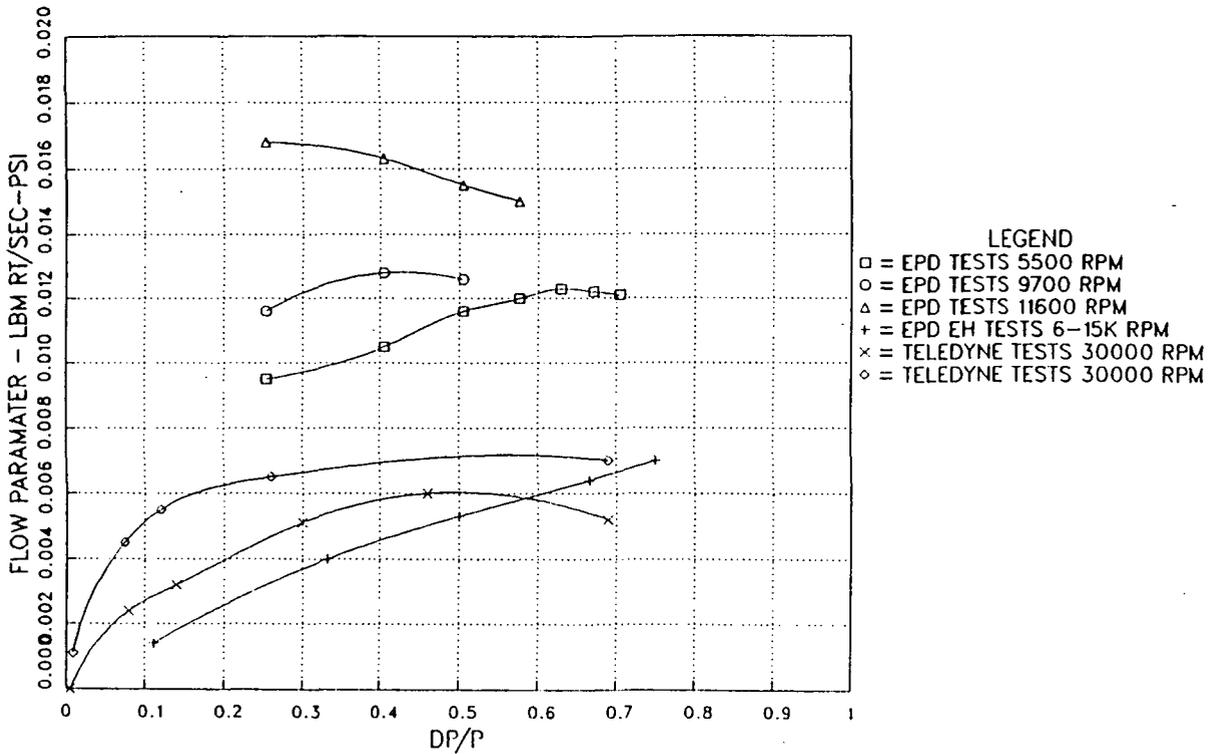
FLOW PARAMATER VS DP/P. COMPARISON OF BRUSH SEAL AND LABYRINTH SEAL LEAKAGE



- LEGEND
- = EPD TESTS 5500 RPM
 - = EPD TESTS 9700 RPM
 - △ = EPD TESTS 11600 RPM
 - + = EPD EH TESTS 6K-15K RPM
 - x = TELEDYNE TESTS 30000 RPM
 - ◇ = EPD 6 FIN LABY (.025 GAP)
 - ▽ = ALLISON 4 FIN (.02 GAP)

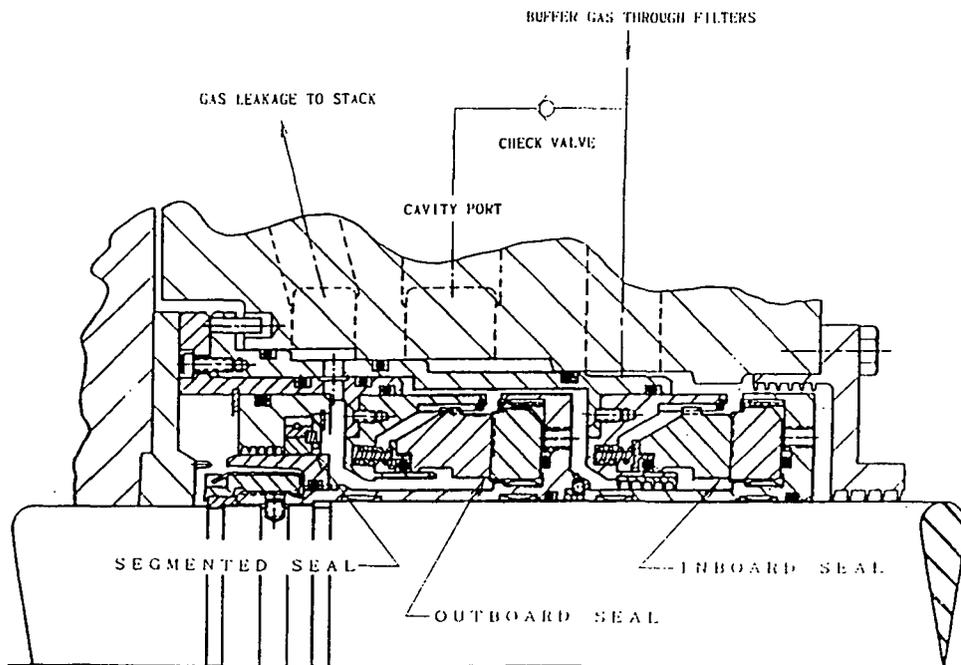
ORIGINAL PAGE IS
 OF POOR QUALITY

BRUSH SEAL LEAKAGE VS PRESSURE DROP



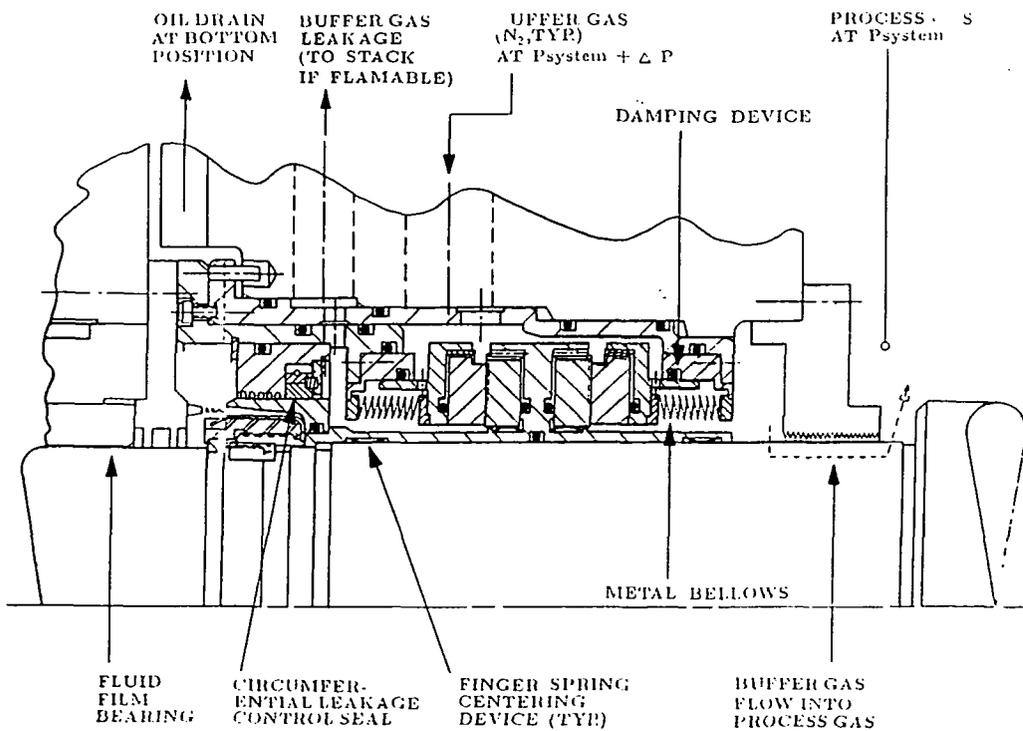
Test seal As installed in Sealers Test Rig

ORIGINAL PAGE IS OF POOR QUALITY

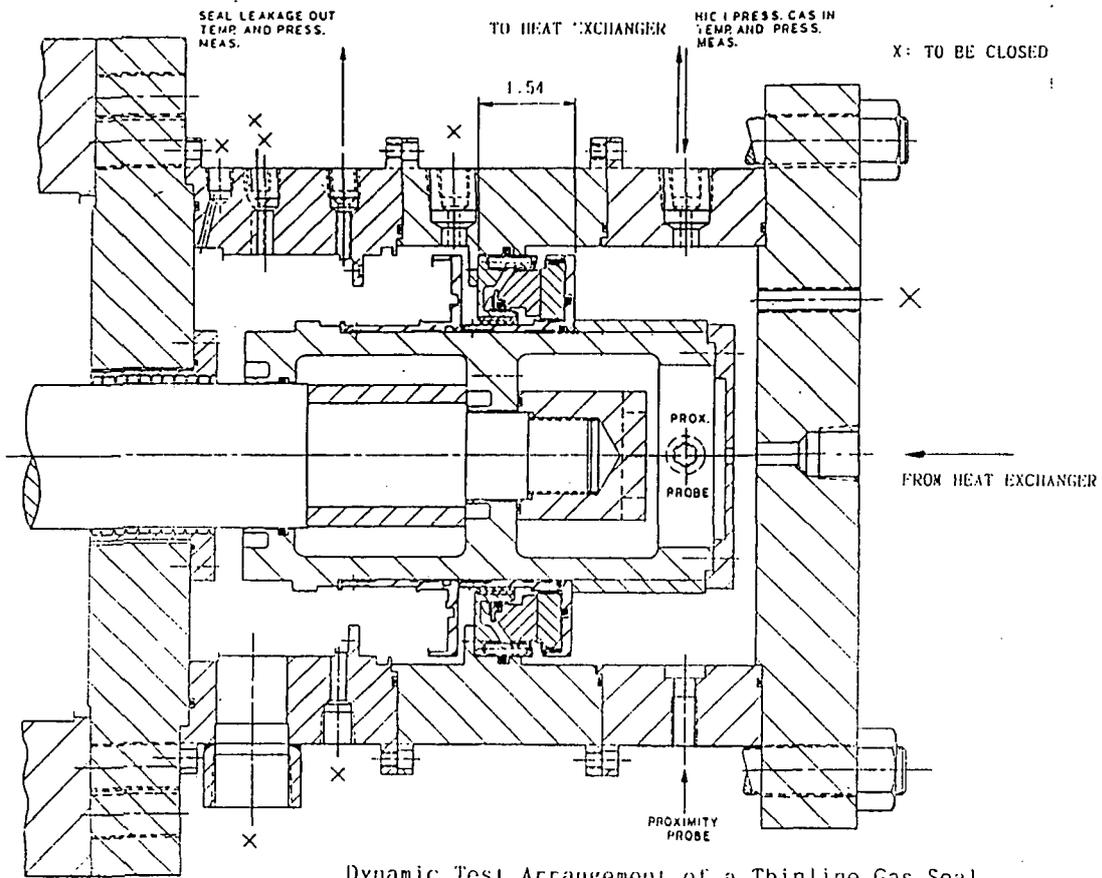


PATENT PENDING

Tandem Gas Face Seal - Shown in Thermodyn Centrifugal Gas Compressor

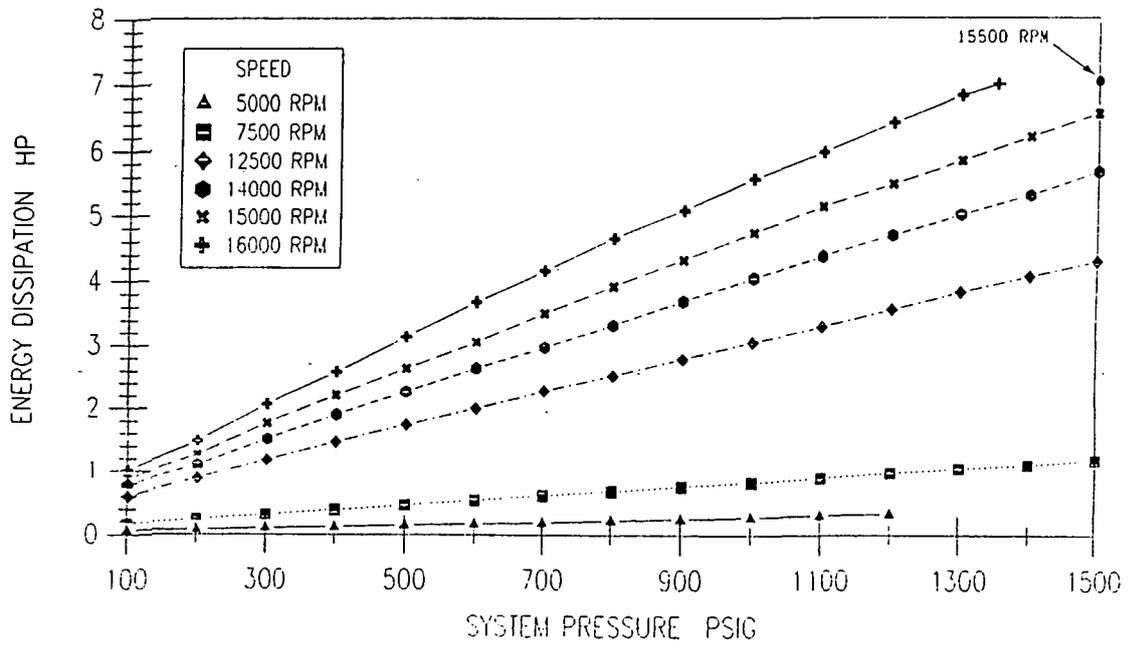


METAL BELLOWS GAS SEAL (PATENT PENDING)
(BUFFER GAS ARRANGEMENT)

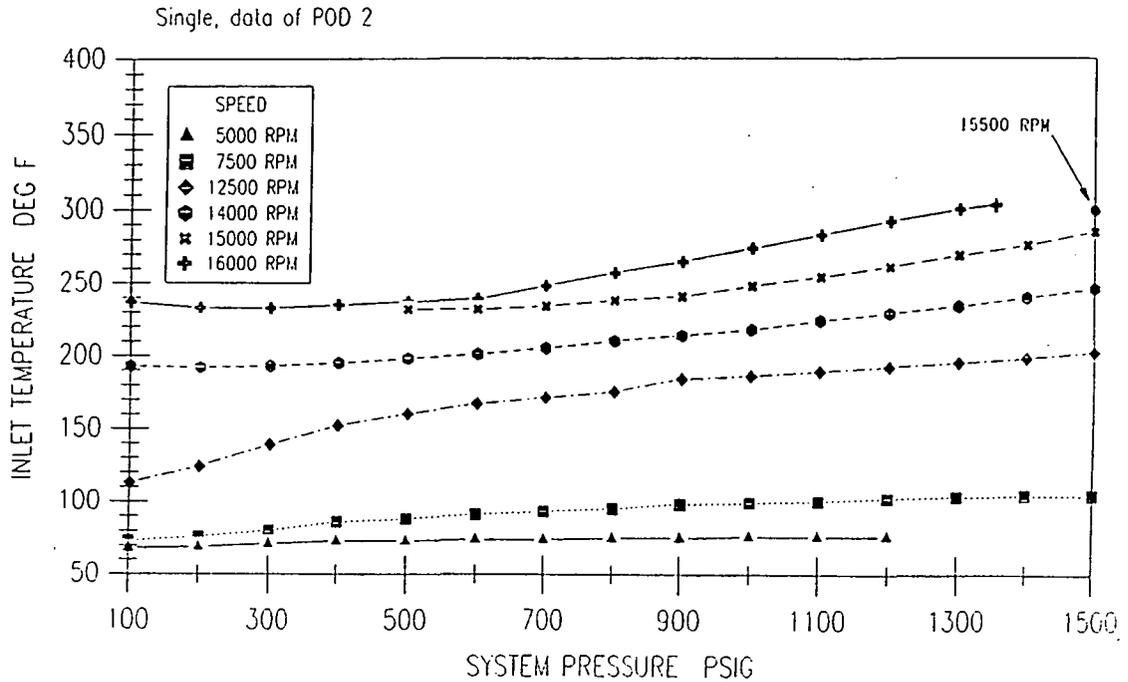


Energy Dissipation vs. Pressure

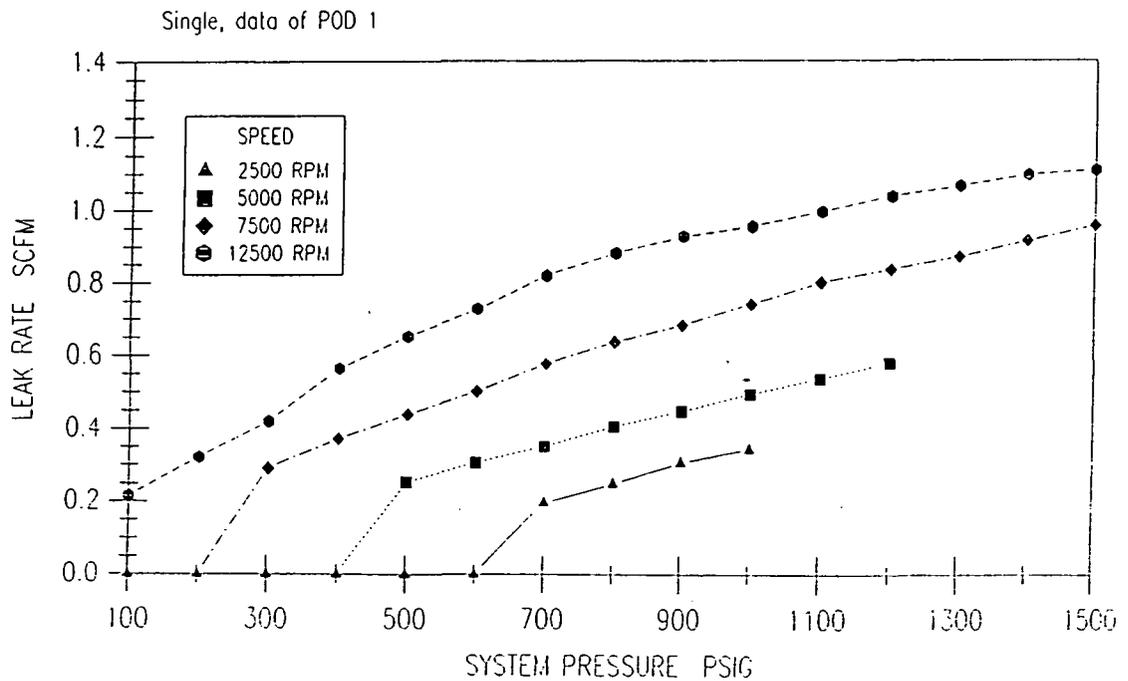
Single, data per pod



Inlet Temperature vs. Pressure

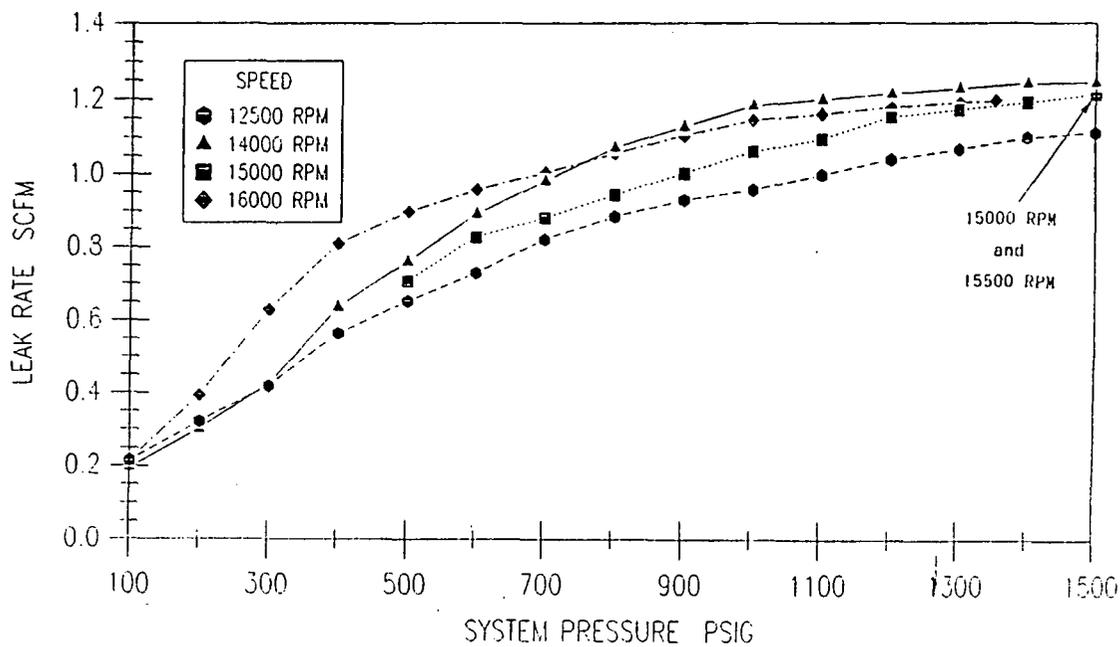


Leakage vs. Pressure



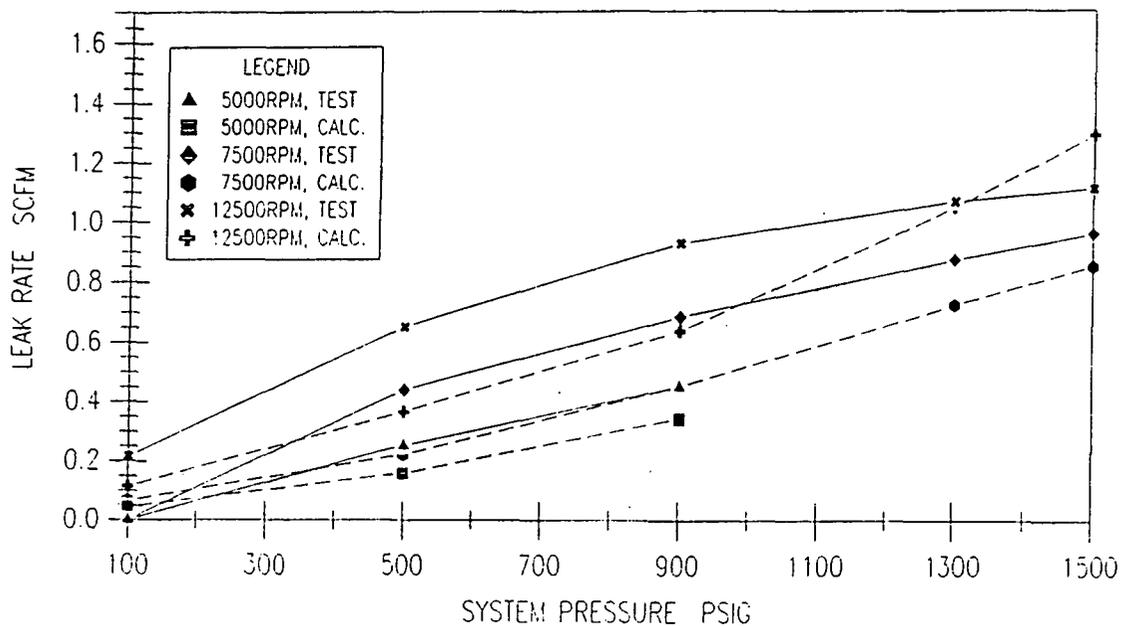
Leakage vs. Pressure

Single, data of POD 1



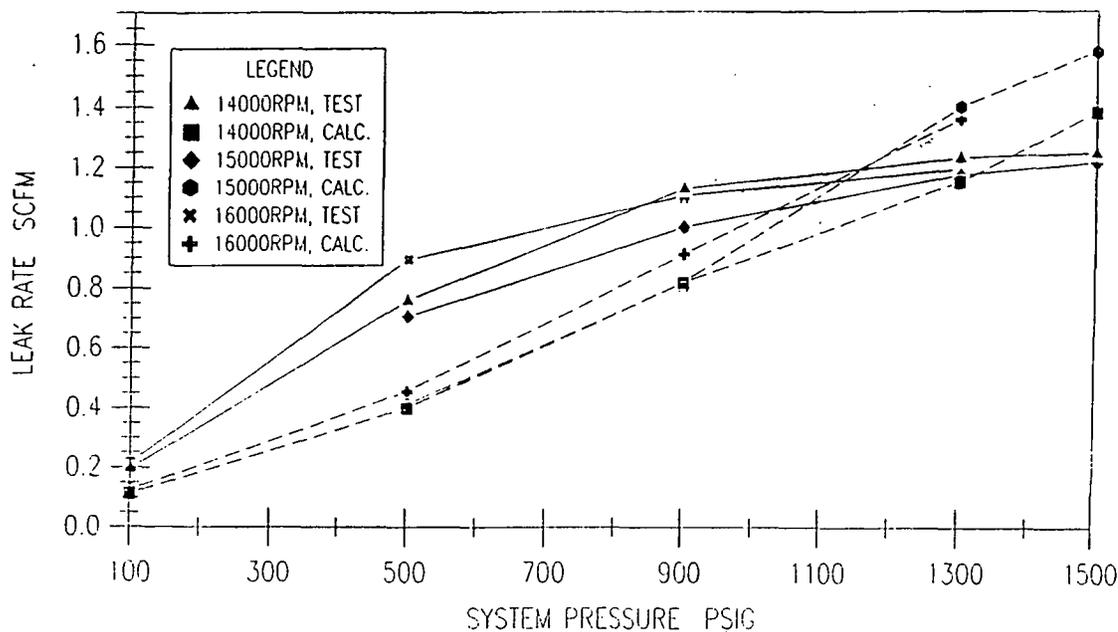
Leakage Correlation

Single, data of POD 1



Leakage Correlation

Single, data of POD 1



Unique Tribology Test Rigs

High Temperature Oscillating Test Rig

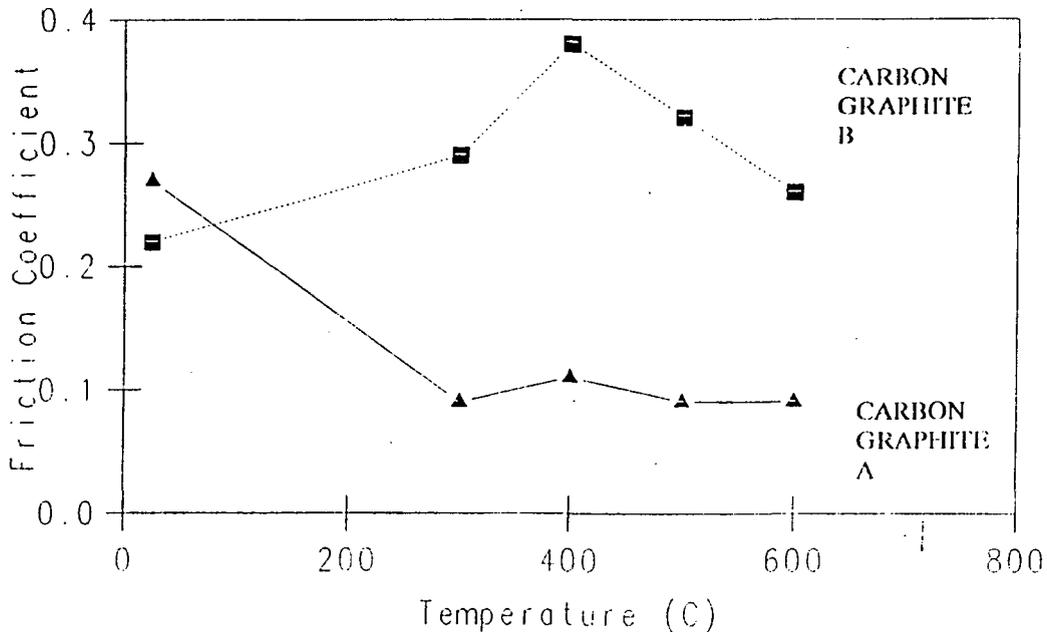
Two unique test rigs have been designed to evaluate the wear and friction of materials for aerospace sealing applications.

The first is a high temperature, oscillating rig used for tribological testing of materials for slide joints, static seals, solenoid valve plungers and similar aerospace applications exhibiting fretting type wear. It was designed and built at Group R&D to accurately record variations in the normal and tangential loads under oscillating conditions at temperatures up to 1400°. The design of this rig uses a programmable motor which can duplicate acceleration and velocity profiles of various oscillating and low speed unidirectional motions. The test samples are enclosed in a furnace which can be purged using various atmospheres. A pneumatic loading system is designed to achieve high contact pressures (500 psi), applied pneumatically.

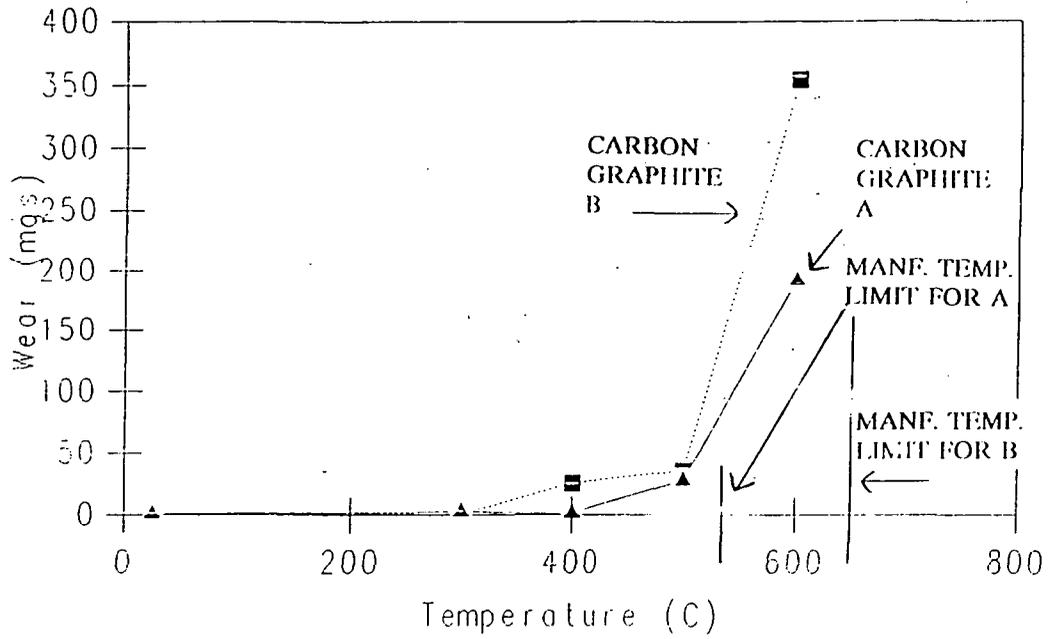
High Speed-High Temperature Test Rig

The second is a high speed/high temperature rig designed to test materials for main shaft and gas-path seal applications where high surface speeds of up to approximately 400 feet per second at a shaft rotation of 60,000 rpm and light loads up to 2psi are used for testing. This rig has the capability of heating the tribo-pairs to 1200° while maintaining precise alignment at the seal interface. Loading of the seal face is accomplished using gas pressure applied to a bellows assembly such that precise increments of pressure can be selected for test purposes. This test rig is currently being used to investigate appropriate tribo-pairs for brush seal fibers and runners.

FRICITION OF CARBON GRAPHITE AT HIGH TEMPERATURES



WEAR OF CARBON GRAPHITE AT HIGH TEMPERATURE



THE APPLICATION OF DIFFERENTIAL ROUGHNESS
TO MITIGATE FRICTION AND WEAR

A. O. Lebeck
Mechanical Seal Technology
Albuquerque, New Mexico

By definition differential roughness occurs where the surface roughness of one region is distinctly different (more or less) than that of an adjacent region. Differential roughness may occur on a sliding surface when the structure of an area of the surface is modified relative to the original material. Differential roughness may be used to effect a film thickness change so as to cause hydrodynamic or hydrostatic lubrication effects just as if the surfaces were machined. The advantage of differential roughness is that the effective offset of film thickness continues to exist even if there is gross wear. One can effect film thickness changes which are smaller than can be made directly. Furthermore, asperity tip load support is the same over both the high roughness and small roughness regions.

The potential uses for differential roughness are seals, bearings, and pumps. Some examples are presented.

SEAL TECHNOLOGY AT ROCKETDYNE

Joe Scharrer
Advanced Rotating Machinery

Rocketdyne's related activities and presentation include:

1. The seal codes currently in use at Rocketdyne and their capabilities.
2. The seal testing currently planned.
3. The fluid-film bearing activity currently underway and planned.

Rocketdyne Seal Technology

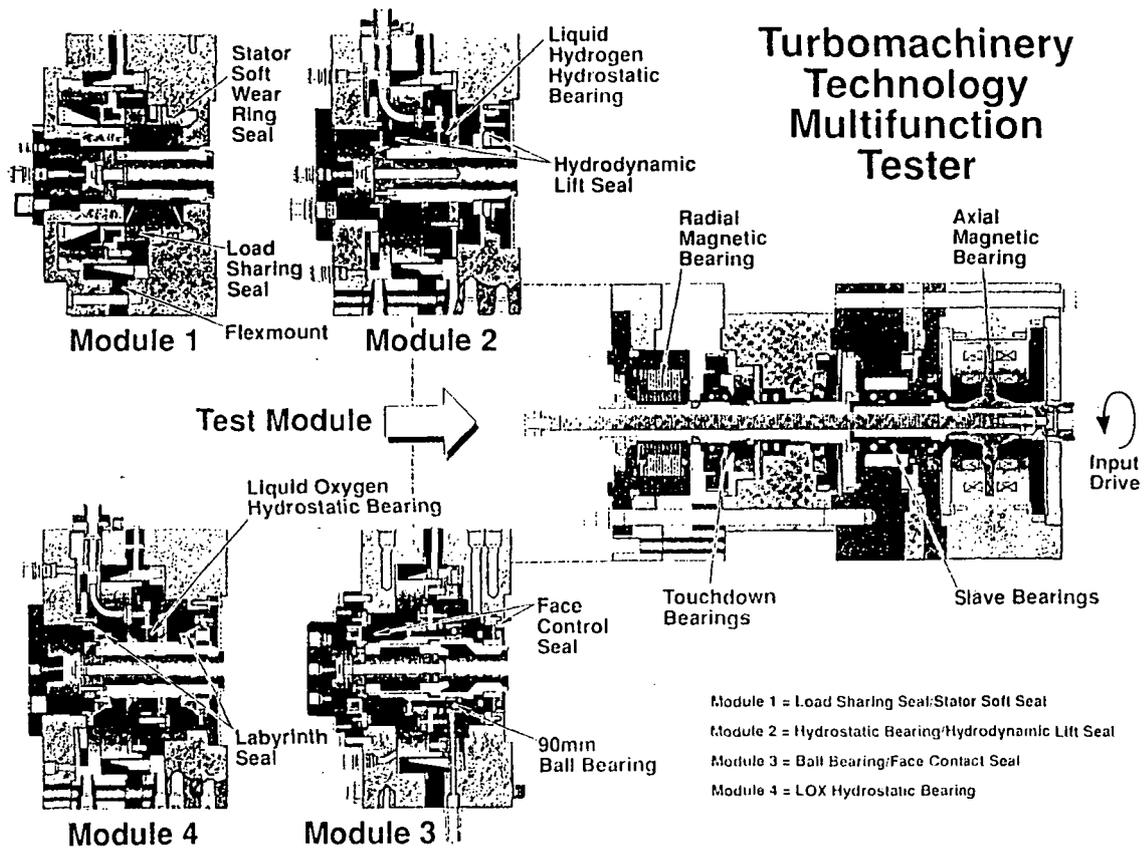
- Rocketdyne has a large collection of seal analysis codes
 - Floating ring seals
 - Static equilibrium
 - Dynamic response
 - Face seals
 - Steady state performance
 - Stability analysis
 - Load sharing seals
 - CFD codes for labyrinth and annular seals
 - Bulk-flow analysis for rotordynamic coefficients

Rocketdyne Seal Technology

- Rocketdyne code development is ongoing
 - Barotropic fluid properties
 - Phase change
 - Brush seal performance
 - Large scale roughness
 - Asymmetric boundary conditions

Rocketdyne Seal Technology

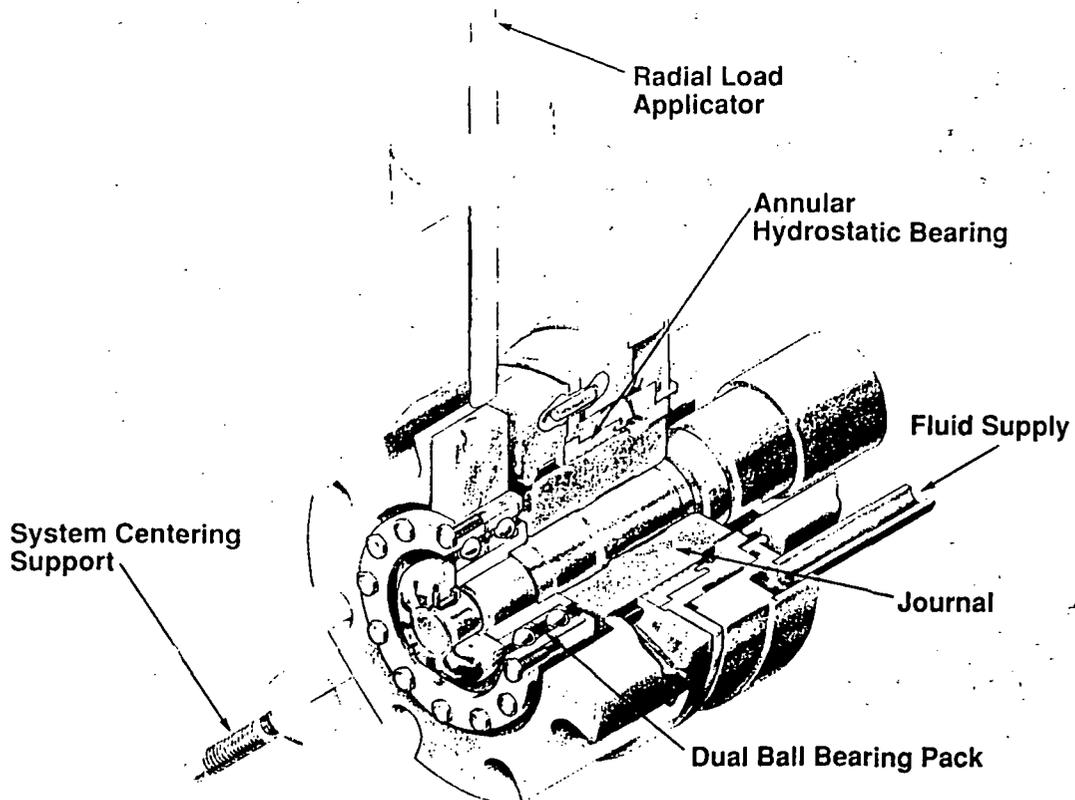
- Rocketdyne has both contract and internal funding for seal testing
 - Contract efforts
 - AFAL LOX/H2 Turbomachinery Technology
 - Extraction of rotordynamic coefficients for knurled damping seal in LH2
 - Dynamic testing of floating ring seal in LH2
 - Dynamic testing of spiral groove face seal in LH2
 - NASP
 - Extraction of rotordynamic coefficients for knurled damping seal in LOX
 - NASA MSFC NRA (with University of Akron)
 - Flow visualization and measurement in knurled damping seal



Rocketdyne Seal Technology

- IR&D funded testing
 - Brush seal performance in LH2
 - Brush seal coatings (with Texas A&M)
 - Flow in large scale roughness (with Texas A&M)
 - Transient load capacity of knurled damping seal in LOX

Annular Hydrostatic Bearing Transient Tester

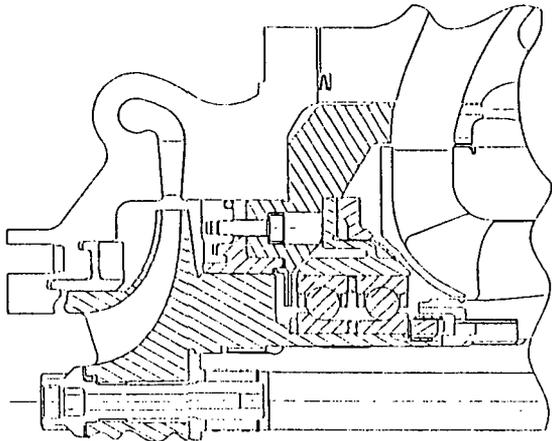


HPOTP PUMP END BEARING CONVERSION Plans

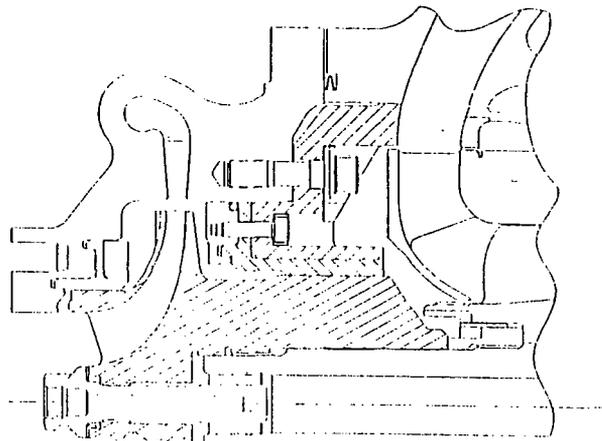
- Design annular LOX hydrostatic bearing/seal
 - Tapered, knurled sterling silver damping bearing
- Eliminate ball bearings No. 1 and No. 2
- IR&D to design and fabricate retrofit hardware
- Contract to assemble and test on TTB
- Design substantiated with component tests in Long Life tester
 - K-monel and Inconel 718 journals
 - 60 start transient simulations per bearing in LOX
- Tribometer tests measure friction and wear in GOX
- Ignition data provided by White Sands testing
- Future plans include upgrading tester to measure coefficients

HPOTP PUMP END BEARING CONVERSION

Flight Phase II Configuration



Hydrostatic Bearing Retrofit



- Twelve parts & bolt pattern removed

- Replaced by three parts

EXPERIMENTAL VERIFICATION OF ROTORDYNAMIC ANALYSIS

MSFC Program Status

- **Complementary damping bearing development initiated in October**
 - Verifies rotordynamic coefficient calculations for hydrostatic bearings
- **Tests four hydrostatic bearings in modified long life tester**
 - HCFC test fluid
 - **Two bearings internally fed through the shaft**
 - Conventional and damping designs TBD
 - **Two bearings externally fed through the stator**
 - Conventional and damping designs TBD
- **Extracts all rotordynamic coefficients**
 - Measures leakage and frictional torque
- **Conceptually designs new HPOTP turbine end package**
 - Includes lowest whirl ratio bearing tested
 - Provides manufacturing estimate

HYDROSTATIC BEARING TECHNOLOGY

Review

- **Problem**
 - Present turbopumps limited by rolling element bearing life
- **Goal**
 - Develop reliable, long life, cryogenic fluid-film bearings
- **Benefits**
 - Eliminate rolling element bearing DN limits and life constraints
 - Add flexibility to optimize rotor mechanical arrangement
 - Increase damping for more stable operation
 - Reduce overhauls and maintenance costs
- **Rocketdyne committed to multiyear IR&D development program**
 - 1990 expenditure of \$1.726M
 - 1991 commitment of \$2.275M
- **NASA and AFAL contracts in place to further advance technology**

HYDROSTATIC BEARING DEVELOPMENT INTEGRATION PLAN

Issue	Task	Funding Source	FY 90				FY 91				FY 92				FY 93				
			1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	
Code	Code development & verification	IR&D																	
Material	Material development (tribology)																		
Environment	Non-contacting bearing study																		
Lift-off	Transient life testing																		
Coefficients	Cryogenic bearing development																		
Tester Demo	Dual rotor support demonstration																		
T/P Demo	Generic turbopump demo, MK29FD																		
Coefficients	LOX/H ₂ MFT bearing development		AFAL																
T/P Demo	HPOTP pump end retrofit																		
Type/Coeff	Int/ext feed damper brg comparison		MSFC																
T/P Demo	HPOTP turbine end retrofit	OPEN																	
Coefficients	LOX bearing coef. testing	NASP																	
Coefficients	ADP bearing validation	MSFC																	
T/P Demo	ADP LH ₂ turbopump	MSFC																	

CFD ACTIVITY AT AEROJET
RELATED TO SEALS AND FLUID FILM BEARING

G. E. Bache

This presentation package covers the CFD activity at Aerojet related to seals and fluid film bearing. The presentation addresses the following topics:

1. Aerovisc Numeric and Capabilities
2. Recent Seal Application
3. Future Code Development

PRESENTATION PREVIEW

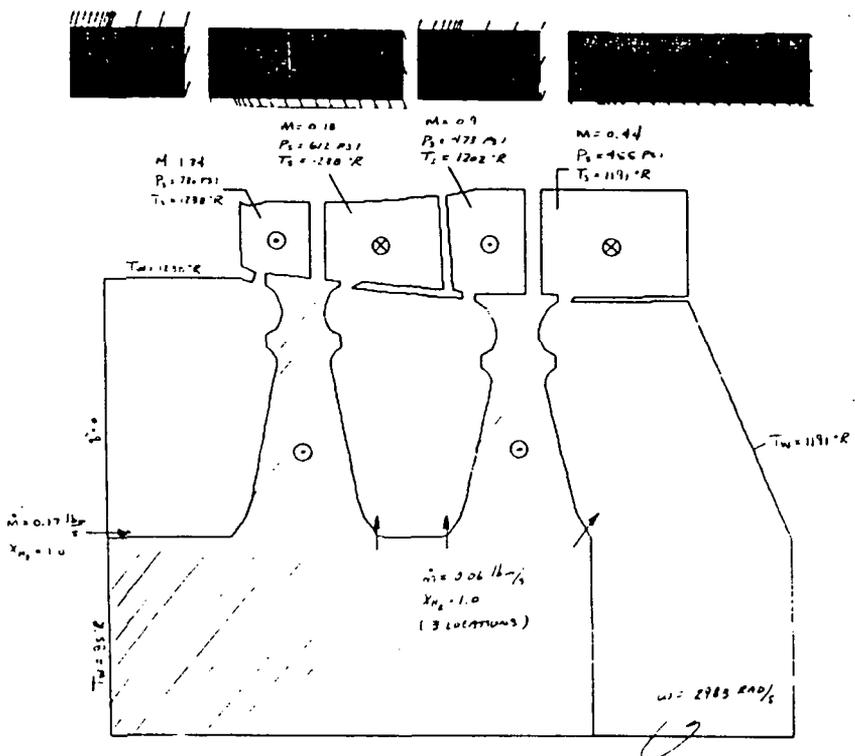
- AEROVISC NUMERICS AND CAPABILITIES
- RECENT SEAL APPLICATION
- FUTURE CODE DEVELOPMENT

AEROVISC Numerics

- **Formulation**
 - Reynolds Stress Averaged Navier-Stokes Equations in Cartesian, Strongly Conservative, Primitive Variable Form
 - k-e and ARS Turbulence Models With Log-Law Wall Functions
- **Discretization**
 - "Flux" Element Based Finite Volume Method
 - General Non-Orthogonal Boundary-Fitted Structured Grid
 - Choice of Advection Schemes
 - Upward Difference (Most Robust, Least Accurate)
 - Mass Weighted Skew (Enhanced Accuracy)
 - Linear Profile Skew (Most Accurate)
 - Second-Order-Accuracy With Physical Advection Correction Term
 - Rhie-Type Pressure Redistribution for Incompressible Flows
- **Algebraic Solver**
 - Choice of Vectorized Gauss-Siedel or Incomplete Cholesky Base Solver
 - Additive Correction Multigrid (Large Grids)
 - Block Correction (High Aspect Ratio Grids)

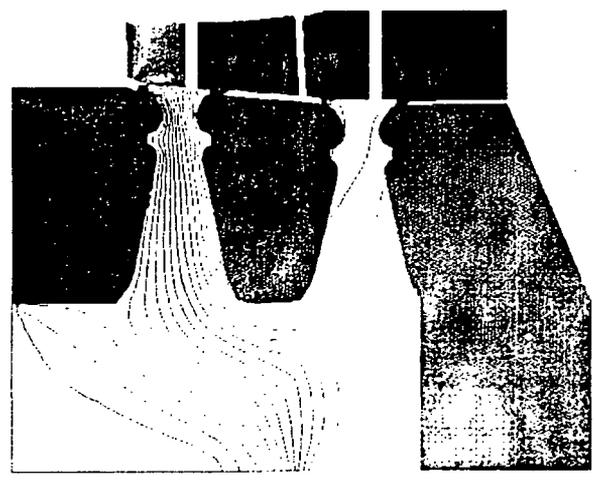
RELEVANT CODE CAPABILITIES

- INCOMPRESSIBLE FLOW
- SUBSONIC, TRANSONIC, AND SUPERSONIC FLOW
- NON-ISOTHERMAL AND ISOTHERMAL FLOW
- LAMINAR, TURBULENT, OR INVISCID FLOW
- CORIOLIS AND CENTRIFUGAL TERMS FOR TURBOMACHINERY APPLICATIONS
- FIXED, MOVING OR ROTATING TURBULENT WALLS
- CONJUGATE HEAT TRANSFER OR SPECIFIED WALL TEMPERATURE/FLUX
- VARIABLE FLUID AND SOLID PROPERTIES
- MULTI-COMPONENT FLOW (N ADDITIONAL SCALAR TRANSPORT EQUATIONS)
- MULTIPLE BLOCKED REGIONS



TEMPERATURE

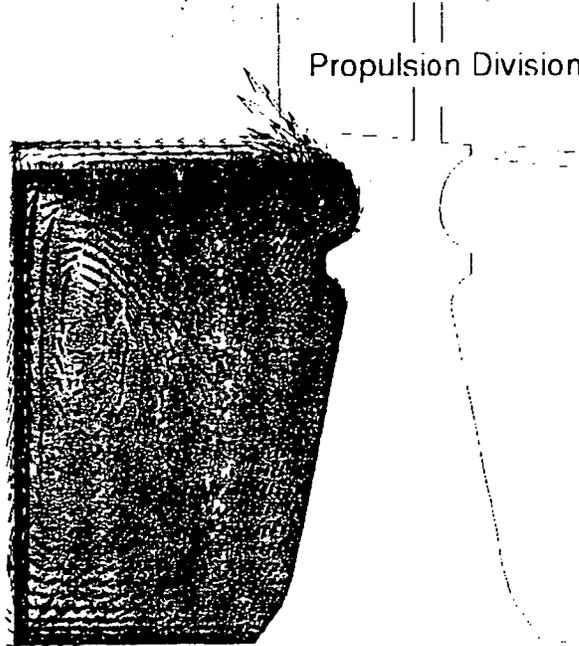
1.400E+00
1.340E+00
1.280E+00
1.220E+00
1.160E+00
1.100E+00
1.040E+00
9.790E-01
9.200E-01
8.590E-01
8.000E-01
7.400E-01
6.800E-01
6.190E-01
5.600E-01
5.000E-01
4.400E-01
3.800E-01
3.200E-01
2.600E-01
2.000E-01



TEMPERATURE

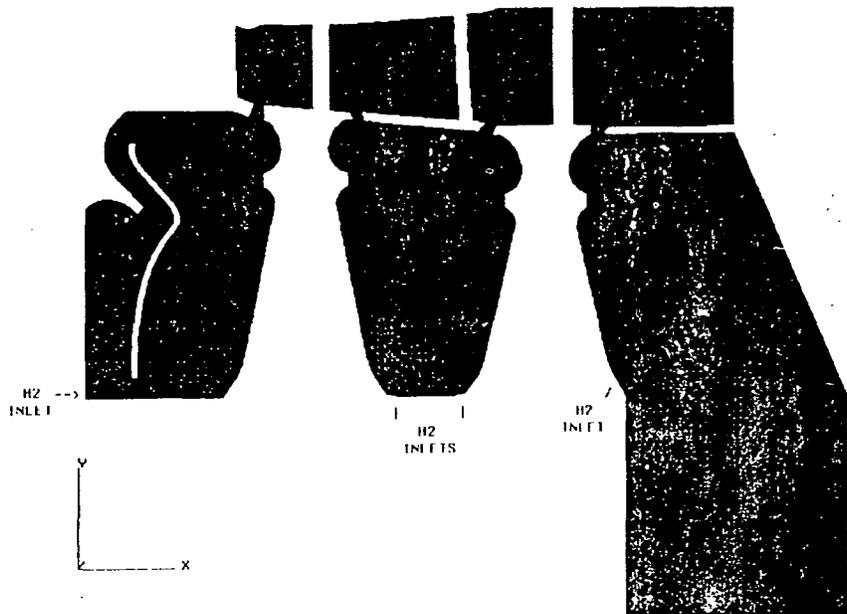
1.287E+03
1.224E+03
1.161E+03
1.097E+03
1.034E+03
9.711E+02
9.078E+02
8.445E+02
7.812E+02
7.179E+02
6.546E+02
5.913E+02
5.280E+02
4.647E+02
4.014E+02
3.381E+02
2.748E+02
2.115E+02
1.482E+02
8.500E+01

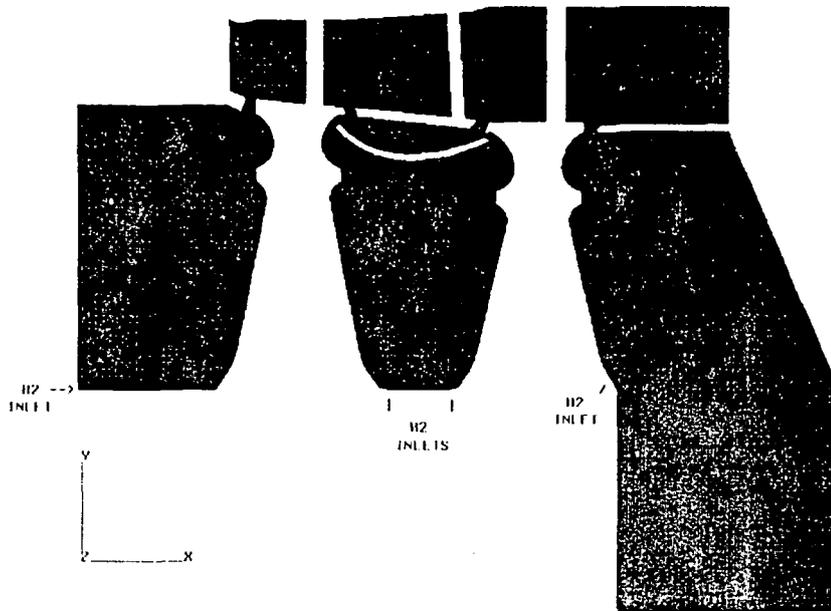
Propulsion Division



TEMPERATURE

7.391E+02
7.064E+02
6.737E+02
6.409E+02
6.082E+02
5.755E+02
5.428E+02
5.101E+02
4.774E+02
4.447E+02
4.120E+02
3.793E+02
3.466E+02
3.139E+02
2.812E+02
2.485E+02
2.158E+02
1.831E+02
1.504E+02
1.177E+02
8.500E+01



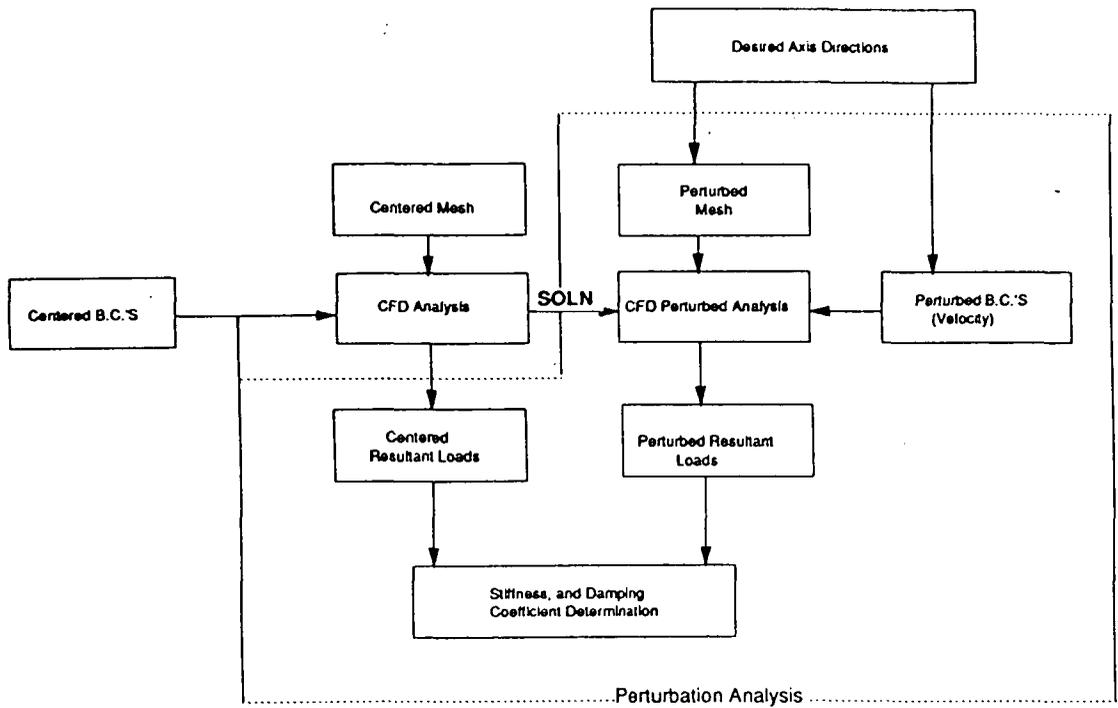


FUTURE CODE DEVELOPMENT

- GRID EMBEDDING/ATTACHING
 - GRID REFINEMENT IN AND NEAR SEALS
 - IMPROVED SOLUTION ACCURACY

- MULTI-LAYER TURBULENCE MODEL

- AUTOMATED PROCEDURE TO PREDICT FLUID SEAL DYNAMIC COEFFICIENTS

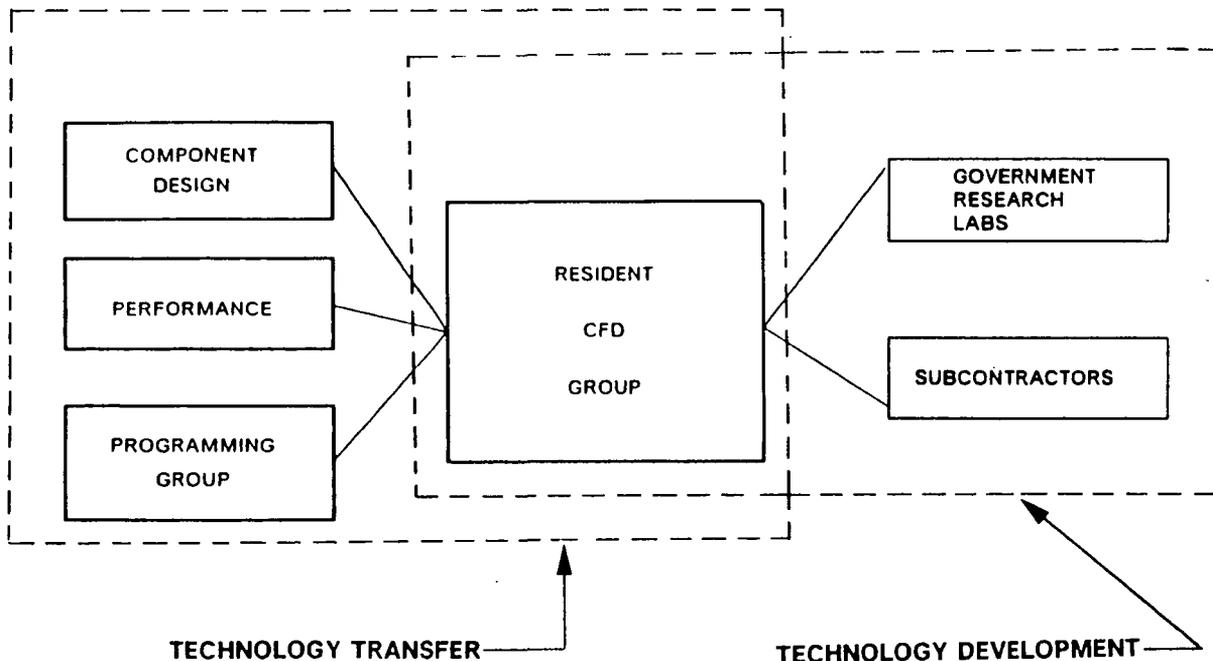


Schematic of Fluid Film Bearing Analysis Methodology

PRATT AND WHITNEY ACTIVITIES
Saadat A. Syed

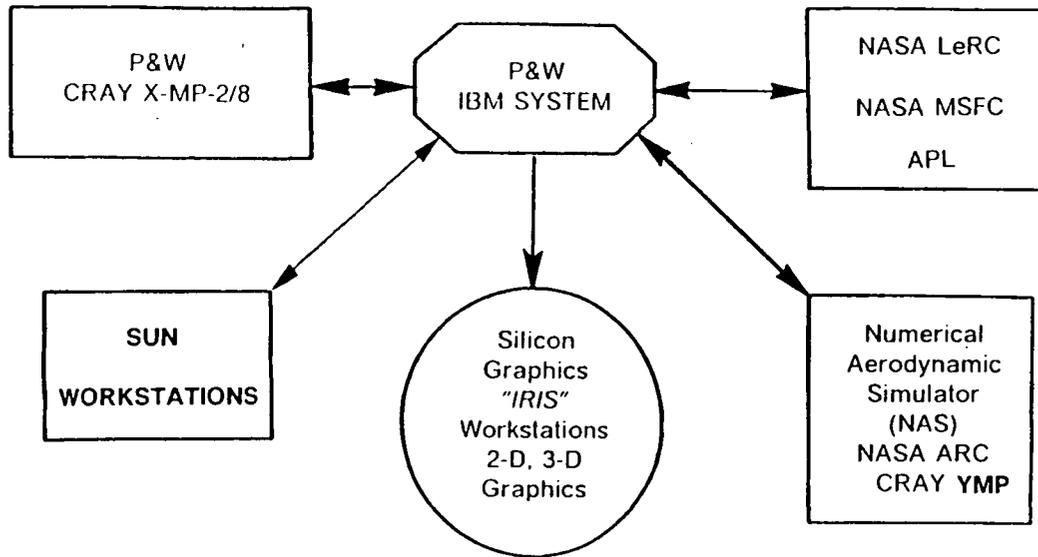
An example of CFD application in the seal area is described. This effort consisted of optimizing specific seals in SSME-ATD and resulted in design of a seal tested at Pratt and Whitney which demonstrated 30% lower leakage than standard design at the same clearance. This example shows the potential of identifying seal geometry parameters which reduce internal flow leakages detrimental to component and turbopump efficiencies. This information can then be used to develop an analytical design procedure for controlling leakage in any given application or environment.

ORGANIZATION



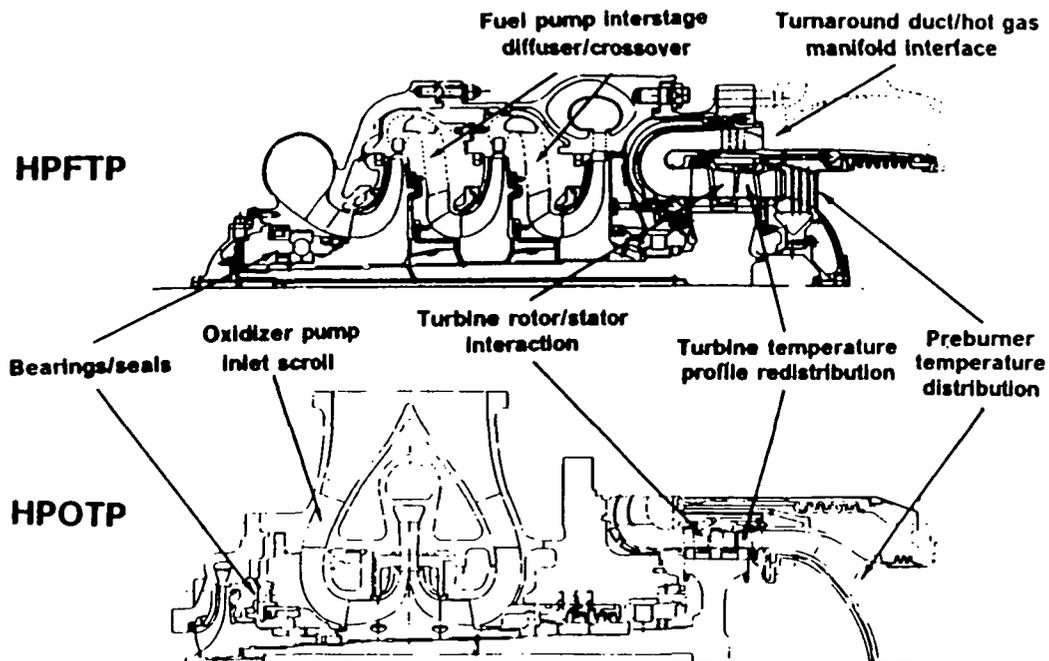
COMPUTATIONAL FLUID DYNAMICS

Significant Computing Power Available



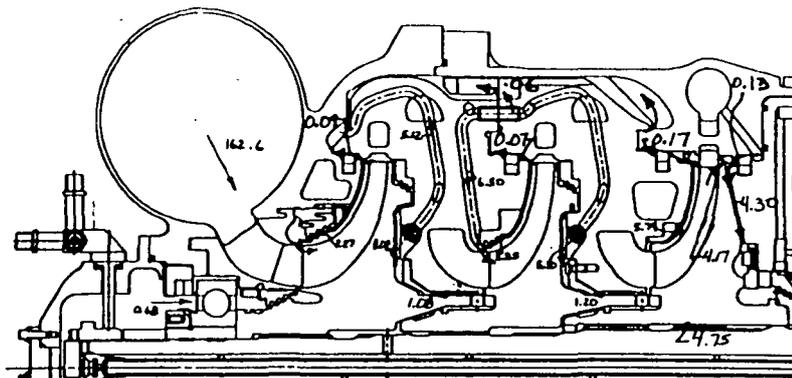
CFD ANALYSES OF TURBOPUMPS

Seven Areas Of Analysis Identified As Important For Successful Turbopump Design.



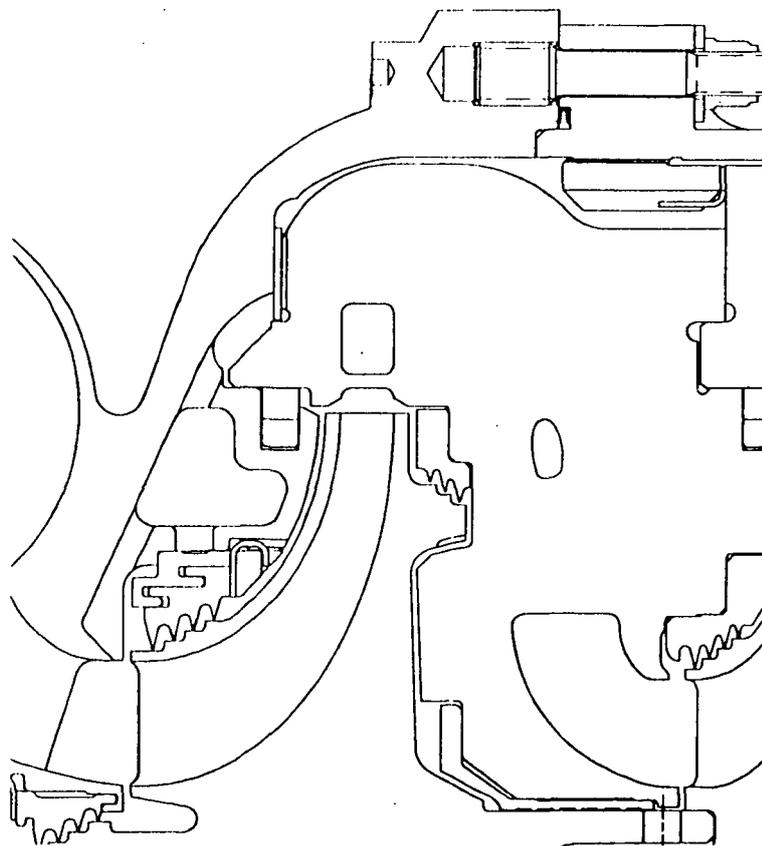
ATD HPFTP INTERNAL FLOW MGMT

Pump Internal Flows



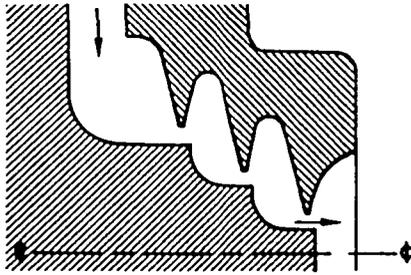
ATD - HPFTP

Seal Detail

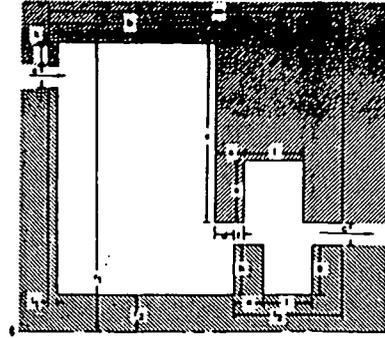


SSME-ATD FUEL PUMP CAVITY

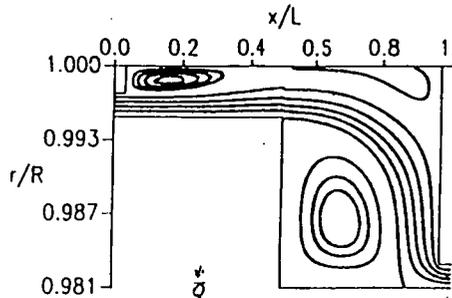
Minimize Leakage



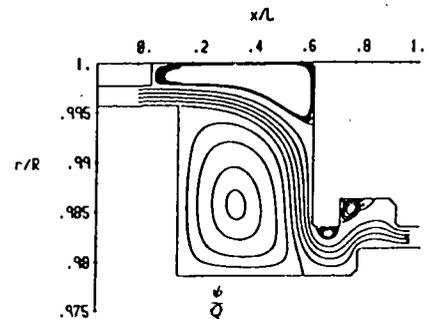
Overall original BI Seal configuration.



Design dimensions for the BI Seal configurations.



Streamline pattern within the idealized original cavity.

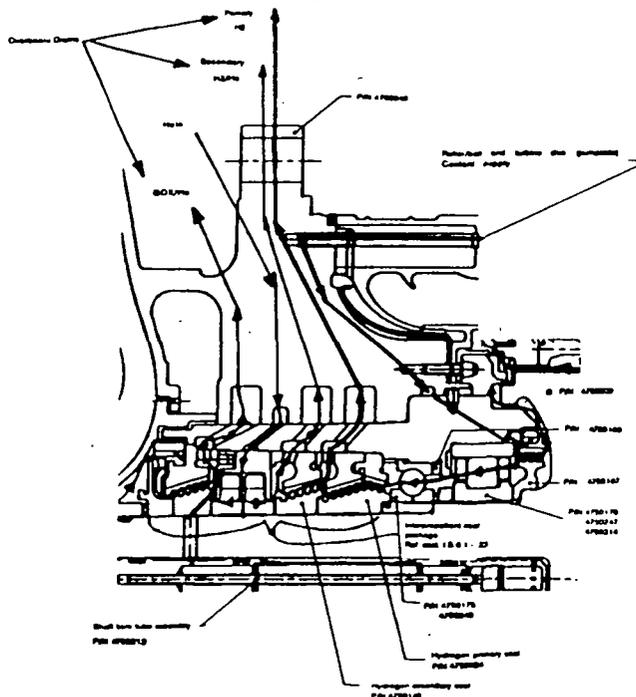


Streamline pattern within the Seal 8 cavity.

ATD HPOTP INTERNAL FLOW MGMT

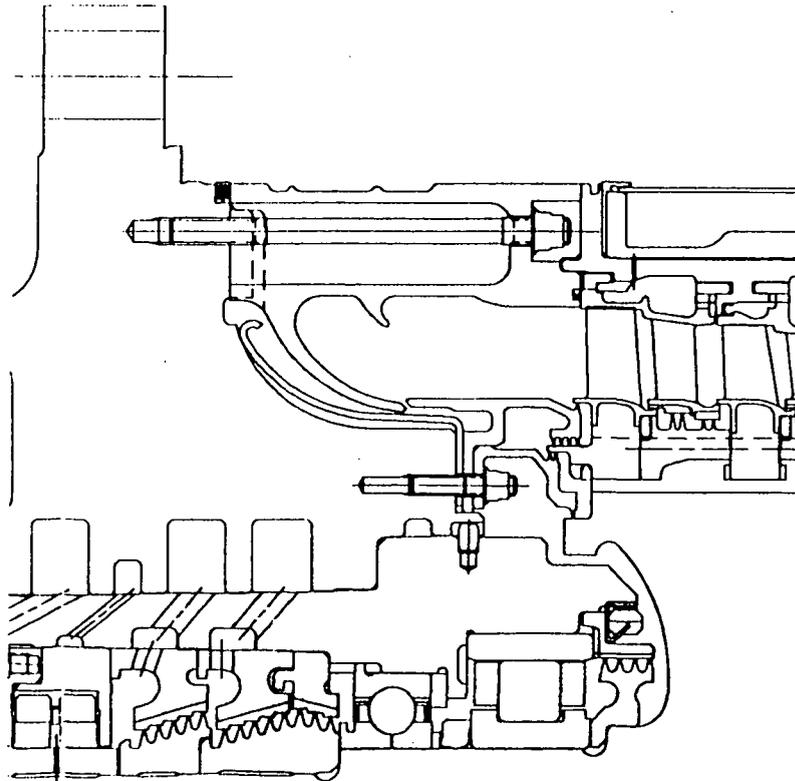
Bearing And Turbine Coolant Flows

Roller Bearing Coolant Flow



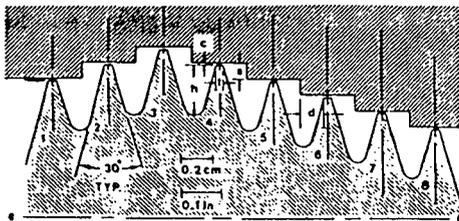
ATD HPOTP

Seal And Bearing Details

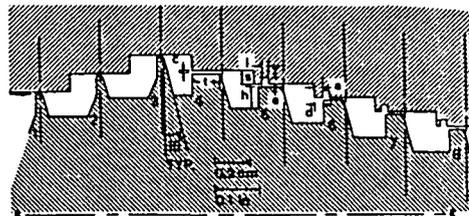


SSME-ATD LOX PUMP CAVITY

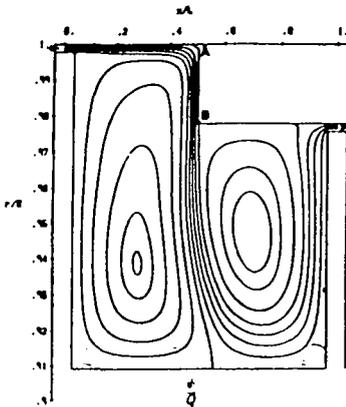
Controlled Leakage



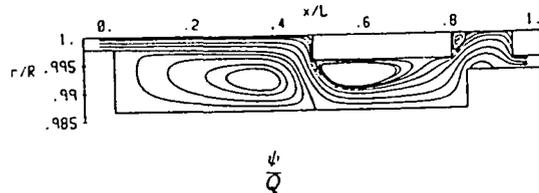
Overall original Interpellent (IP) Seal design.



Recommended design configuration for the IP Seal utilizing the new leakage stability concept.



Streamline pattern within an idealized original IP Seal cavity.



Streamline pattern within Seal 75 cavity.

CFD Applications in Propulsion

Charles L. Merkle
The Pennsylvania State University
Department of Mechanical Engineering
University Park, PA 16802

An overview of various applications of CFD algorithms to propulsion problems is given. Problems of interest include incompressible, low speed compressible, transonic and supersonic. A common family of algorithms is used for all applications and emphasis is placed on maintaining accuracy and convergence efficiency for all problems. Specific problems include pump hydrodynamics, combustion and mixing simultaneous in rocket engines, viscous nozzle flow, and CFD applications to combustion stability.

CURRENT PROJECTS

- ROCKET COMBUSTOR MODELING
- COMBUSTION INSTABILITY MODELING
- PUMP FLOWFIELDS
- VISCOUS NOZZLE/PLUME FLOWS
- MAXWELL/NAVIER-STOKES ANALYSIS
- AUXILIARY PROPULSION
- LOW SPEED COMPRESSIBLE FLOWS

CFD PROBLEM FORMULATION

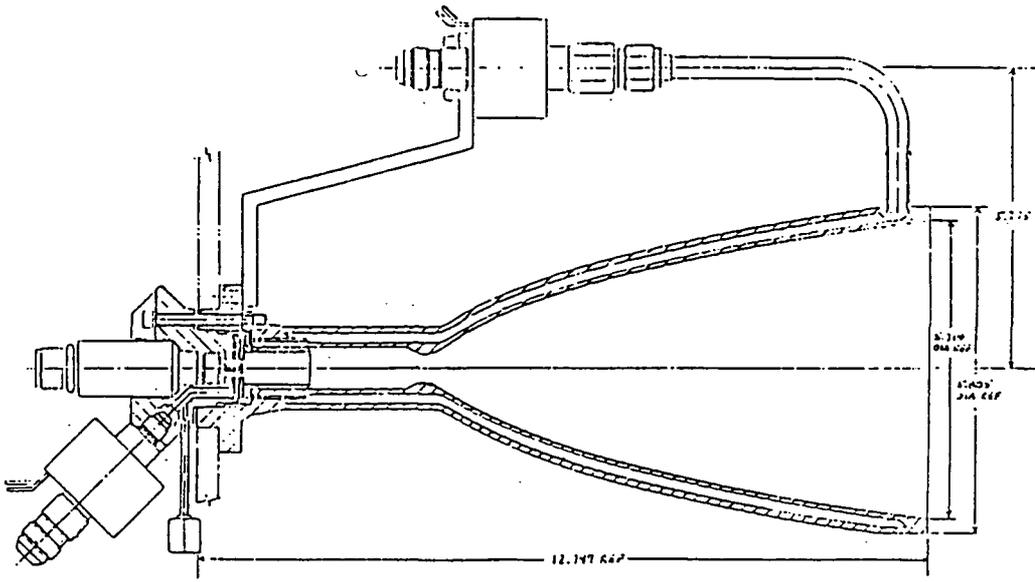
$$\Gamma \frac{\partial \rho}{\partial t} + \frac{\partial E_i}{\partial x_i} = \frac{\partial}{\partial x_i} R_{ik} \frac{\partial \bar{Q}_k}{\partial x_j} + H$$

Steady Compressible

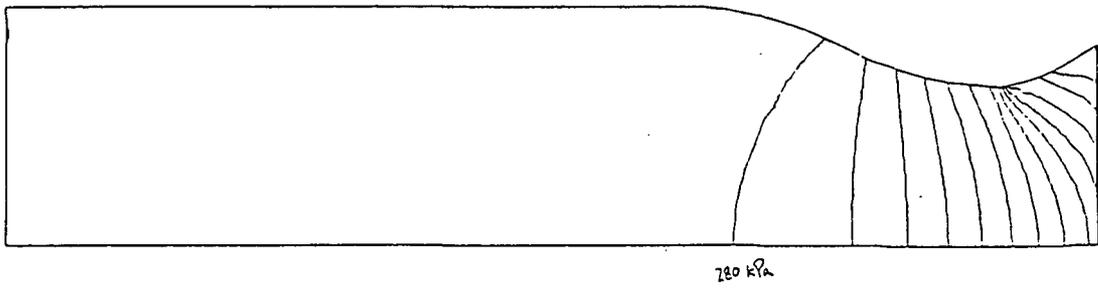
Unsteady Incompressible

Viscous Upwind

Inviscid Central



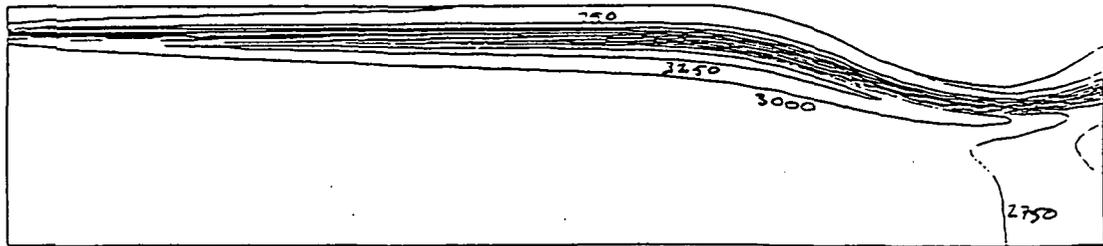
Schematic of small thruster geometry.



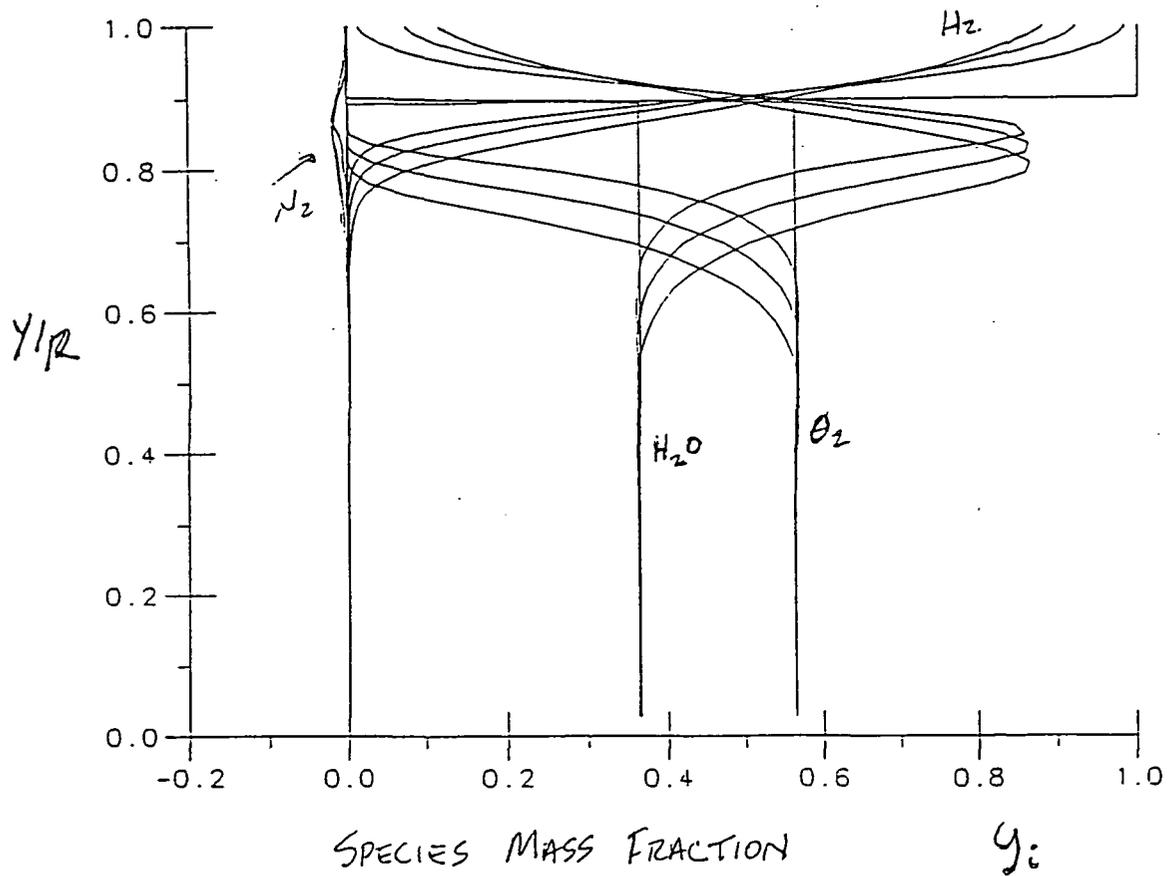
PRESSURE CONTOURS

min = 23.4 kPa
 max = 304 kPa
 delta = 20 kPa

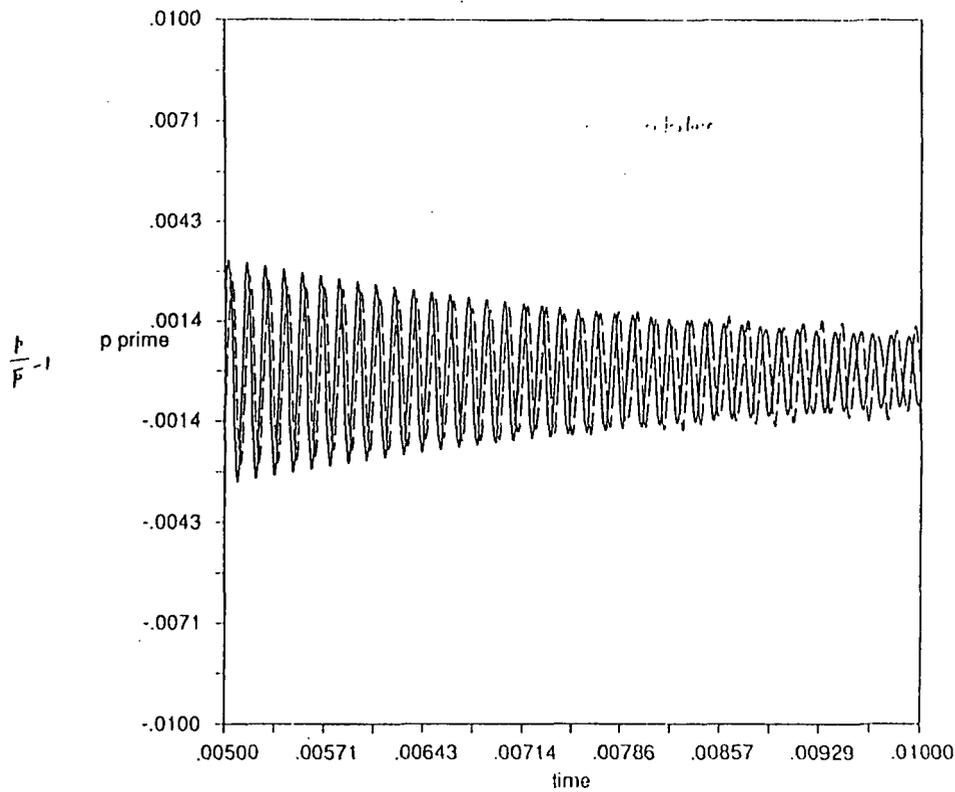
TURBULENT REACTING FLOW



TEMPERATURE CONTOURS
 MIN = 346.9 K
 MAX = 3302 K
 delta = 250 K

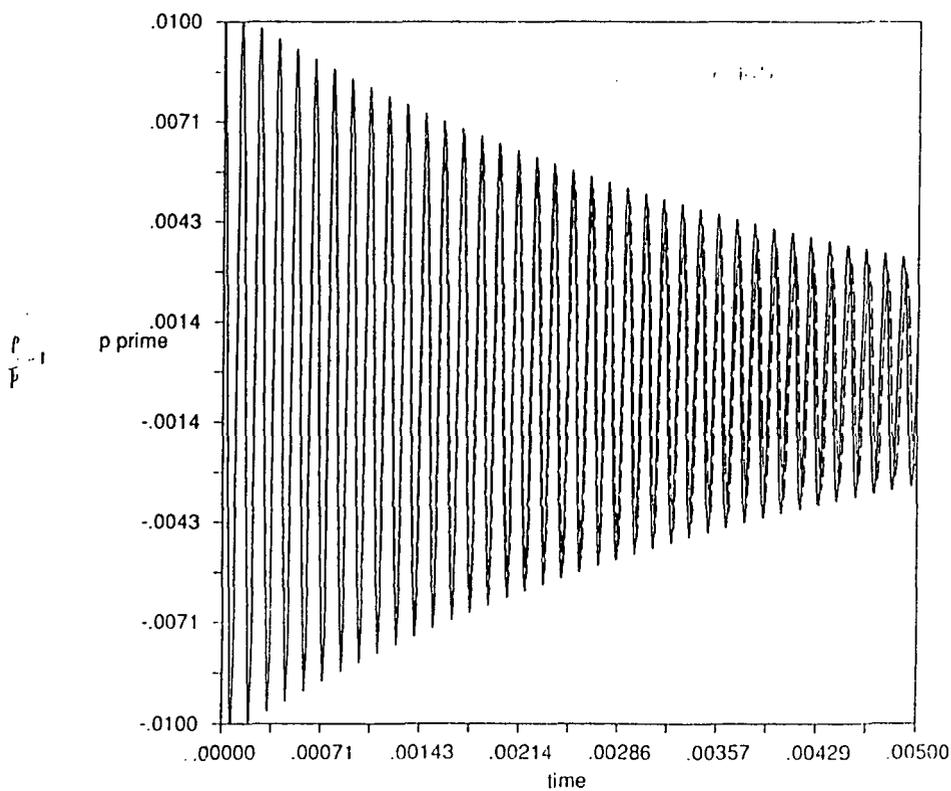


P Fluct vs. Time Case1 Priem i=101 j=51 cfl=0.5



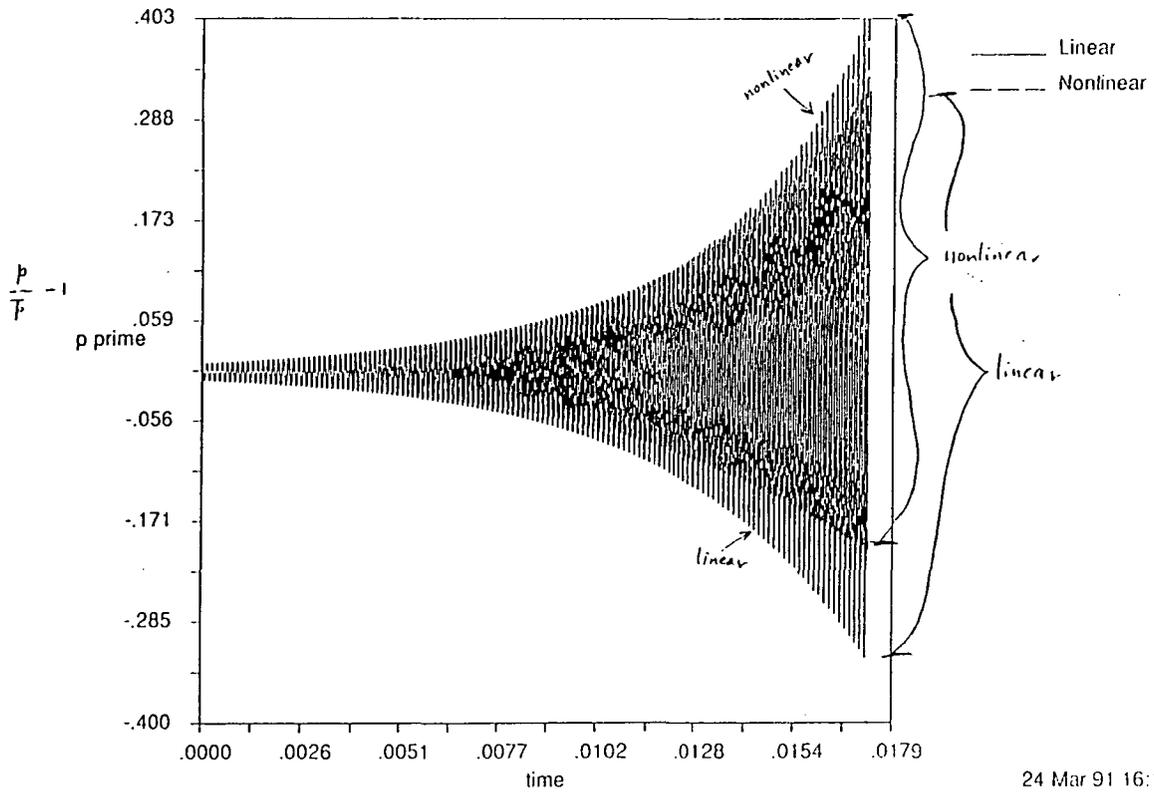
23 Mar 91 16:59:49

P Fluct vs. Time Case1 Priem i=101 j=51 cfl=0.5



23 Mar 91 16:59:49

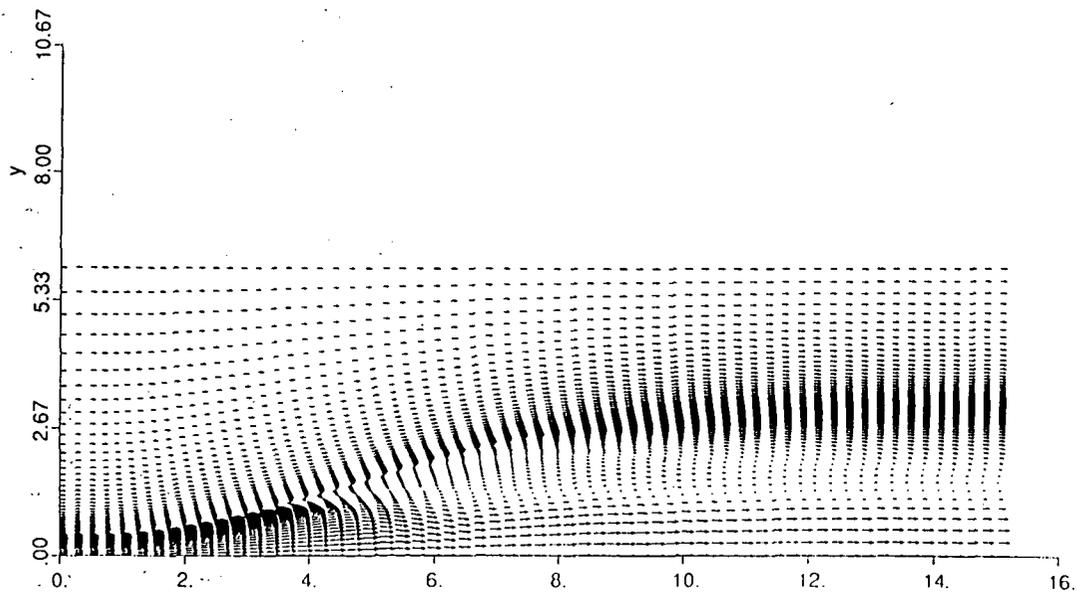
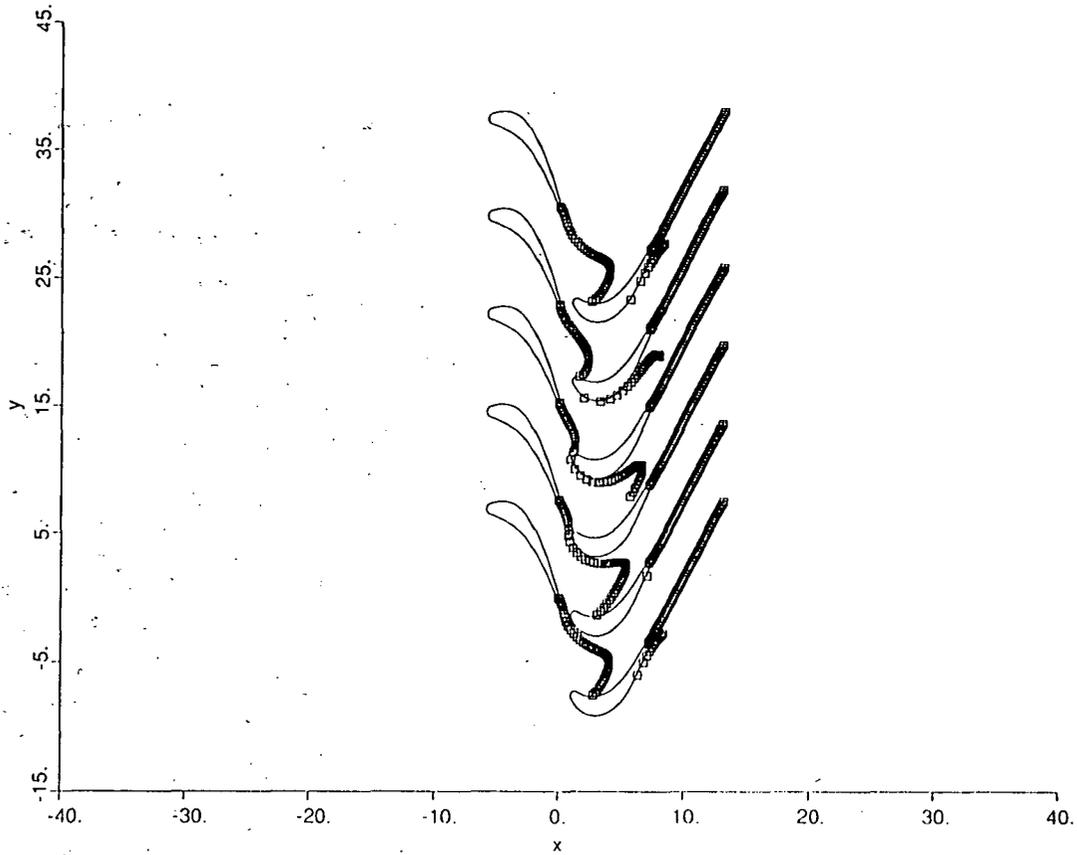
P Fluct vs. Time Case2 Priem i=101 j=51 cfl=0.5

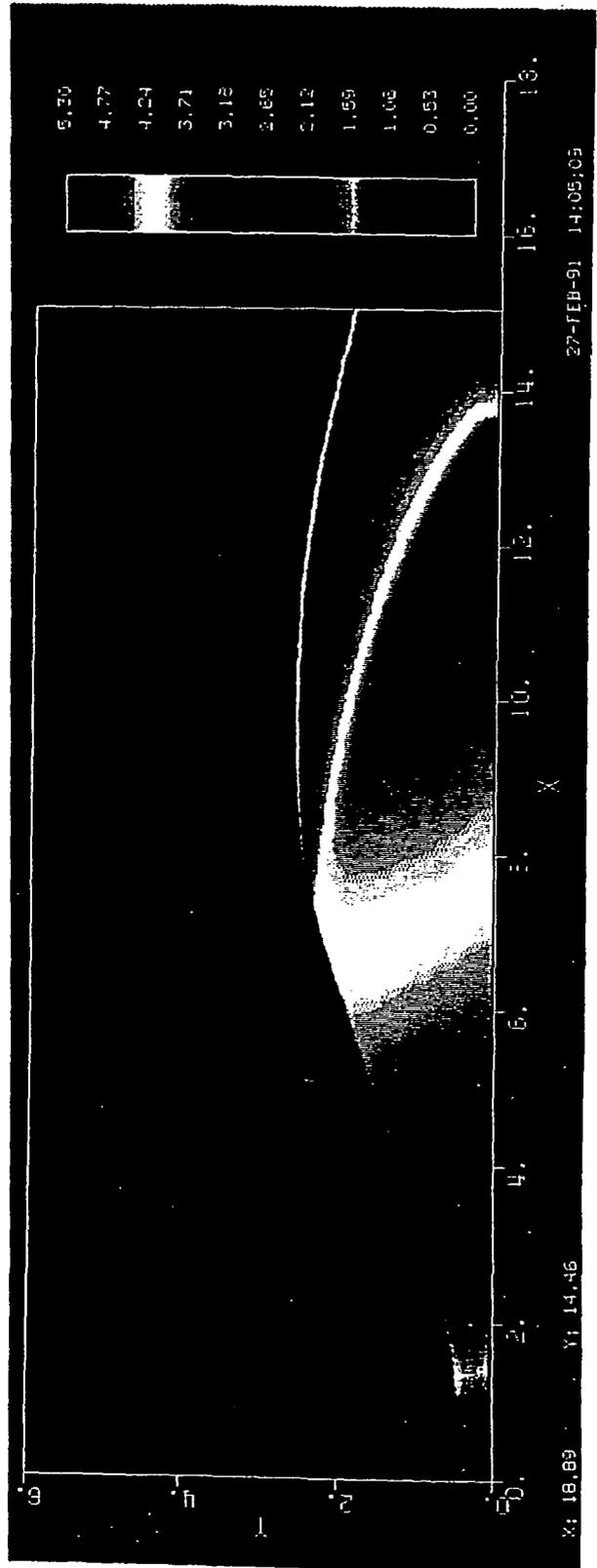
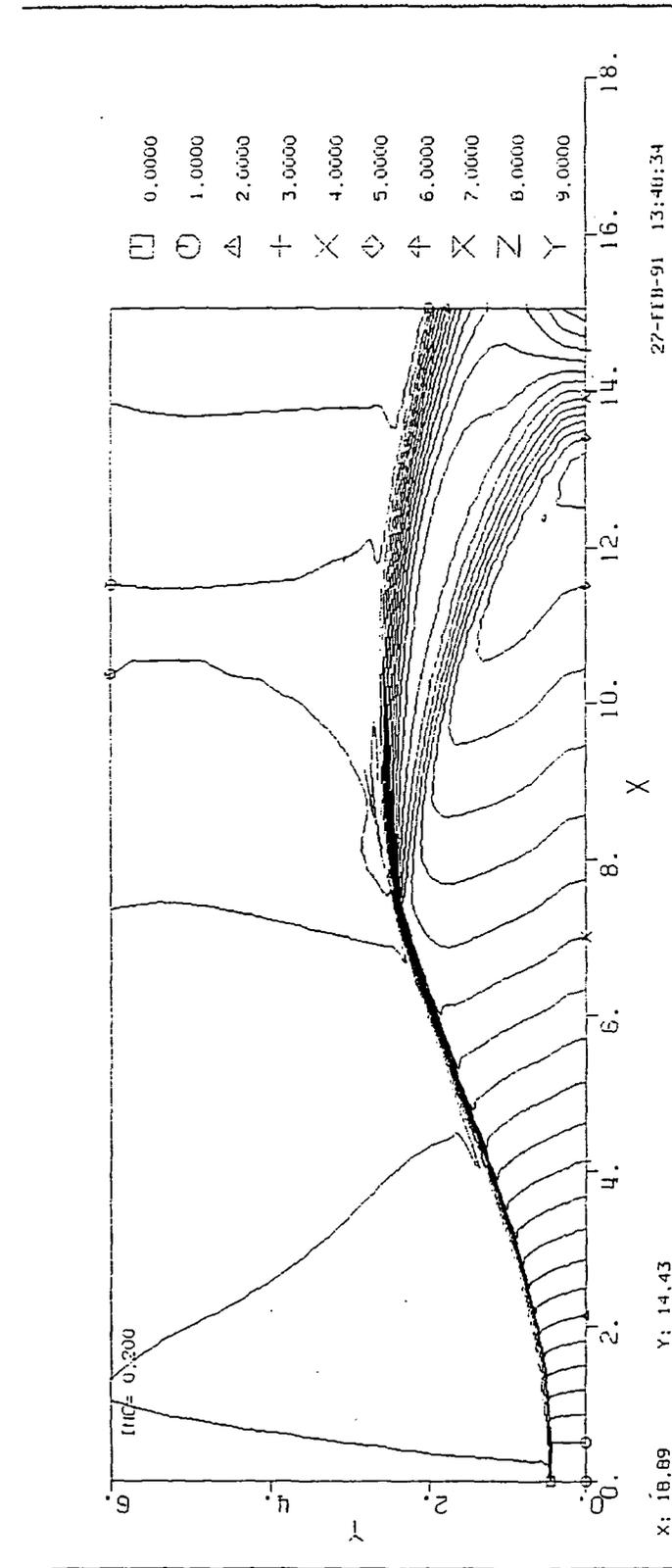


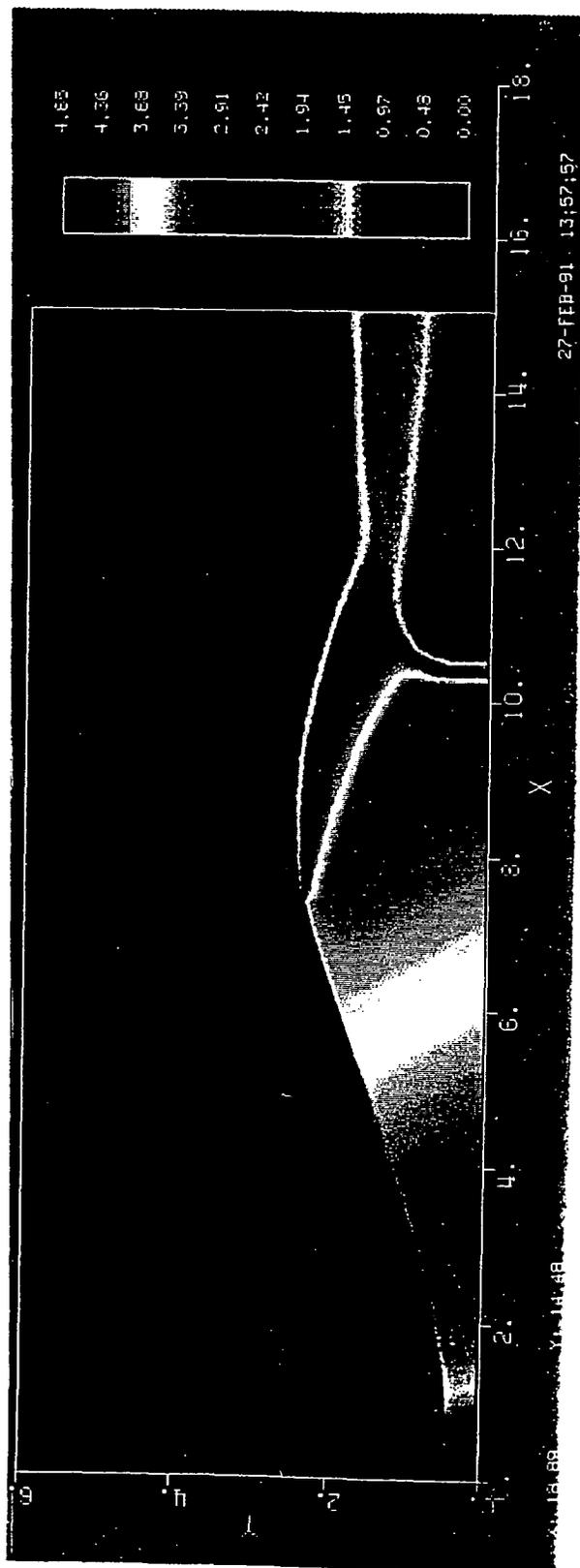
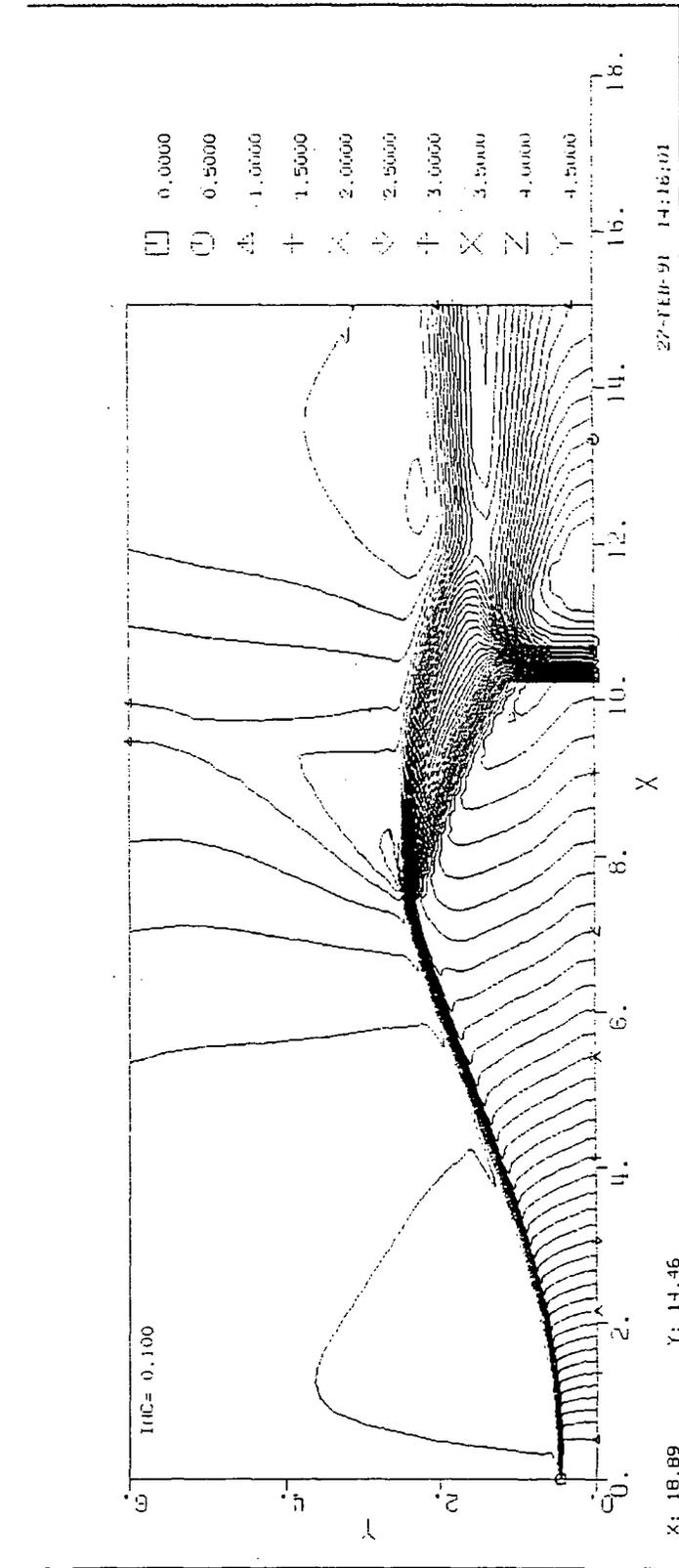
Plunging Airfoil

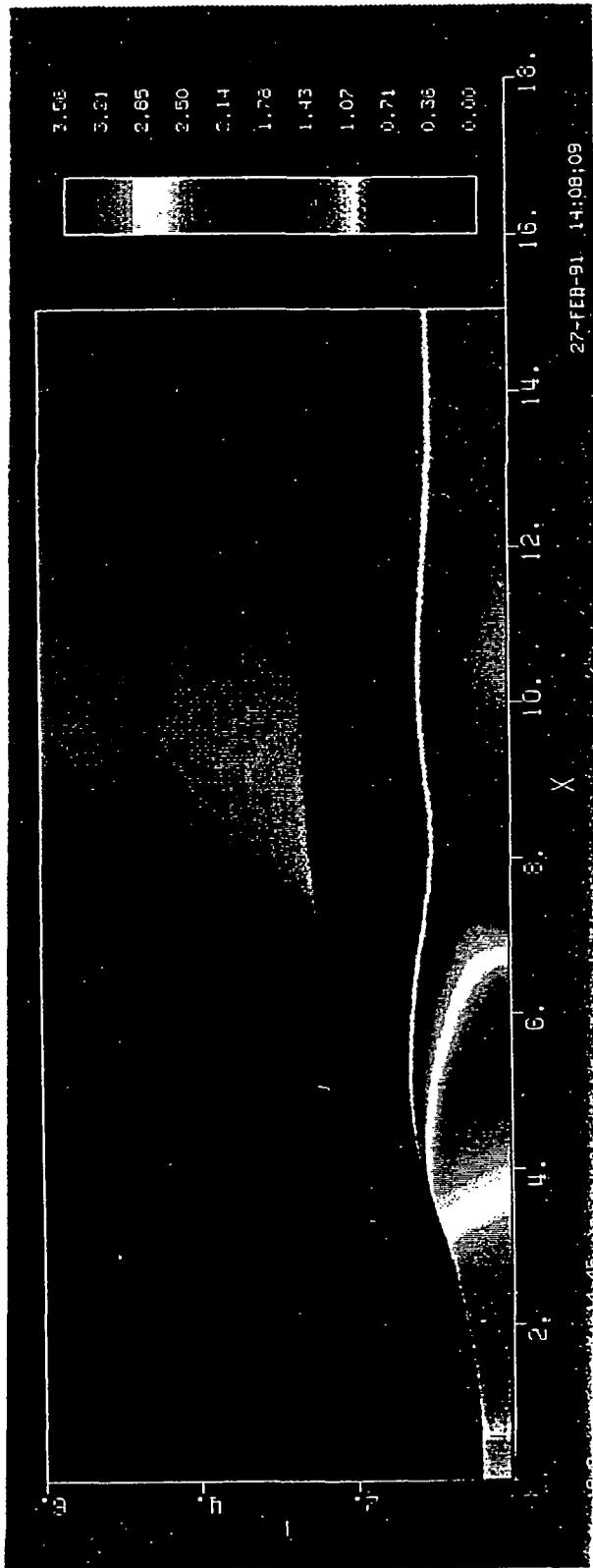
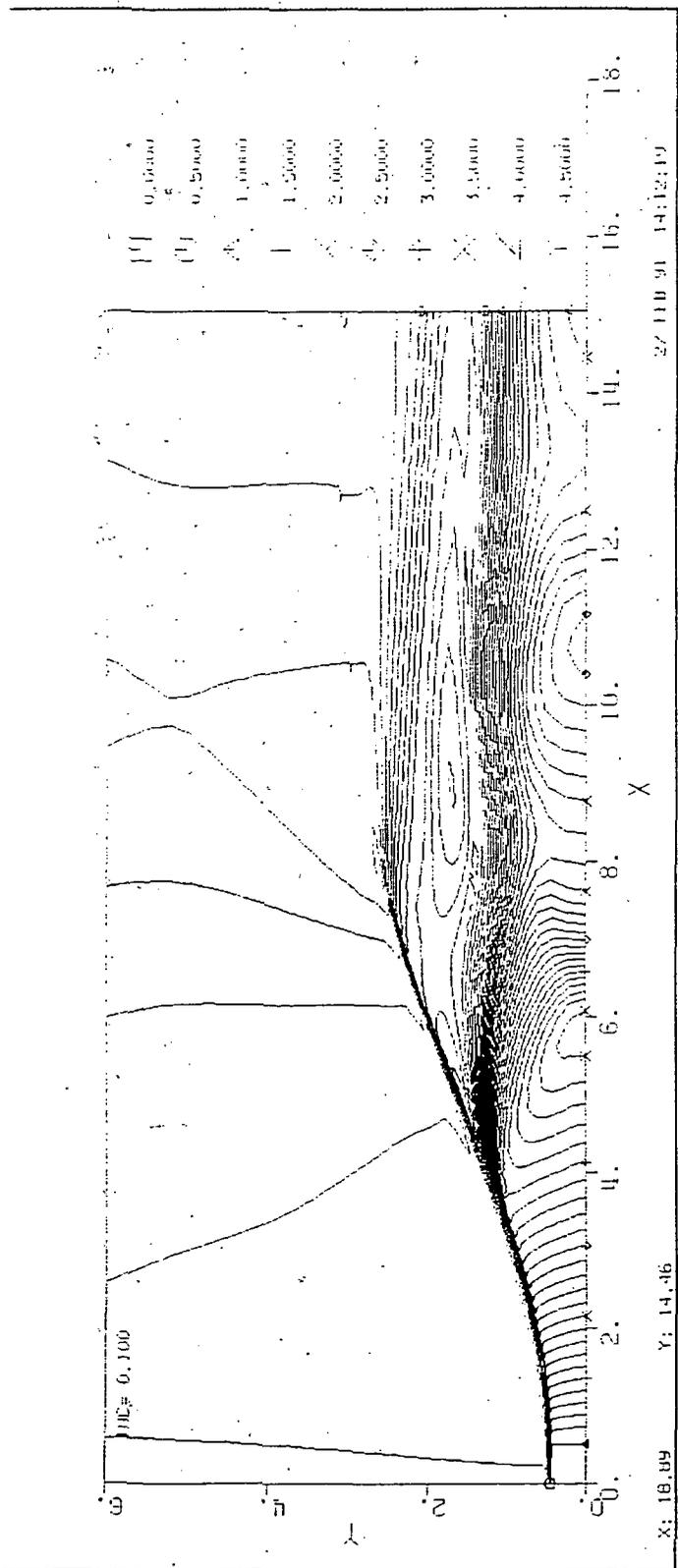


Wake behind utrc stator/rotor









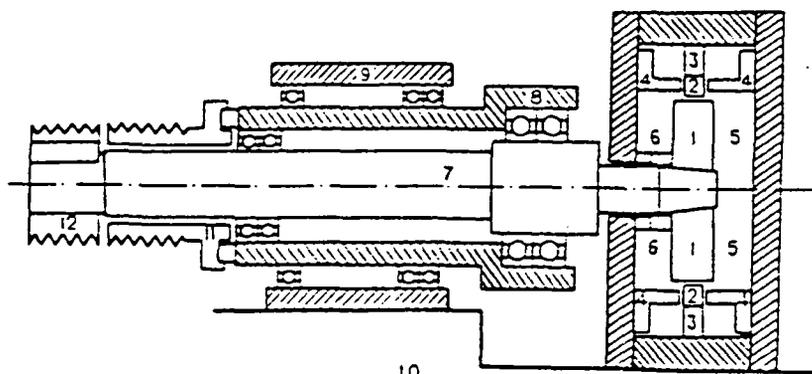
Status Update On The Seal/Bearing Rotordynamics Test
Facility At Case Western Reserve University

M.L. Adams, Professor
Department of Mechanical & Aerospace Engineering
Case Western Reserve University
Cleveland, Ohio 44106

OVERVIEW

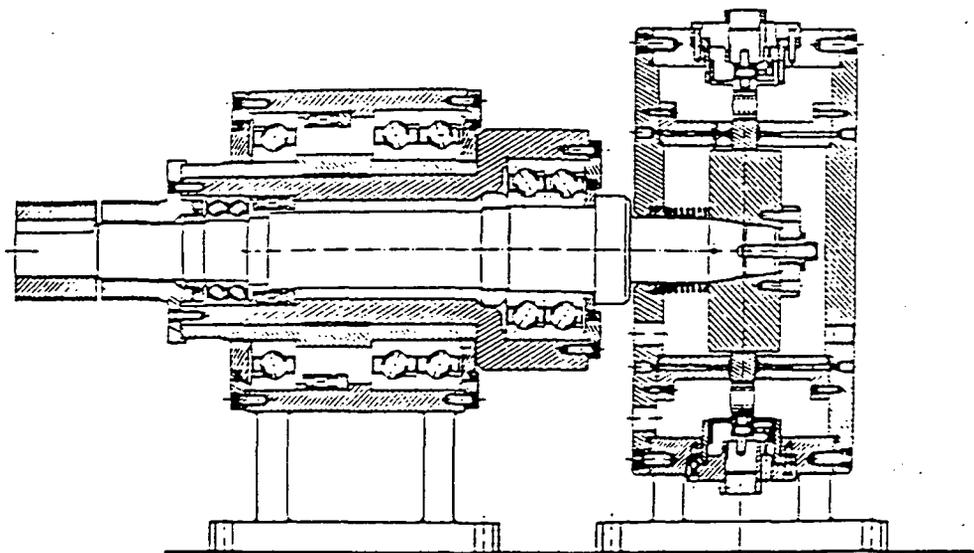
The CWRU Seal/Bearing test facility is shown in Figures 1 through 3, and the revised force measuring system is sketched in Figure 4. This facility has recently been retrofitted with a high-pressure high-flow oil system, which was acquired to conduct basic research on hydrostatic journal bearings for NASA Lewis Research Center. Mr. Russell Capaldi is the NASA grant monitor. The high-pressure high-flow water system remains in place to test seals. Also, a new high-flow air system is now installed. Thus, testing to determine static and dynamic properties can now be performed using oil, water or air on this single facility.

We are currently using the oil system to determine rotordynamic properties of a NASA four-pocket hydrostatic journal bearing. The revised dual system force measuring configuration (see Figure 4) is performing with excellent accuracy. That is, the dynamic force measurements are made simultaneously with two independent systems, one with piezoelectric load cells and the other with strain gage load cells. The difference is less than 2% (see Figure 5 through 7) between these two sets of load cell measurements on recent tests with a static eccentricity set close to zero ($e = 0.001$ inch, $C = 0.009$ inch) and an orbit radius of 0.0004 inch. Table 1 shows the extracted stiffness, damping and inertia coefficients for the test conditions shown, as extracted from the two independent dynamic force measurements. These coefficients were extracted using a linear-regression least-squares fit of the dynamic force and orbit displacement signals over a frequency range of 250 to 2,400 cpm, without constraining the inertia matrix to be symmetric.



- | | |
|-------------------------------------|-------------------------|
| 1 - Test rotating element | 7 - Inner spindle rotor |
| 2 - Test annulus ring | 8 - Outer spindle rotor |
| 3 - Piezoelectric load cells | 9 - Spindle housing |
| 4 - Hydrostatic axial ring supports | 10 - Support base |
| 5 - High-pressure compartment | 11 - V-belt pulley |
| 6 - Low-pressure compartment | 12 - V-belt pulley |

1(a) Conceptual Sketch of Rotor Support Component Test Apparatus



1(b) Assembly Layout of Rotor Support Component Test Apparatus

Figure 1. Test Apparatus

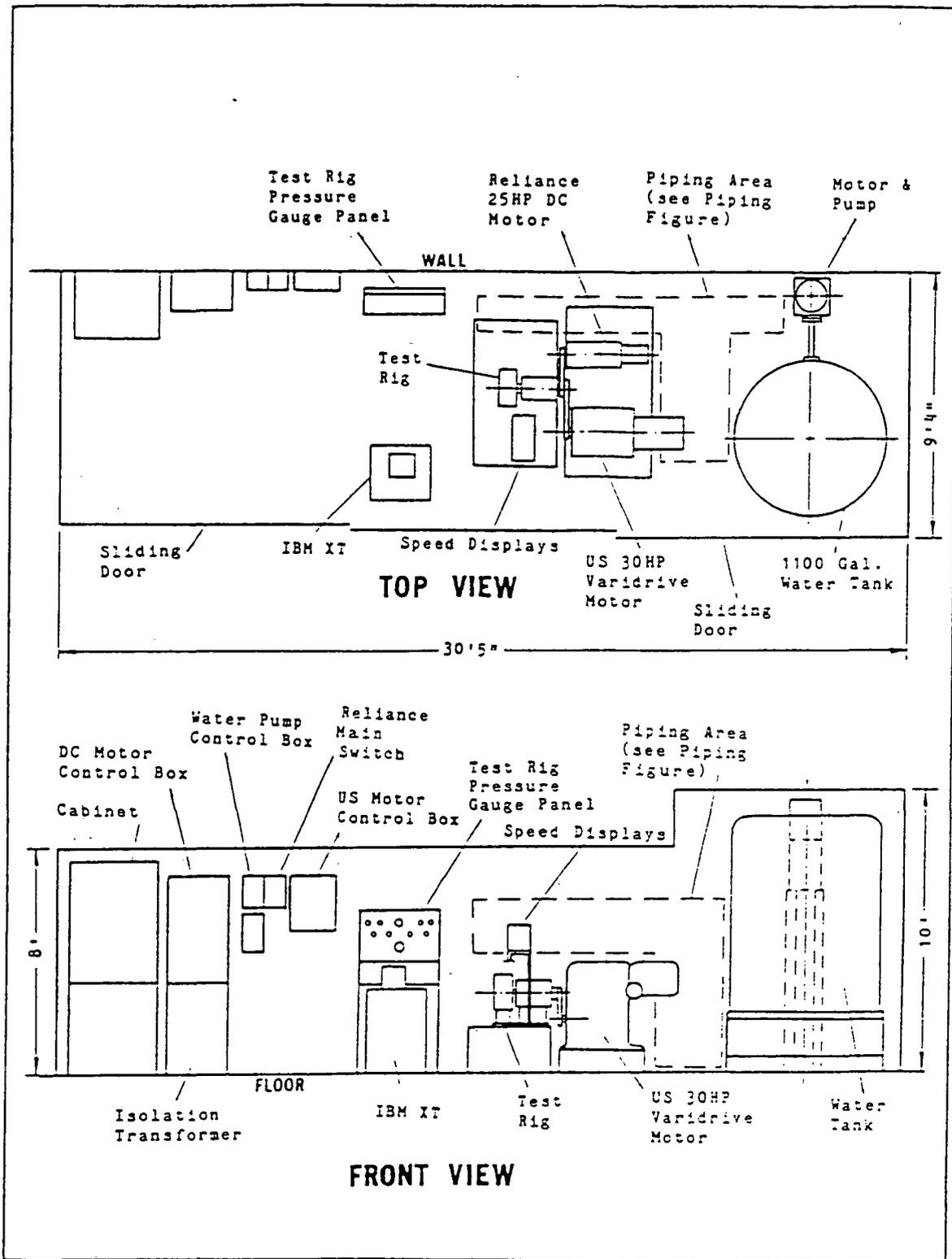


Fig. 2. Floor plan and elevation view of test facility.

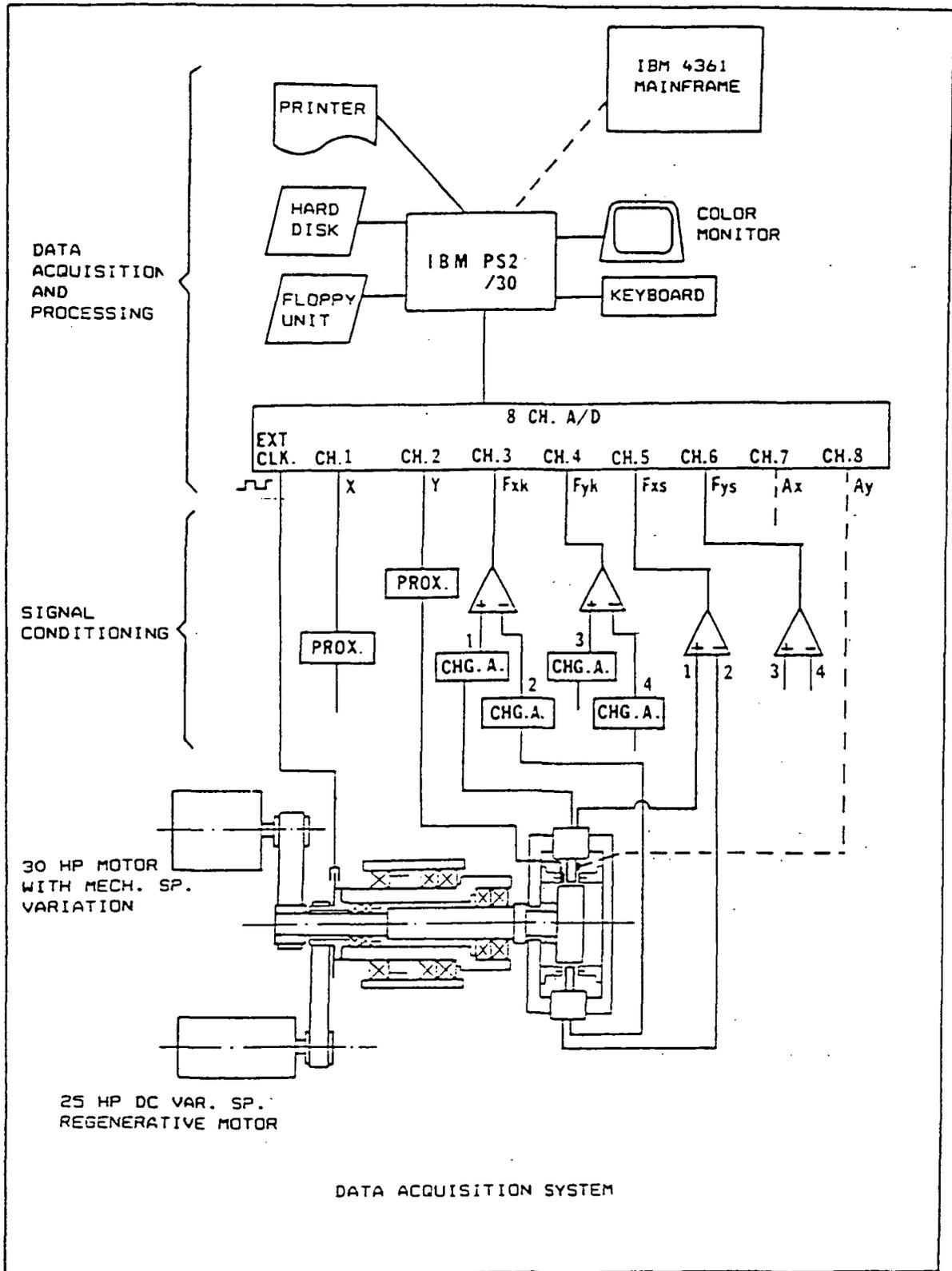


Fig. 3. Schematic of data acquisition system.

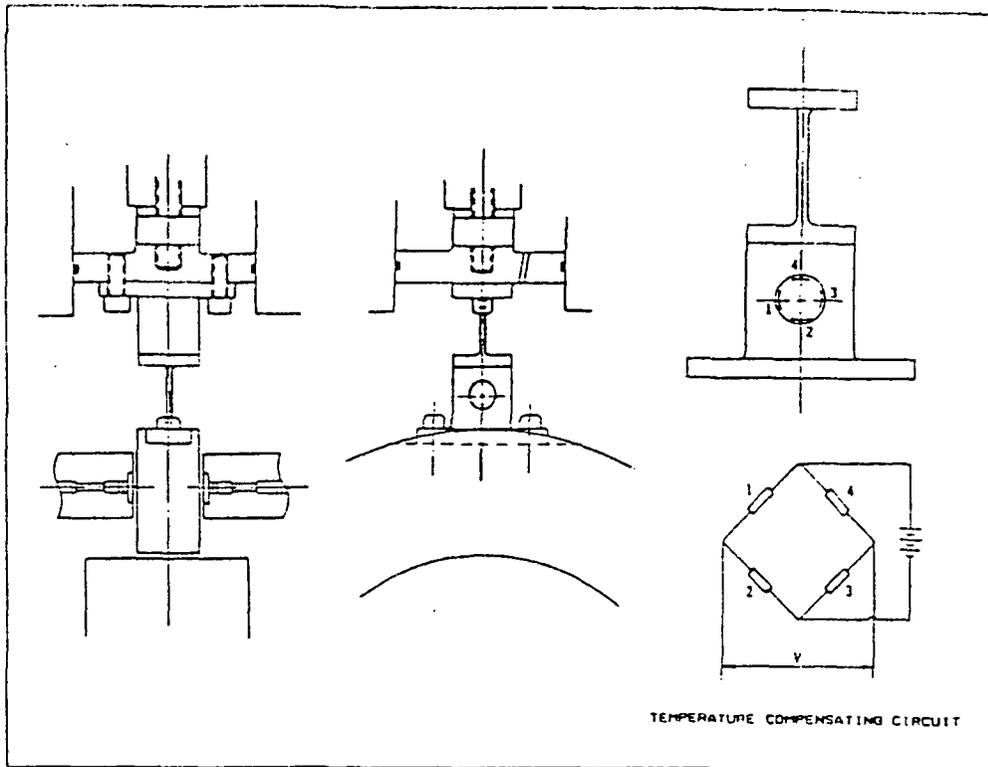


Figure 4(a) New load measuring and support system with strain gage transducer.

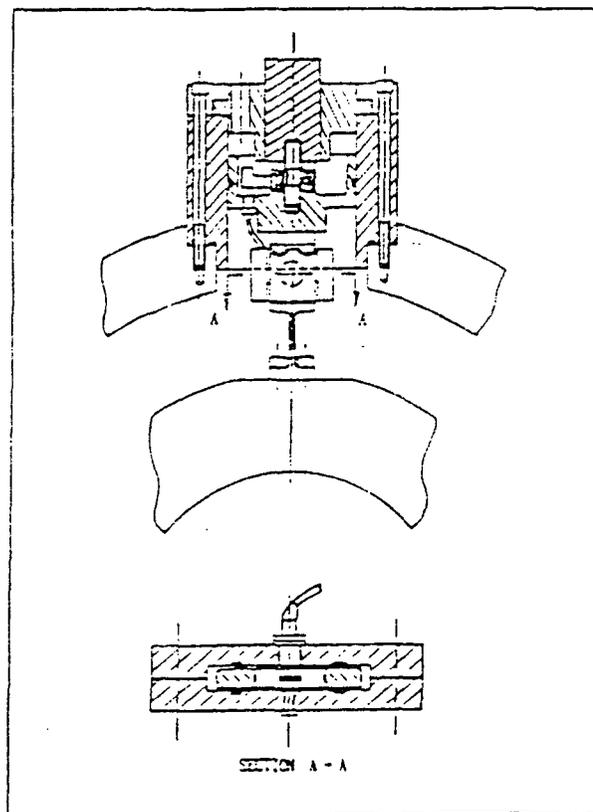


Figure 4(b) New load measuring system, showing complete assembly with water-seal barrier.

TOTAL TIME-AVERAGED SIGNAL (50 cycles)

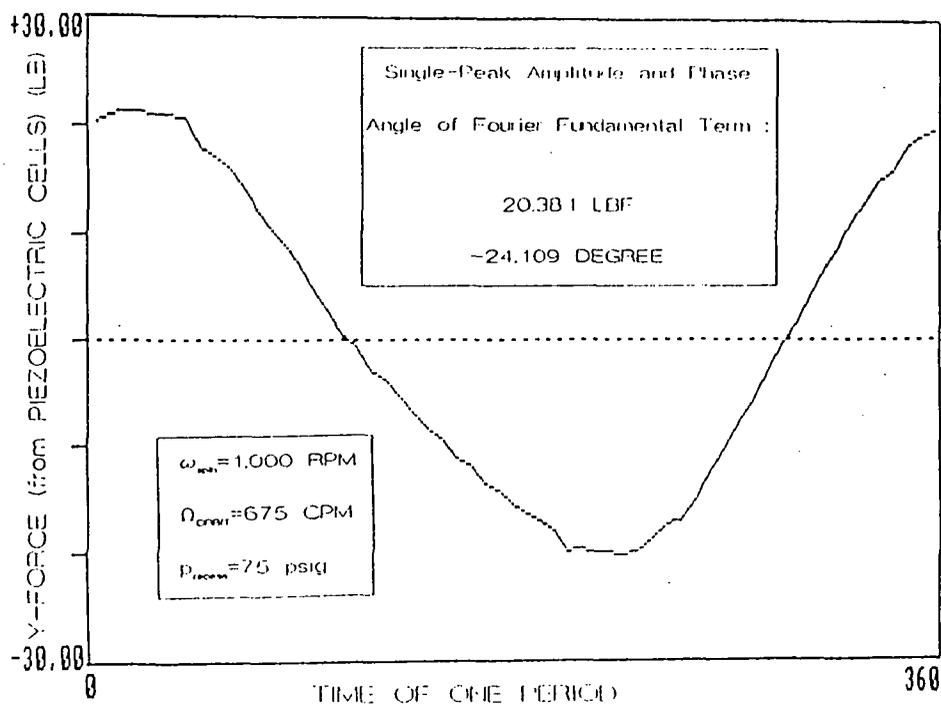


Figure 5

TOTAL TIME-AVERAGED SIGNAL (50 cycles)

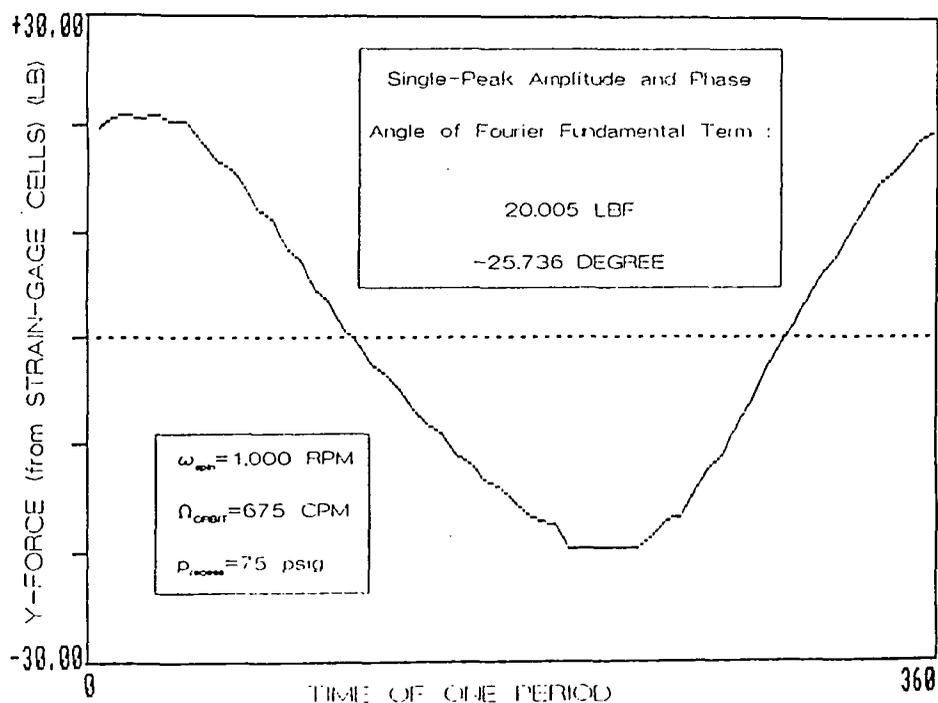


Figure 6

FIRST TERM OF FOURIER DECOMPOSITION

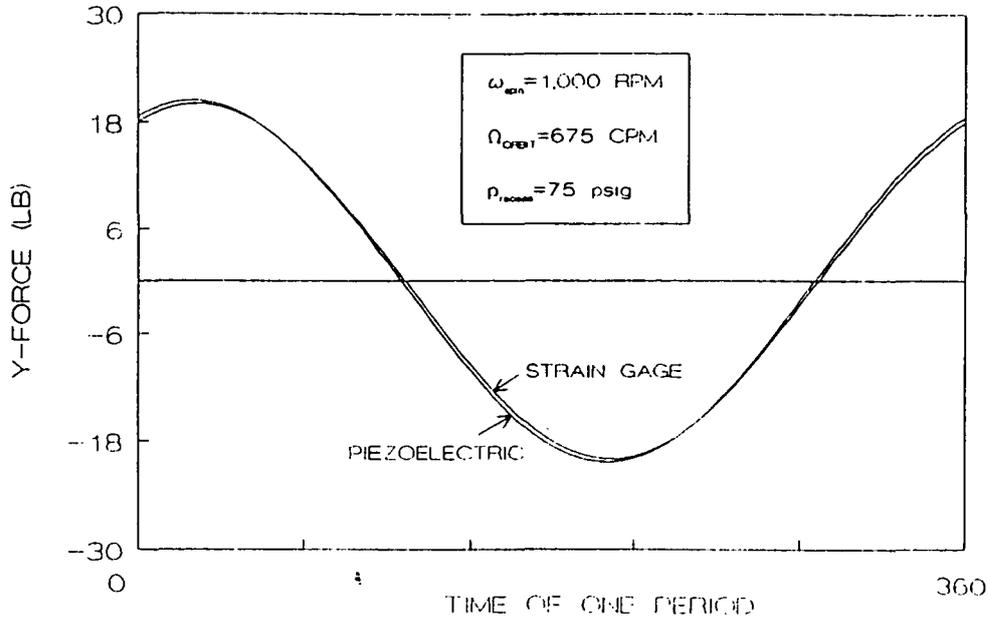


Figure 7

DYNAMIC COEFFICIENTS REPORT

SPECIAL FILENAME IS : CCF.INP

TOTAL INPUT FS DATA FILE IS : 10

SHAFTSPEED (RPM) IS : 1000

RECESS PRESSURE (PSI) IS : 75

INPUT DATA FILENAME	NO. OF CYCLE	ORBIT FREQUENCY (RPM)
CC1F.FS	1	147
CC2F.FS	1	363
CC3F.FS	1	478
CC4F.FS	1	569
CC5F.FS	1	677
CC6F.FS	1	765
CC7F.FS	1	871
CC8F.FS	1	1041
CC9F.FS	1	1139
CC10F.FS	1	1247

ROTOR DYNAMIC COEFFICIENTS :

[KX] LB/INCH		[Ks]	
0.102362E+06	0.295070E+05	0.127923E+06	0.470067E+05
-0.441426E+05	0.104812E+06	-0.470378E+05	0.132163E+06
[CK] LB*SEC/INCH		[Cs]	
0.623928E+03	-0.244494E+03	0.652728E+03	-0.303505E+03
0.101049E+03	0.934374E+03	0.978187E+02	0.951065E+03
[DK] LB*SEC*SEC/INCH		[Ds]	
-0.142564E+01	-0.213640E+01	-0.159256E+01	-0.256475E+01
0.189671E+01	-0.607746E+00	0.201067E+01	-0.499795E+00

Table 1(a)

DYNAMIC COEFFICIENTS REPORT

SPECIAL FILENAME IS : IIF.INP
 TOTAL INPUT FS DATA FILE IS : 10
 SHAFTSPEED (RPM) IS : 2000
 RECESS PRESSURE (PSI) IS : 75

INPUT DATA FILENAME	NO. OF CYCLE	ORBIT FREQUENCY (RPM)
II1F.FS	1	384
II2F.FS	1	523
II3F.FS	1	775
II4F.FS	1	979
II5F.FS	1	1181
II6F.FS	1	1377
II7F.FS	1	1572
II8F.FS	1	1783
II9F.FS	1	2135
II10F.FS	1	2375

 ROTORDYNAMIC COEFFICIENTS:

[KK] LB/INCH		[Ls]	
0.136658E+06	0.740254E+05	0.126282E+06	0.739171E+05
-.968657E+05	0.139754E+06	-.689112E+05	0.133641E+06
[CK] LB*SEC/INCH		[Cs]	
0.501801E+03	0.114119E+03	0.448838E+03	0.104627E+03
-.192791E+03	0.871380E+03	-.206396E+03	0.874430E+03
[DK] LB*SEC*SEC/INCH		[Ds]	
0.660029E-01	-.304506E+00	0.730574E-01	-.240757E+00
0.767267E+00	0.754499E+00	0.825507E+00	0.814563E+00

Table 1(b)

N92-15102

SEAL TEST PROGRAM AT MIT

Manual Martinex-Sanchez and K.T. Millsaps, Jr.
Massachusetts Institute of Technology

MIT reports on a seal test program that was conducted in a dynamic rig. Four different 1-gland labyrinths were tested. The eccentricity, spin rate, whirl rate and flow were varied independently.

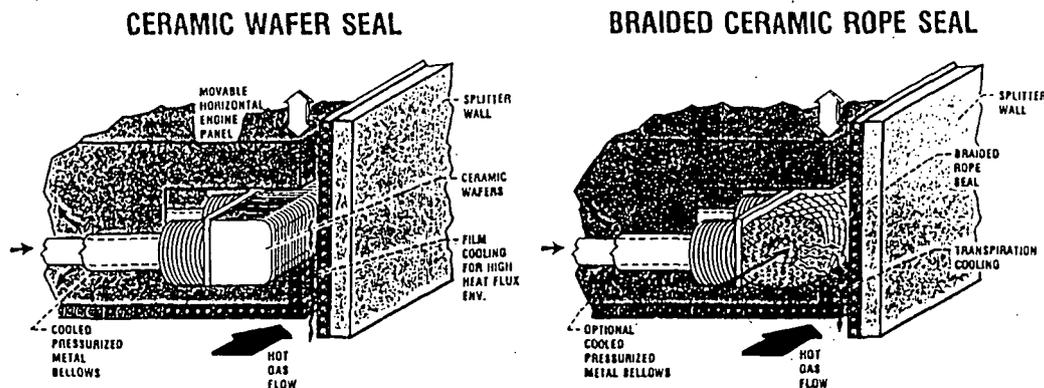
NATIONAL AEROSPACE PLANE ENGINE SEALS
 High Temperature Seal Performance Evaluation

Bruce M. Steinetz
 NASA Lewis Research Center

Key to the successful development of the single-stage-to-orbit National Aerospace Plane (NASP) is the successful development of combined cycle ramjet/scramjet engines that can propel the vehicle to 17,000 mph to reach low earth orbit. To achieve engine performance over this speed range, movable engine panels are used to tailor engine flow that require low-leakage high-temperature seals around their perimeter. NASA Lewis is developing a family of new high temperature seals to form effective barriers against leakage of extremely hot (>2000 °F), high pressure (up to 100 psi) flow path gases containing hydrogen and oxygen. Preventing backside leakage of these explosive gas mixtures is paramount in preventing the potential loss of the engines or the entire vehicle.

Described in the subsequent pages of this report are seal technology development accomplishments in the three main areas of concept development, test and evaluation and analytical development. The presentation closes with a brief discussion of future plans.

SEAL CONCEPTS UNDER DEVELOPMENT (U)



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SUMMARY OF TECHNOLOGY DEVELOPMENT

SEAL DEVELOPMENT:

- o ADVANCED CONCEPT DEVELOPMENT
- o FABRICATION TECHNOLOGY

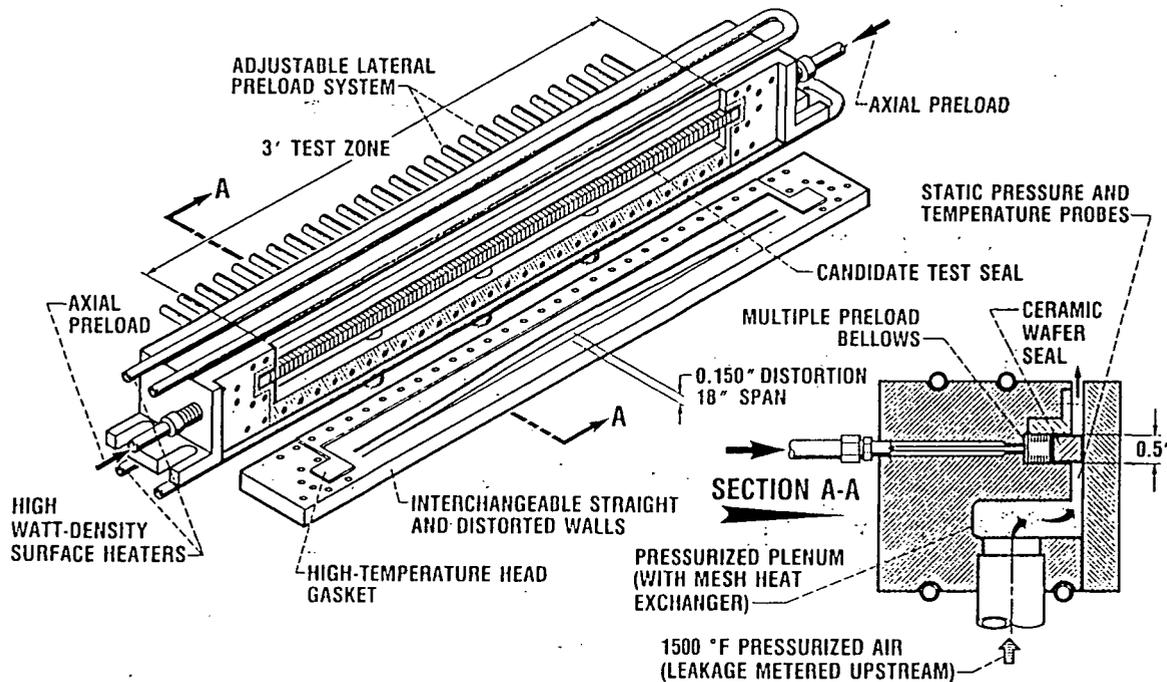
ANALYTICAL DEVELOPMENT:

- o SEAL LEAKAGE FLOW MODELING
- o THERMAL-STRUCTURAL ANALYSES

EXPERIMENTAL DEVELOPMENT AND EVALUATION:

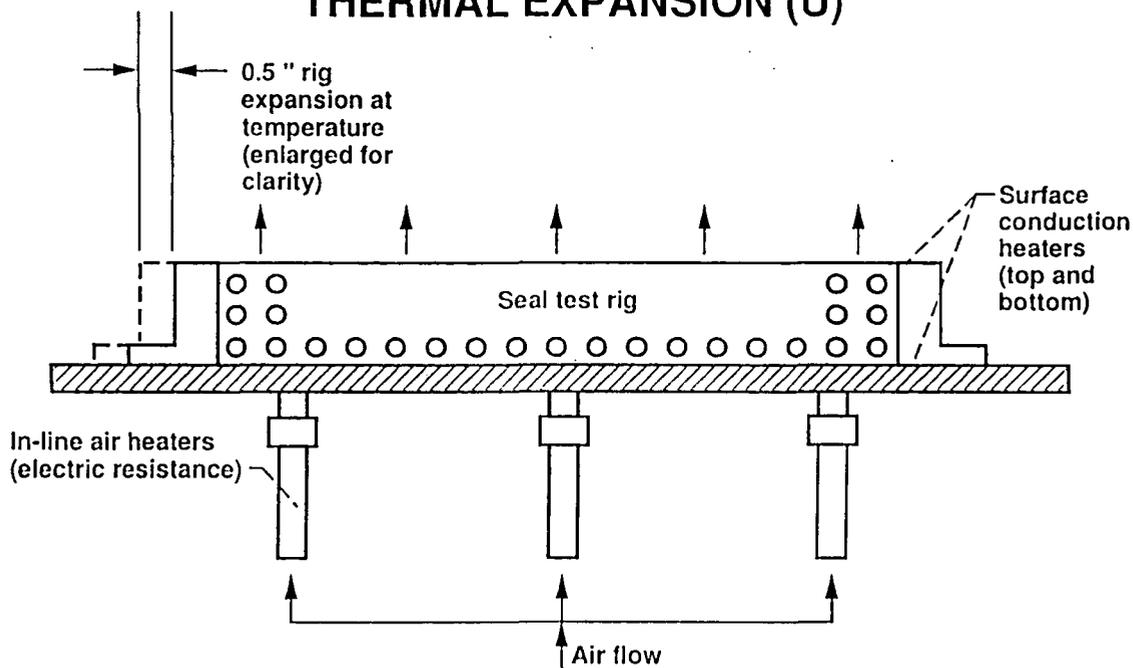
- o HIGH TEMPERATURE LEAKAGE PERFORMANCE EVALUATION
- o HIGH TEMPERATURE FRICTION AND WEAR ASSESSMENTS
- o SOLID FILM LUBRICANT DEVELOPMENT

SCHMATIC OF HIGH-TEMPERATURE PANEL-EDGE SEAL RIG (U)



UNCLASSIFIED

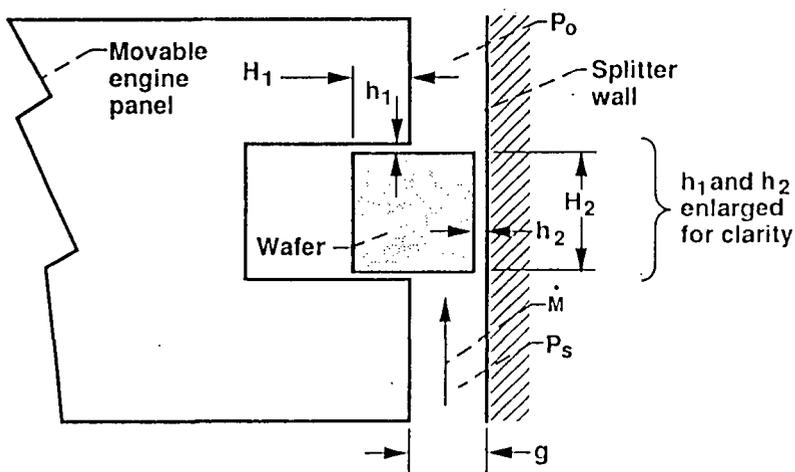
SEAL TEST FIXTURE THERMAL EXPANSION (U)



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CERAMIC WAFER SEAL LEAKAGE MODEL (U)



Where:

\dot{M} = Seal leakage rate
 h_1, h_2 = Eff surface leakage gap
 L = Seal length

$\mu(T)$ = Power law viscosity

$h_s = \frac{\Delta CTE \times L \times \Delta T}{N}$ = small inter-wafer gap

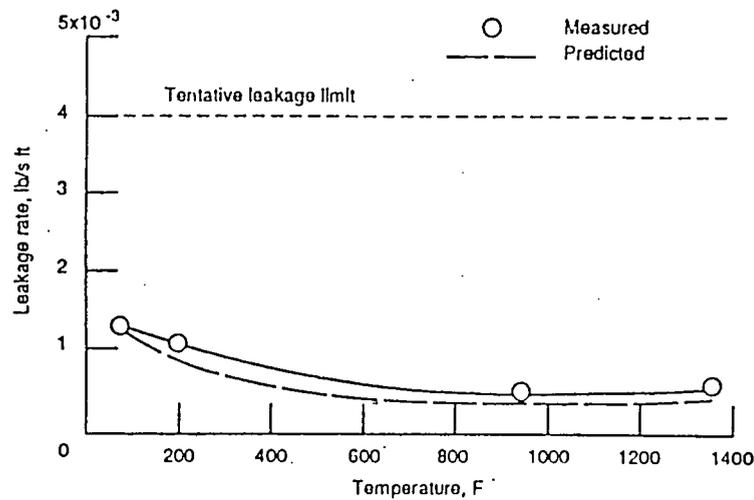
N = No. of interfaces

$$\dot{M} = \frac{(P_s^2 - P_0^2)}{24 \mu R T} \left(\frac{L h_1^3}{H_1} + \frac{L h_2^3}{H_2} + \frac{N g h_s^3}{H_2} \right)$$

Parasitic leakage around wafers CTE mismatch induced leakage

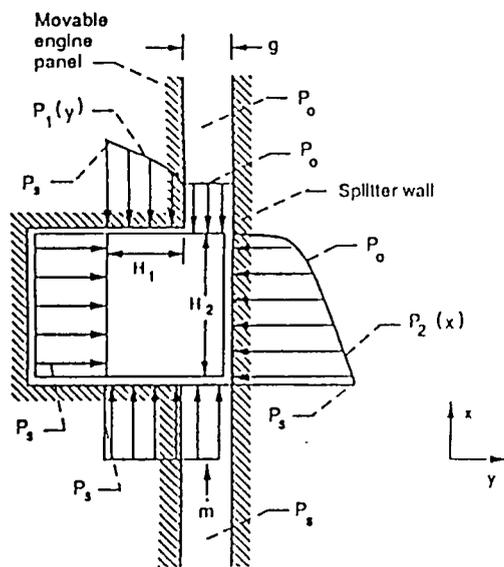
COMPARISON OF MEASURED AND PREDICTED LEAKAGE RATES VS TEMP.

FIXED PRESSURE DIFFERENTIAL: 40 psi



PRESSURE INDUCED WAFER LOADS

PRESSURE DISTRIBUTION:



FORCE BALANCE:

$$\sum \frac{F_y}{L} = \frac{F_y}{L} = \int_0^{H_2} (P_3 - P_2(x)) dx$$

$$\sum \frac{F_x}{L} = \frac{F_x}{L} = \int_0^{H_1} (P_3 - P_1(y)) dy + \int_{H_1}^{H_1+g} (P_3 - P_0) dy$$

$$\sum \frac{M}{L} = \frac{M}{L} = \int_0^{H_2} (P_3 - P_2(x)) x dx + \int_0^{H_1} (P_1(y) - P_3) y dy + \int_{H_1}^{H_1+g} (P_0 - P_3) y dy$$

Pressure profiles: $P_1(y) = \left\{ P_0^2 + \frac{(P_3^2 - P_0^2)}{H_1} (H_1 - y) \right\}^{1/2}$

$$P_2(x) = \left\{ P_0^2 + \frac{(P_3^2 - P_0^2)}{H_2} (H_2 - x) \right\}^{1/2}$$

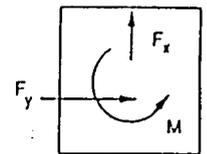
Resultants:

$$\frac{F_y}{L} = \left(P_3 - \frac{2}{3} \frac{(P_3^3 - P_0^3)}{(P_3^2 - P_0^2)} \right) H_2$$

$$\frac{F_x}{L} = \left(P_3 - \frac{2}{3} \frac{(P_3^3 - P_0^3)}{(P_3^2 - P_0^2)} \right) H_1 + (P_3 - P_0)g$$

$$\frac{M}{L} = \frac{P_3^3}{2} (H_2^2 - H_1^2) + \frac{2}{3} \frac{P_0^3}{(P_3^2 - P_0^2)} (H_2^2 - H_1^2) - \frac{4}{15} \frac{(P_3^5 - P_0^5)}{(P_3^2 - P_0^2)^2} (H_2^2 - H_1^2)$$

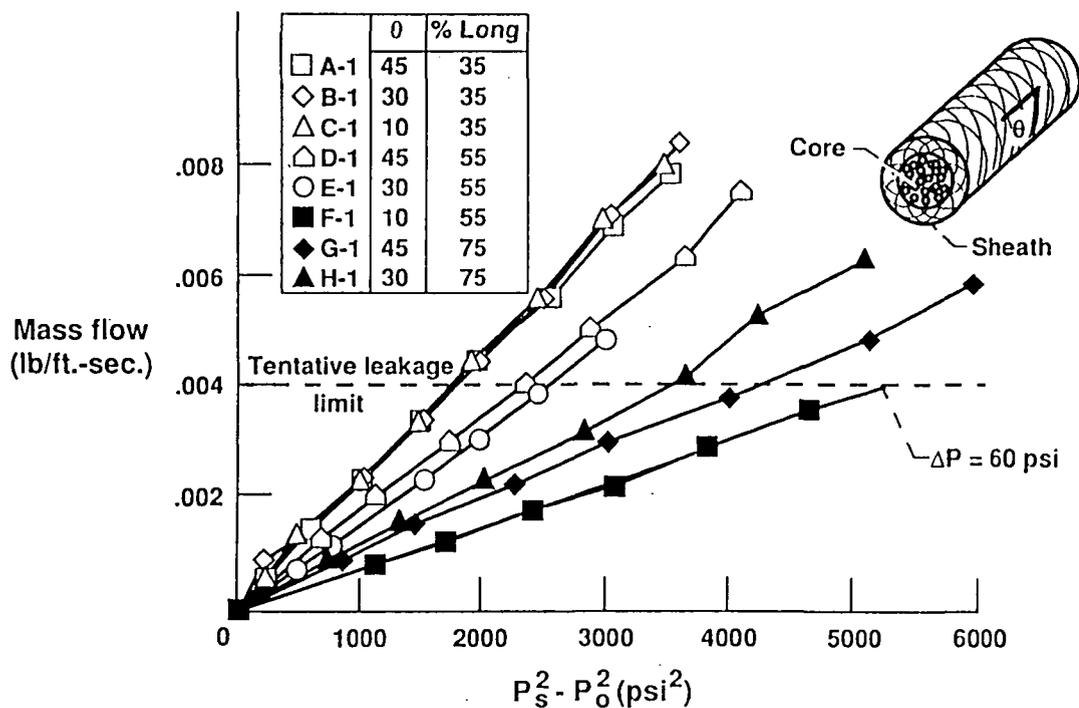
$$- \frac{(P_3 - P_0)}{2} (2H_1g + g^2)$$



Resultant loads

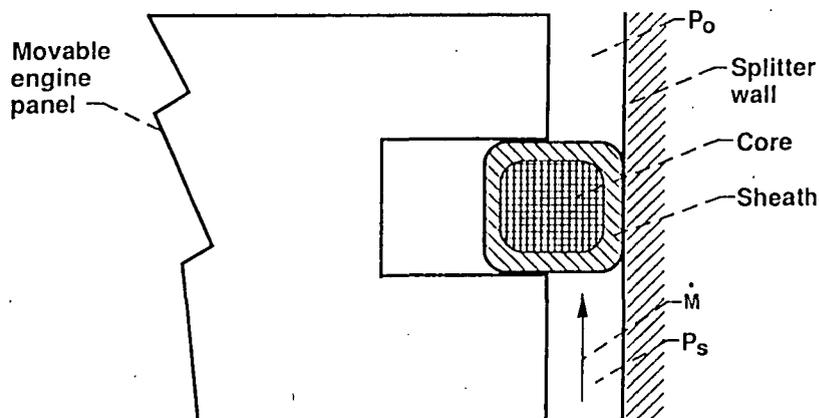
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2-D BRAIDED ROPE SEAL LEAKAGE PERFORMANCE (U) ROOM TEMPERATURE AIR, 80 PSI PRELOAD



UNCLASSIFIED

BRAIDED ROPE SEAL LEAKAGE MODEL (U)



$$\frac{\dot{M}}{L} = \frac{P_s^2 - P_o^2}{R}; \quad \frac{1}{R} = \left(\text{Eff Seal Resistance} \right)^{-1} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4} + \frac{1}{R_5 + R_6 + R_7}$$

Where:

\dot{M}/L = Seal leakage per unit length

R_1, R_2 = Resistance to flow behind and in-front of seal

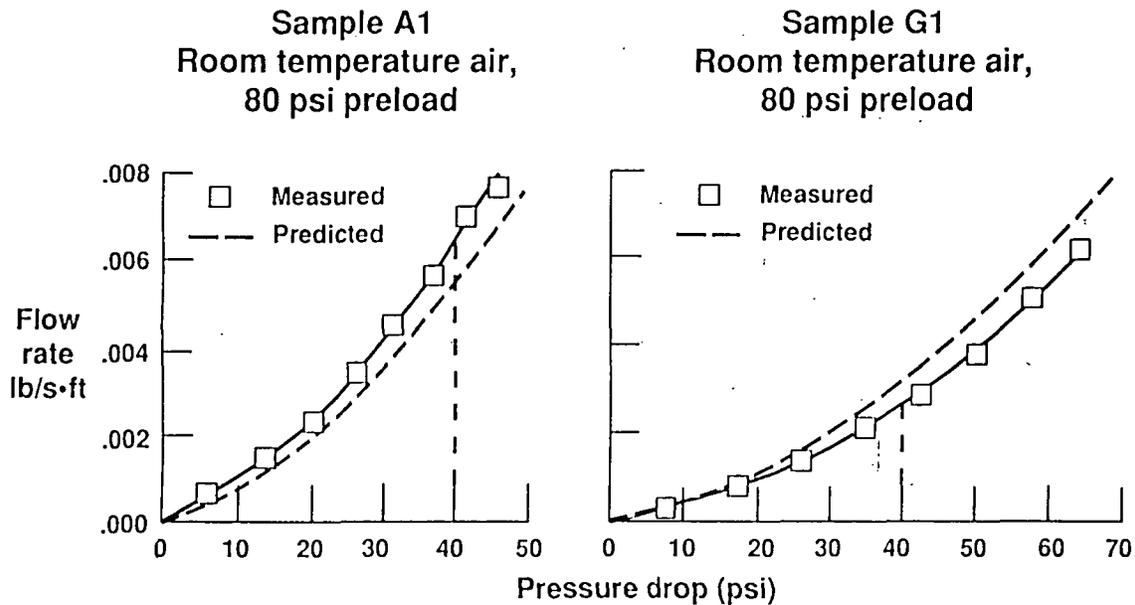
R_3, R_4 = Sheath resistance (eg parallel to flow direction)

R_5, R_7 = Sheath resistance (eg perpendicular to flow direction, upstream and downstream)

R_6 = Core resistance

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BRAIDED ROPE SEAL LEAKAGE MEASURED AND PREDICTED (U)



SEAL DEVELOPMENT FUTURE PLANS

- o EVALUATE ALTERNATE FIBER TOW DURABILITY OVER SIMULATED TEMPERATURES.
- o EVALUATE COMBINED DURABILITY/LEAKAGE PERFORMANCE OF ADVANCED BRAID ARCHITECTURES UNDER ENGINE SIMULATED SLIDING CONDITIONS, TEMPERATURES AND PRESSURES.
- o EVALUATE SURVIVABILITY OF BRAIDED ROPE SEALS UNDER THE ENGINE SIMULATED EROSIIVE SUPERSONIC FLOW FIELD.
- o EXPERIMENTALLY ASSESS REQUIRED TRANSPIRATION COOLANT FLOW RATES TO SURVIVE THE HIGH ENGINE-SIMULATED HEAT FLUXES.

N92-15104

VOLUME VISUALIZATION AND KNOWLEDGE INTEGRATION

Thomas Cochrane
Yosemite Systems, Inc.

Mr. Cochrane discusses how advanced computer graphics visualization techniques and integration of knowledge throughout the concept to production cycle are providing tools to revolutionize the design process. Relevant projects that are used as examples are at USAF, Ford, Digital, EPA and DOE.

N92-15105

FLUID SEALS TECHNOLOGY AT BHR GROUP LTD.

Simon Leefe
BHR Group Ltd.

A mathematical model has been developed by BHR Group (formerly the British Hydromechanics Research Association) for the European Space Agency. The model couples the rigid body dynamics in four degrees of freedom of a flexibly-mounted stator (with Coulomb damping) of a turbopump face seal with the fluid film behavior. The interfacial film is assumed gaseous, and the model incorporates laminar/turbulent flow, inertia and sonic choking. Seal faces may be wavy and coned, whilst the rotating ring can be eccentrically mounted, misaligned with the shaft and oscillate axially at arbitrary frequency. The model is currently being coded into software. An experimental programme using a high speed cryogenic/hot gas test rig is being conducted to verify the output of the computer program. Future work planned for later in the year will incorporate mechanical contact effects.

APPENDIX A
WORKSHOP AGENDA

INTRODUCTION	Anita Liang	9:00- 9:30
NASA/MTI CONTRACT SPECIFICS		
MTI Industrial Codes	Wilbur Shapiro	9:30- 9:50
CFDRC Scientific Codes	Andrzej Przekwas	9:50-10:10
KBS Development	Bharat Aggarwal	10:10-10:30
BREAK		10:30-10:45
DEMONSTRATION OF CYLINDRICAL AND SPIRAL-GROOVE INDUSTRIAL CODES	MTI	10:45-12:00
LUNCH (Main Cafeteria)		12:00- 1:00
NASA SPONSORED ACTIVITIES		
LeRC Related Activities	Bob Hendricks	1:00- 1:15
MSFC Related Activities	Ted Benjamin	1:15- 1:30
Army Related Activities	Bob Bill	1:30- 1:40
Texas A&M Activities	Gerald Morrison	1:40- 1:50
Akron University Activities	Jack Braun	1:50- 2:00
PRESENTATION BY PEER REVIEW MEMBERS		
o Programs for Gas Turbine Engine Mainshaft Air/Oil Seals (AFSC)	Ronald Dayton	2:00- 2:10
o Allison's Film Riding Face Seal and Brush Seal Work	John Munson	2:10- 2:20
o Overview of GE's Seals Programs	Nelson Pope	2:20- 2:30
o EG&G Fluid Components Technology Group Capabilities	Harold Greiner	2:30- 2:40
o Application of Differential Roughness for Wear and Friction	Alan Lebeck	2:40- 2:50
o Rocketdyne Fluid Seals/Bearing	Joe Scharrer	2:50- 3:00
o Aerojet Activities	George Bache	3:00- 3:10
o P&W Activities	Saadat Syed	3:10- 3:20
o CFD Applications in Propulsion	Charles Merkle	3:20- 3:30
OPEN PRESENTATION		
o Cross Manufacturing's Brush Seal Activities	Ralph Flower	3:30- 3:40
o Seal/Bearing Rotordynamics Test Facility at CWRU	Mike Adams	3:40- 3:50
o Labyrinth Seals Work at MIT	Knox Millsaps	3:50- 4:00
o High T NASP Engine Seals	Bruce Steinetz	4:00- 4:10
o Computer Interfaces for Knowledge Integration	Tom Cochrane	4:10- 4:20
ADJOURNMENT	Anita Liang	4:30

APPENDIX B
WORKSHOP ATTENDANCE LIST

Mike Adams
Case Western Reserve University

Bharat Aggarwal
Mechanical Technology, Inc.

Mahesh Athavale
CFD Research Corp.

Carlos Bailey
Turbo Components Textron

Theodore Benjamin
NASA MSFC

Bob Bill
U.S. Army

Marc Carpino
Penn Statue University

Tom Cochrane
Yosemite Systems, Inc.

Ron Dayton
U.S. Air Force

Hung M. Do
Dresser-Rand

T. I. Eldridge
Stein Seal Company

Rob Evenson
NOVA Corporation of Alberta

Ralph Flower
Cross Manufacturing

Sol Gorland
NASA LeRC

Alston Gu
Allied Signal Aerospace Co.

George Hosang
Sundstrand Power Systems

Albert Kascak
US Army

Gene Addy
NASA LeRC

Antonio Artiles
Mechanical Technology, Inc.

George Bache
Aerojet

Prithwish Basu
EG&G Fluid Components Technology

Donald Bently
Bently Nevada Corporation

Jack Braun
Akron University

F. K. Choy
Akron University

Ray Chupp
Teledyne CAE

Florin Dimofte
NASA LeRC

Constance Dowler
U.S. Air Force

John Eppehimer
Stein Seal Company

Frank Ferlita
Pratt & Whitney

Jim Gardner
EG&G Fluid Components Technology

Harold Greiner
EG&G Fluid Components

Bob Hendricks
NASA LeRC

Gene Jackson
Rocketdyne

John Kocur
Pratt & Whitney

Sunil B. Kulkarni
Durametallic

Anita Liang
NASA LeRC

Mark Makhobey
Car-Graph, Inc.

Alan D. McNickle
Stein Seal Company

K. T. Millsaps
MIT

Bahram Z. Movahed
Sundstrand Corporation

Agnes Muszynska
Bentley Nevada Corporation

Mike O'Brien
Component Engineering

Bart Olson
Sparta Inc.

Bruce S. Place
Magnetic Seal Corporation

Margaret Proctor
NASA LeRC

Steve Riddlebaugh
NASA LeRC

James Saunders
Battelle

Joe Scharrer
Rocketdyne

Stephen Shamroth
Scientific Research

Ashok Singhal
CFD Research Corp.

Bruce Steinetz
NASA LeRC

Dan B. Van Fossen
Finite Element Technology Corp.

Alan O. Lebeck
Mechanical Seal Technology

Robert G. Loewenthal
EG&G Fluid Components Technology

Manuel Martinez-Sanchez
MIT

Charles Merkle
The Pennsylvania State University

Gerald Morrison
Texas A&M University

John Munson
Allison Gas Turbine

Chuck Nevola
EG&G SEALOL

Jim O'Donnell
NAVAL Air Propulsion Center

Glenn Pecht
John Crane, Inc.

Nelson Pope
General Electric

Andrzej Przekwas
CFD Research Corp.

Norman Samurin
Dresser-Rand

Marshall Saville
Allied-Signal Aerospace Co.

Julie Schlumberger
NASA LeRC

Wilbur Shapiro
Mechanical Technology, Inc.

Paul Sirocky
Sverdrup

Saadat A. Syed
Pratt & Whitney

Manik Vasagar
Kaydon Ring & Seal, Inc.

Joe Veres
NASA LeRC

David Westcott
Pratt & Whitney

Jim Walker
NASA LeRC

Mark Wilson
Allison Turbine Division

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13. ABSTRACT (Maximum 200 words) In recognition of a deficiency in the current modeling capability for seals, a seven-year effort was established in 1990 by NASA's Office of Aeronautics, Exploration, and Technology under the Earth-to-Orbit Propulsion program of the Civilian Space Technology Initiative to develop verified computational-fluid-dynamic (CFD) concepts, codes, and analyses for seals. The objectives were to develop advanced concepts for the design and analysis of seals, to effectively disseminate the information to potential users by way of annual workshops, and to provide experimental verification for the models and codes under a wide range of operating conditions. The first annual workshop on "Seals Flow Code Development" was conducted at the NASA Lewis Research Center in Cleveland, Ohio, on March 26, 1991. The purpose was to report the progress of this program and to provide a forum for information exchange with the potential end-users. The presented material is documented in the NASA Proceedings.				
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