SCISEAL: A CFD CODE FOR ANALYSIS OF FLUID DYNAMIC FORCES IN SEALS

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OUTLINE

- Objectives
- Status Report
- Code Capabilities
- Test Results
- Concluding Remarks and Future Plans

OBJECTIVES (CFDRC)

- Develop Verified CFD Code for Analyzing Seals
- Required Features Include:
  - Applicability to a Wide Variety of Seal Configurations such as: Cylindrical, Labyrinth, Face, and Tip 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

SCIENTIFIC CODE DEVELOPMENT

Task 1: Develop a 3D CFD Code (SCISEAL) for Cylindrical Seals

- for Annular, Tapered, Stepped
- Verification of Code Accuracy
- Rotordynamic Coefficient Calculations

Future Tasks: Augmentation of SCISEAL

- Incorporation of Multi-Domain Capabilities
- Extension to Labyrinth, Damper, Face, and Tip Seals

Note: Starting CFD Code = REFLEQS (developed by CFDRC under a contract from NASA MSFC/ED32)

STATUS: 1992 WORKSHOP

- Numerical Methods in 3D Code
  - Colocated Grids
  - High-Order Schemes
  - Rotating and Moving Grid Systems

- Rotordynamic Coefficient Calculation Methods (CFD Solutions)
  - Circular Whirl
  - Moving Grid (numerical shaker)

- Seal Specific Interface
  - Grid Generation
  - Pre-Processing

CURRENT STATUS

Augmentation Effort on SCISEAL:

- Implementation of Small Perturbation Model for Rotordynamics
  - Treat Eccentric as well as Centered Seals
  - Efficient, Economic Solutions
- Addition of 2-Layer Turbulence Model
  - Very Small Seal Clearances → Very Small y^+
  - Standard k-ε Model Inaccurate, Low Re Model Stiffness Problems, etc
  - 2-Layer Model Overcomes this Difficulty to Significant Extent
- Code Validation
  - Rotordynamics: Long & Short Annular Seals, Eccentric Seals
  - Labyrinth Seal Flow Computations
  - Entrance Loss Coefficients

CURRENT CODE CAPABILITIES

- Seals Code has:
  - Finite Volume, Pressure-Based Integration Scheme
  - Colocated Variables with Strong Conservation Approach
  - High-Order Spatial Differencing - up to Third-Order
  - Up to Second-Order Temporal Differencing
  - Comprehensive Set of Boundary Conditions
  - Variety of Turbulence Models (k-ε, Low Re k-ε, multiple scale k-ε, 2-Layer Model), Surface Roughness Treatment
  - Moving Grid Formulation for Arbitrary Rotor Whirl
  - Rotordynamic Coefficient Calculation Methods, CFD Based Centered Seals: (i) Circular Whirl (ii) Numerical Shaker
  - Small Perturbation: Centered & Eccentric Seals

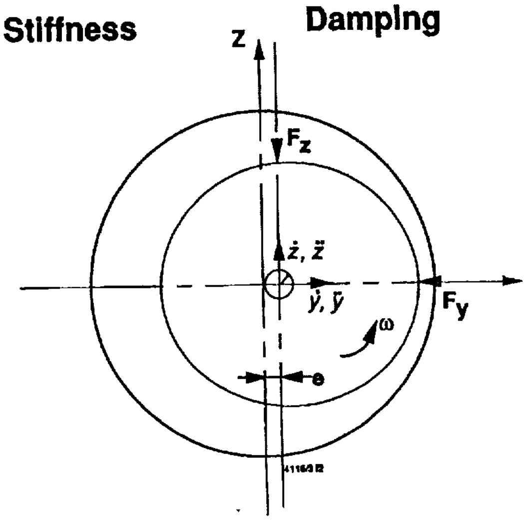
SEAL SPECIFIC CAPABILITIES

- GUI and Preprocessor - Geared for Seals Problems
- Easy, Quick Geometry Definition and Grid Generation
- Four Types of Cylindrical Seals:
  - Annular, Axial Step-Down, Axial Step-Up, and Tapered
- Pull-Down Menus for Problem Parameter Specification
- One Line Commands for
  - Automatic Grid Generation
  - Integrated Quantities: Rotor Loads, Torque, *etc.*
  - Rotordynamic Coefficients

ROTORDYNAMIC COEFFICIENTS

- Relation Between Fluid Reaction Forces and Rotor Motion

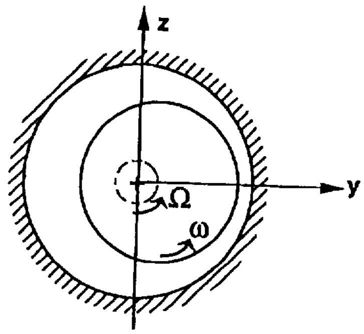
$$-\begin{bmatrix} F_y \\ F_z \end{bmatrix} = \underbrace{\begin{bmatrix} K_{yy} & K_{yz} \\ -K_{zy} & K_{zz} \end{bmatrix}}_{\text{Stiffness}} \begin{bmatrix} y \\ z \end{bmatrix} + \underbrace{\begin{bmatrix} C_{yy} & C_{yz} \\ -C_{zy} & C_{zz} \end{bmatrix}}_{\text{Damping}} \begin{bmatrix} \dot{y} \\ \dot{z} \end{bmatrix} + \underbrace{\begin{bmatrix} M_{yy} & M_{yz} \\ -M_{zy} & M_{zz} \end{bmatrix}}_{\text{Inertia (mass)}} \begin{bmatrix} \ddot{y} \\ \ddot{z} \end{bmatrix}$$



ROTORDYNAMIC COEFFICIENT METHODS

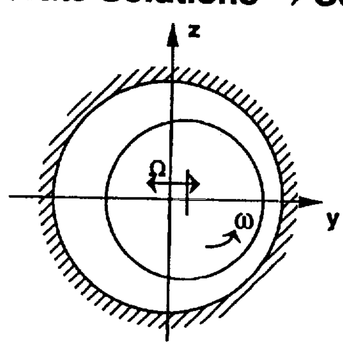
- Circular Whirl Orbit Method
  - Rotor Undergoes Circular Whirl
  - Rotating Frame → Quasi-Steady Solution
  - CFD Solutions at Several Whirl Frequencies
  - Pressure Integration to Yield Rotor Loads
  - Curve Fit to Force vs Whirl Frequency

*For Centered Rotor with Skew Symmetry Coefficient Matrices



ROTORDYNAMIC COEFFICIENTS

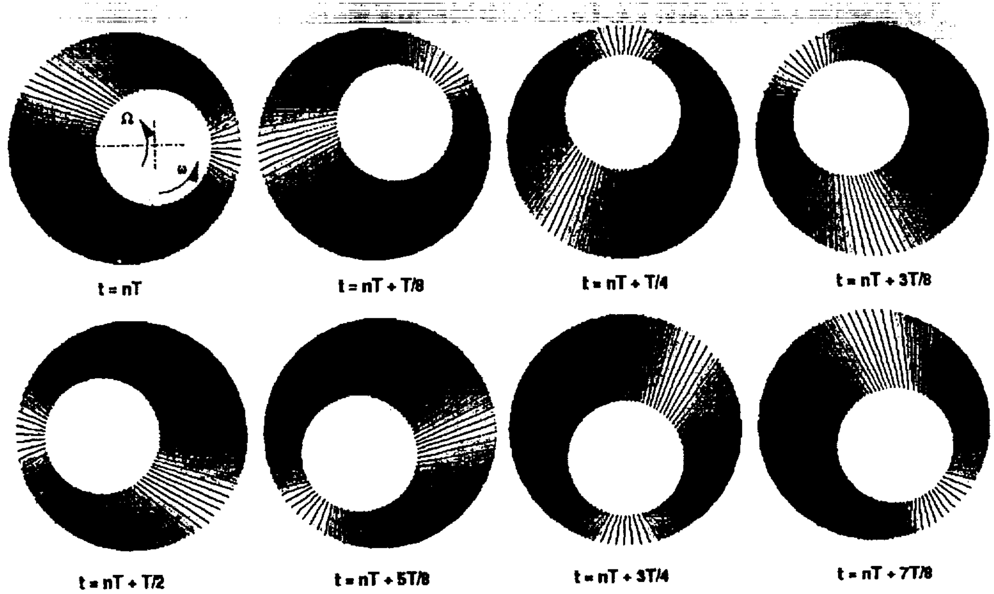
- Numerical Shaker Method
  - Rotor Motion Along a Radial Direction
  - Time-Dependent Solutions
  - Moving Grid Algorithm for Grid Deformation
  - Time-Dependent Pressure Loads → Rotordynamic Coefficients
  - Can Treat Centered as well as Eccentric Seals
  - Time Accurate Solutions → Computationally Slower



ROTORDYNAMIC COEFFICIENT CALCULATIONS

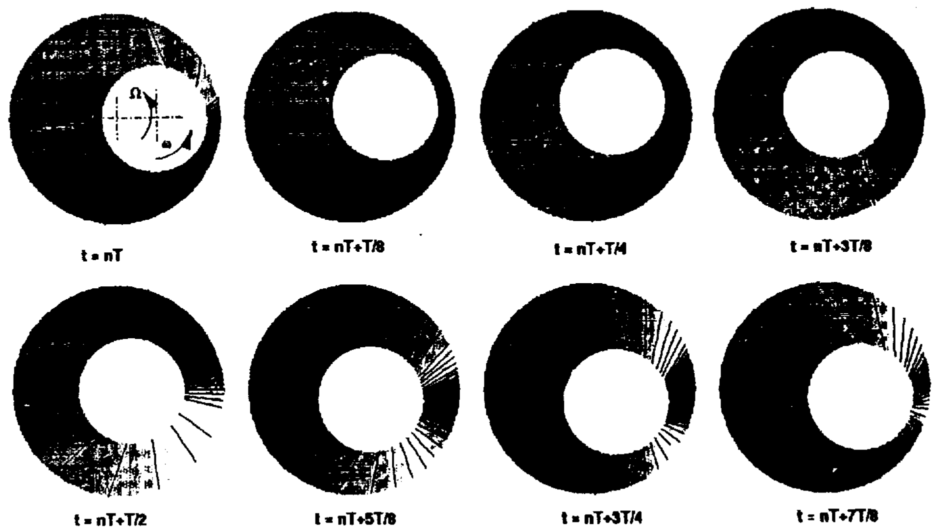
- **Small Perturbation Method**
  - **For Centered or Eccentric/Misaligned Seals**
  - **Rotor Undergoes Circular Whirl with Very Small Radius**
  - **Resulting Perturbations in Flow Variables:**

    $\phi = \phi^0 + \varepsilon\phi^1$
  - **Generate 0th and 1st Order Flow Equations**
  - **Use Fournier Series in Time for Perturbations:**
    - **Complex Form of 1st Order Variables;**
    - **Flow Equations are Quasi-Steady**
  - **Complex Flow Perturbations Solved at Several Whirl Frequencies**
  - **Integrate Pressure Perturbations for Rotor Loads**
  - **Curve Fit for Rotordynamic Coefficients**



Time–dependent solutions of the perturbation pressure

ε = 0.0, Plane at half seal length, Ω = 2.0ω



Time-dependent solutions of the perturbation pressure
$\varepsilon = 0.7$, Plane at half seal length, $\Omega = 2.5\omega$

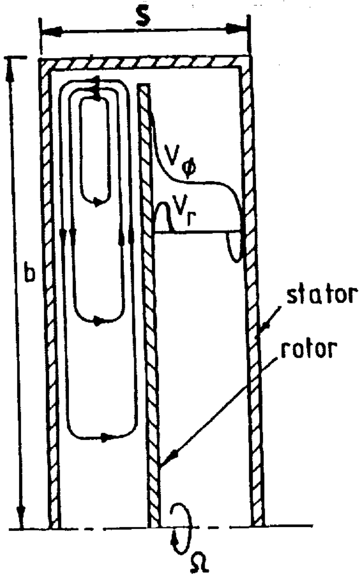
2-LAYER TURBULENCE MODEL

- Small Seal Clearances → very Low y^+ Values
- Standard Wall Functions → Inaccurate
- Low Re k-ε Model for Very Low y^+
  - can generate very stiff systems
- 2-Layer Model Uses
  - wall functions for large y^+
  - Low Re k-ε model for very low y^+
- A Buffer Zone Used to Smoothly Merge the Two Treatments
- Model has been Tested for a Number of Seal and Rotating Flow Problems

*Work Performed by Drs. Avva and Lai of CFDRC

SAMPLE RESULTS

- **Computation of Flow in Enclosed Rotor System (Dailey and Nece)**



Torque coefficients,
Experimental value ~ 4×10^{-3}

k-ε with wall function		2-layer model	
near wall y^+	C_m	near wall y^+	C_m
16	3.58×10^{-3}	21	3.9×10^{-3}
0.7	5.28×10^{-3}	0.7	4.64×10^{-3}
0.04	5.59×10^{-3}	0.04	4.25×10^{-3}

CODE VALIDATION AND DEMONSTRATION

- Code has been Validated for a Large Number of Benchmark Problems
  - A List of 29 Relevant Problems Included in the Interim Report
- Extensive Validation Effort Conducted for Practical Seals:
  - Annular and Tapered Seals
  - Labyrinth Seals
- Annular Incompressible Seals (Dietzen and Nordmann, 1987)
- Long Incompressible Seals (Kanemori & Iwatsubo, 1992)
- Eccentric Annular Seal (Simon & Frene, 1991)
- Annular and Tapered Gas Seal (Nelson, 1985)
- Labyringth Seals Planar, (Wittig et al, 1987)
- Labyrinth Seals, Tapered Knives; stepped (Tipton et al, 1986)

VALIDATION CASES

1. Fully-developed flow in a pipe and channel.
2. Developing laminar flow in a narrow annulus between two cylinders. Slug flow at inlet, fully-developed flow at outlet.
3. Laminar flow between rotating cylinders. Below critical Taylor number, tangential flow only.
4. Flow between two cylinders, rotating inner cylinder. Taylor vortex flow, Laminar and turbulent.
5. 2-D driven cavity flow, Reynolds number up to 10,000. Comparisons with numerical results by Ghia et.al.
6. 3-D driven cavity flow.
7. Couette flow under different pressure gradients. With and without heat transfer.
8. Planar wedge flow in a slider bearing.
9. Laminar flow over a back step. Reattachment length comparison with experiments by Armaly and Durst.
10. Laminar flow in a square duct with a 90° bend. Comparison with experimental data by Taylor et.al.
11. Shock reflection over a flat plate.
12. Turbulent flow in a plane channel. Fully-developed solution at exit compared with experiments by Laufer.
13. Turbulent flow induced by rotating disk in a cavity. Comparison with experiments by Daily and Nece.
14. Centripetal flow in a stator-rotor configuration. Comparison with experiments by Dibelius et.al.
15. Flow between stator and whirling rotor of a seal. 2-D results for 0, 0.5, and synchronous whirl frequencies

VALIDATION CASES

16. Flow over a bank of tubes.

17. Turbulent flow in an annular seal. Comparison with experiments by Morrison et.al.

18. Turbulent flow in a 7-cavity labyrinth seal. Comparison with experiments by Morrison et.al.

19. Turbulent compressible flow and heat transfer in turbine disk cavities Athavale et.al.

20. 3-D driven cavity flow with lid clearance and axial pressure gradient. Control of flow through vortex imposition.

21. Flow in cavities on a rotor for an electrical motor. Interaction of Taylor vortices with driven cavity flow.

22. Flow in infinite and finite length bearings (without cavitation). Comparison of calculated attitude angles with theory.

23. Flow and rotordynamic coefficient calculation for straight, incompressible seals. Comparison with results from other numerical and analytical solutions; Dietzen and Nordmann.

24. Flow and rotordynamic coefficients in tapered compressible flow seals. Comparison with bulk-flow theory results; Nelson.

25. Rotordynamic Coefficients in a long annular incompressible flow seal. Comparison with experimental data; Kanemori and Iwatsubo.

26. Calculation of entrance loss coefficients in the entrance region of a generic seal. Effect of flow and geometry on the loss coefficient values; Athavale et.al.

27. Flow coefficient and pressures in a 5 cavity, straight knife, look-through labyrinth seal. Comparison with experimental data ; Witting et.al.

28. Flow coefficients and pressures in a 3 cavity, tapered knife, look-through labyrinth seal. Comparison with experimental data; Tipton et.al.

29. Flow coeffients and pressures in a 2 cavity, straight-knife, stepperd labyyrinth seal. Comparison with experimental data; Tipton et.al.

LONG ANNULAR SEALS

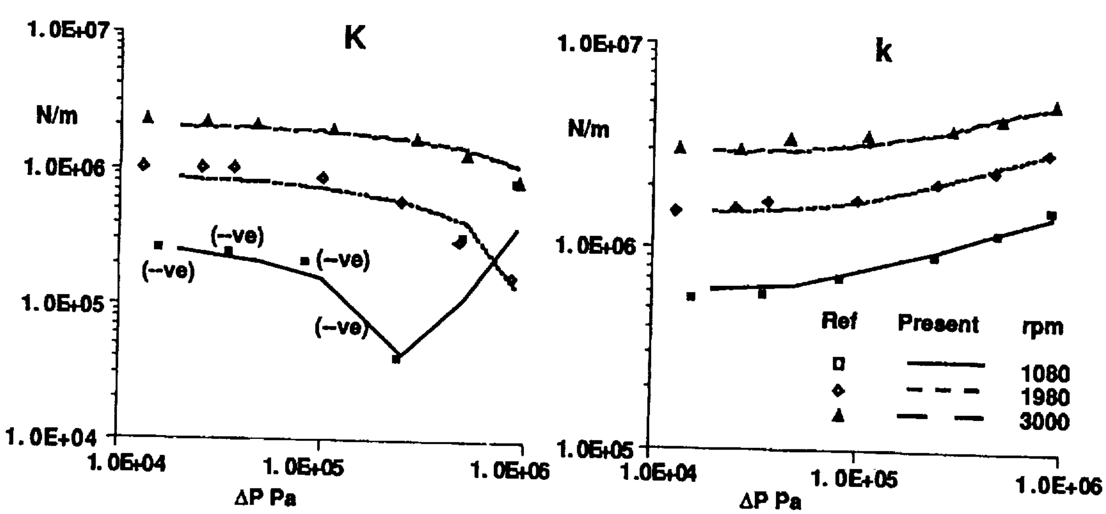
- **Experimental Data by Kanemori & Iwatsubo (1992)**

- **R = 39.656 mm, L = 240 mm, Rotor Speed = 600-3000 rpm**
  Clearance = 0.394 mm, Δp = 20 kPa - 900 kPa
  Specified Inlet Loss Coefficient, Ra = 1000-18000

- **Various Models Checked:**

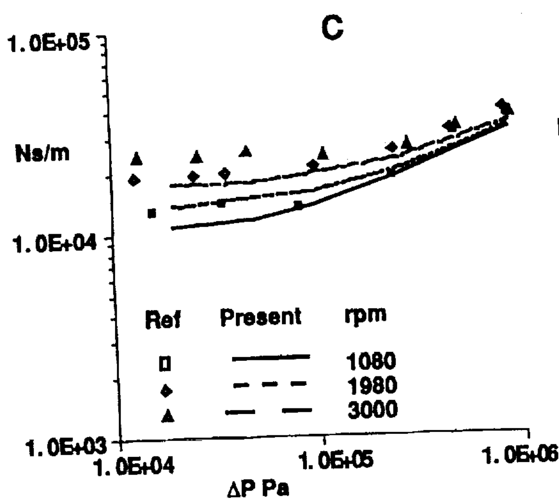
  - **Whirl Method, Perturbation Method**
  - **Low Re k-ε Model, 2-Layer Model**
  - **20x15x30 grid**

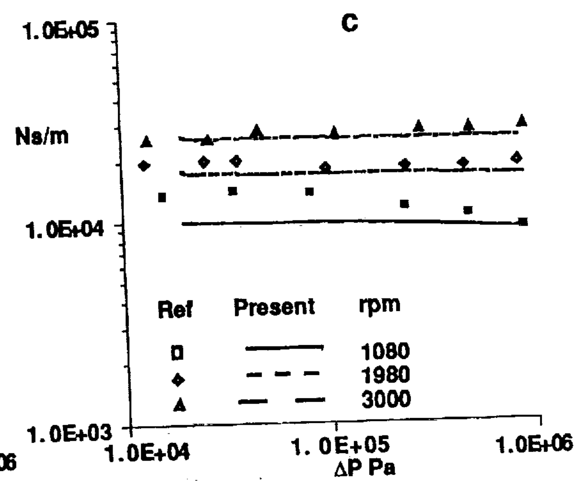
DIRECT & CROSS-COUPLED STIFFNESS



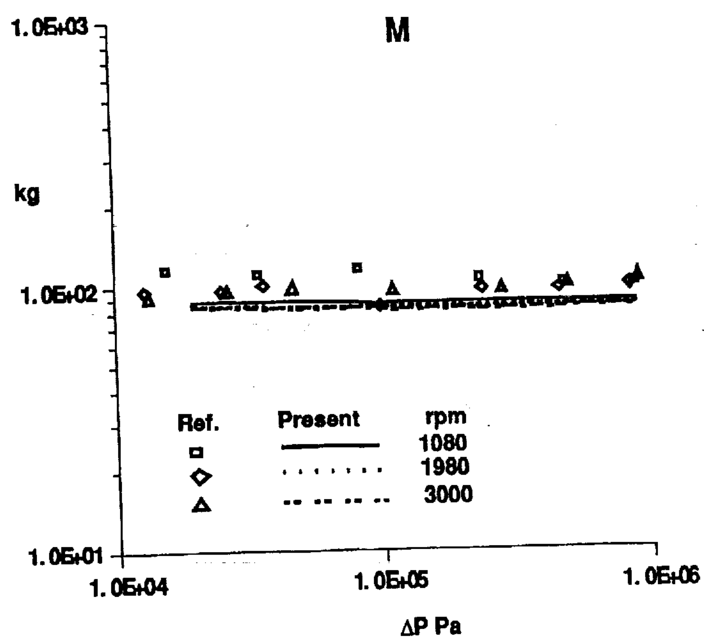
Symbols: Experimental Data by Kanemori and Iwatsubo
Lines: Numerical Results from SCISEAL

DIRECT & CROSS-COUPLED DAMPING





DIRECT MASS (INERTIA)



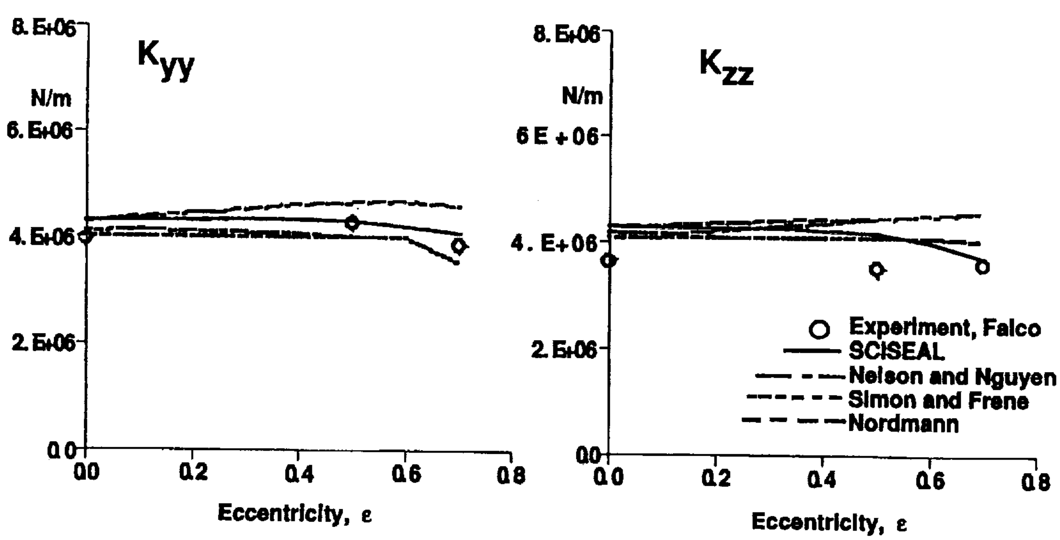
ECCENTRIC SEAL

- Experimental Data by Falco et al (1984)
  Numerical Data by Nordmann (1987), Simon & Frene (1991)

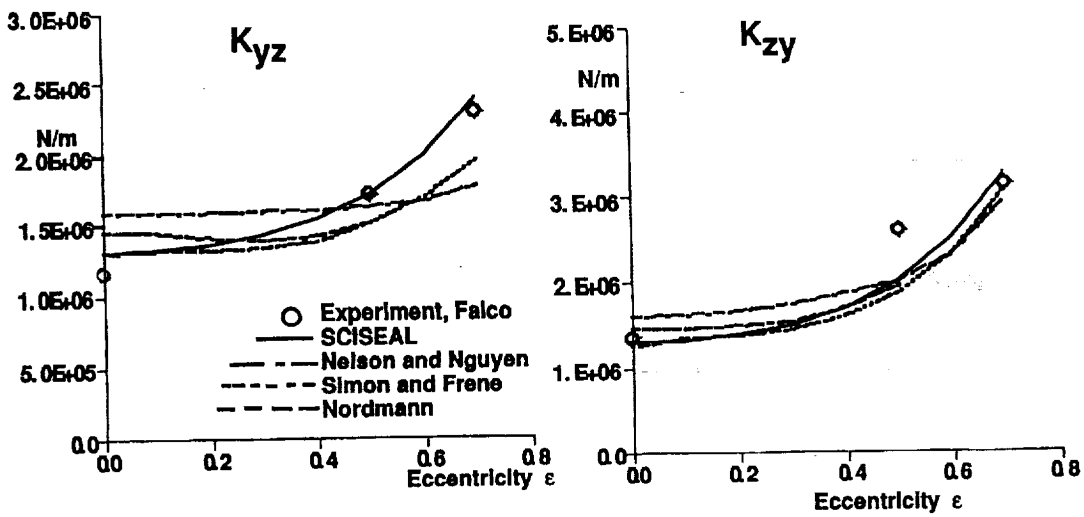
- Radius = 80 mm, Length = 40 mm, $\varepsilon = 0.1 \rightarrow 0.7$
  4000 rpm, Δp = 1MPa, Entrance Loss Coefficient = 0.5

- Physical Models
  - Standard k-ε Model
  - Small Perturbation Method
  - 12x6x30 grid

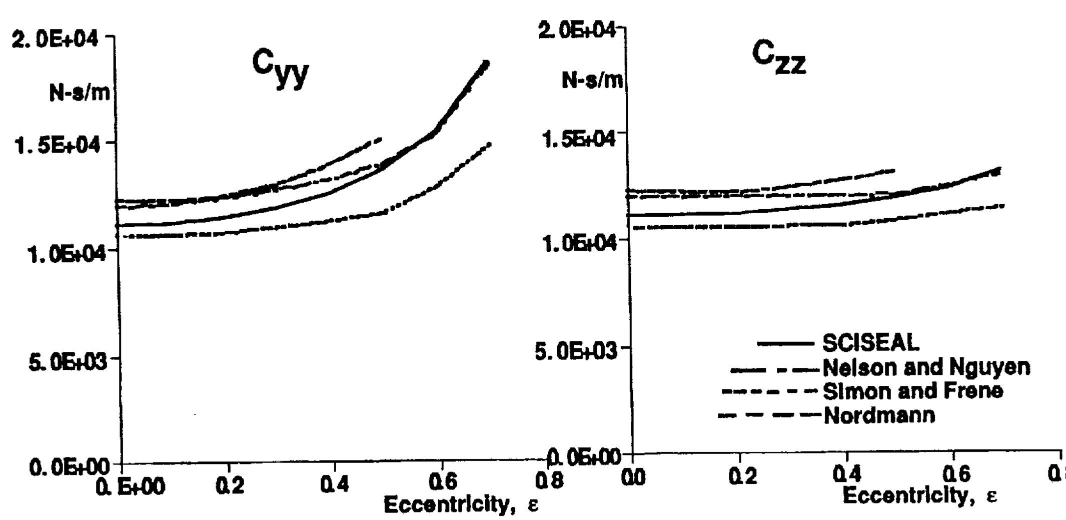
DIRECT STIFFNESS COEFFICIENT, K_{yy}, K_{zz}



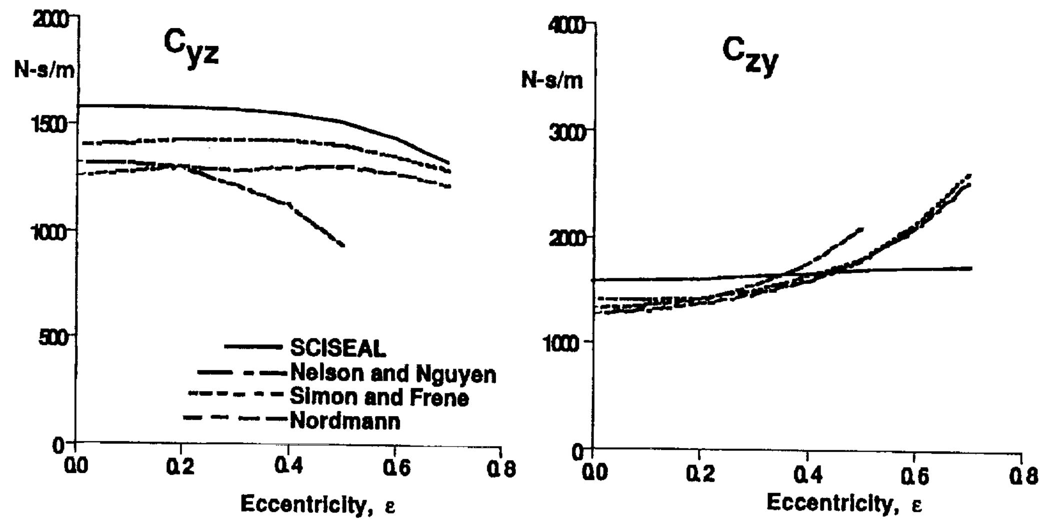
CROSS-COUPLED STIFFNESS, K_{yz}, K_{zy}



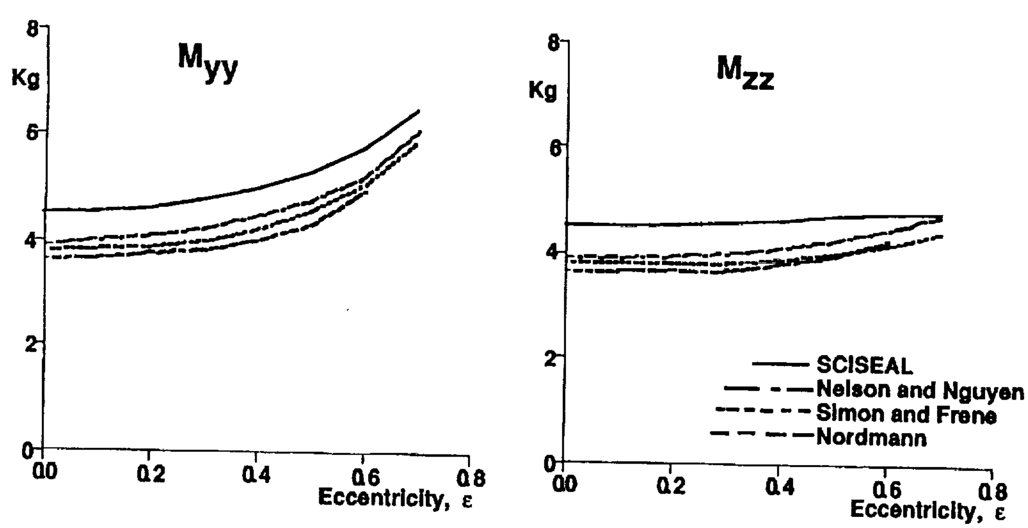
DIRECT DAMPING, C_{yy}, C_{zz}



CROSS-COUPLED DAMPING, C_{yz}, C_{zy}



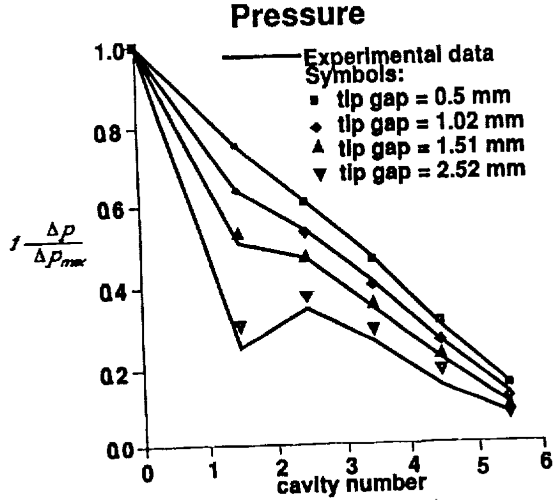
DIRECT INERTIA M_{yy}, M_{zz}

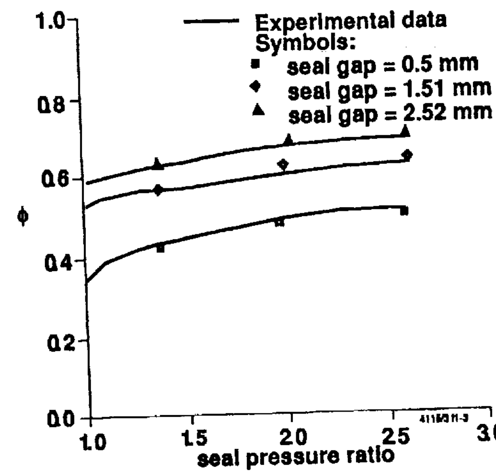


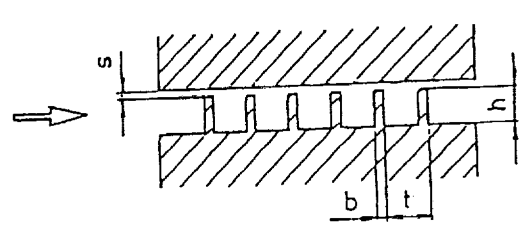
STRAIGHT LABYRINTH SEAL

- Experimental Data by Wittig et al (1987)
- 5 Cavity, Planar Look Through Seal
- Physical Models
  - 30x30 Cells in each Cavity, 8/12 Cells in Gap
  - Compressible Flow, Standard k-ε Model
  - Specified Pressure Ratio Across Seal
- Results: Numerical Results Compared with Experimental Data
  - Pressure Along the Seal Length for Different Tip Gaps
  - Mass Flow Rates at Different Tip Gaps and Pressure Ratios

RESULTS FOR STRAIGHT LABYRINTH SEAL





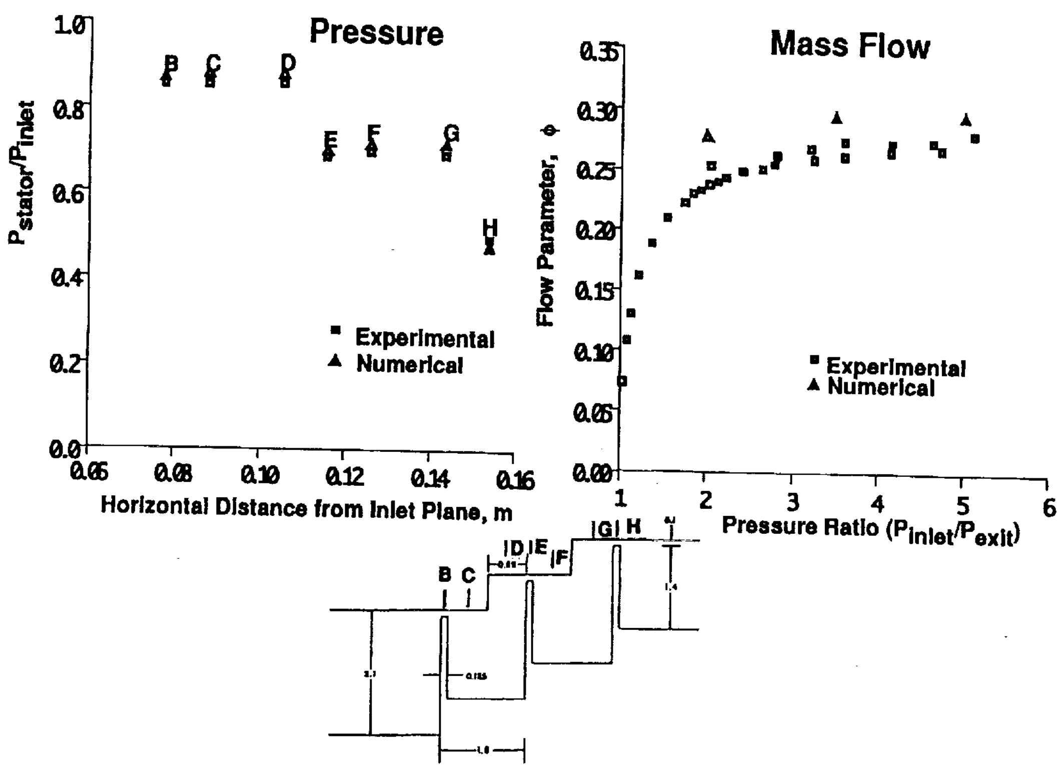


STEPPED LABYRINTH SEAL

- Experimental Data by Tipton et al (1986)
- 2 Cavity, Planar, Stepped Labyrinth Seal
- Physical Models:
  - Compressible Flow, Specified Pressure Ratio
  - Standard k-ε Model
  - 26x53, 26x62 Cells in Cavities; 10 Cells in Tip Gap
- Results: Numerical Results Compares with Experimental Data
  - Pressure Along Stator and Rotor Surfaces at One Pressure Ratio
  - Mass Flow Rates at Different Pressure Ratios

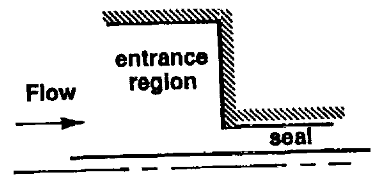
*Work Performed by Dr. Makhijani of CFDRC

RESULTS FOR STEPPED LABYRINTH SEAL



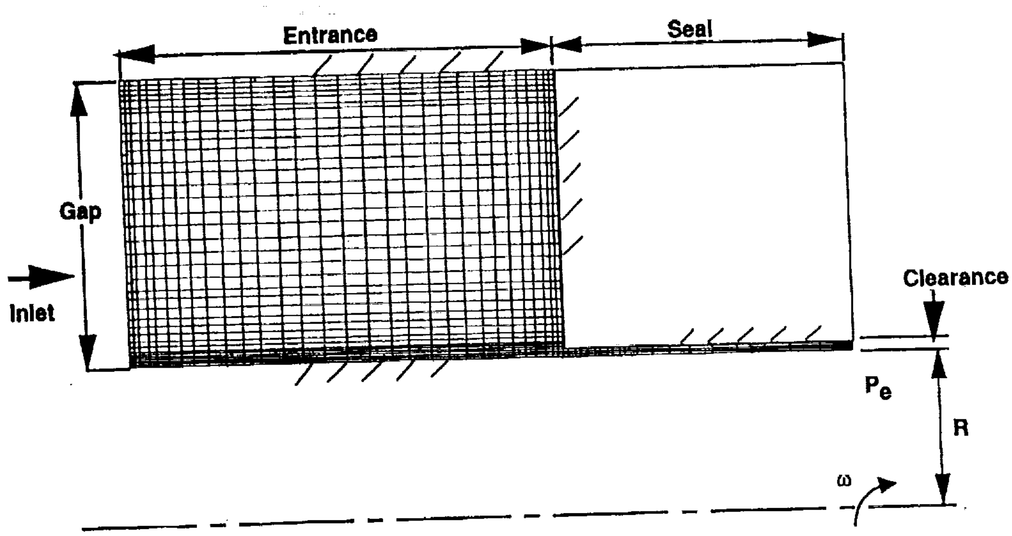
ENTRANCE LOSS COEFFICIENTS

- Measure of Flow Losses at Entrance Region
- SCISEAL Used to Compute ξ with CFD Solution
- Variation of ξ with
  - Axial Reynolds Number
  - Seal Clearance-to-Radius Ratio
  - Entrance Gap-to-Clearance Ratio



- Physical Models
  - Incompressible Flow, Standard k-ε Model
  - Fully Developed Flow Upstream, Pressure Downstream
  - 50 Cells in Axial Direction, 5 in Clearance, 30 or 50 in Entrance Region

FLOW GEOMETRY FOR ENTRANCE LOSS



RESULTS

Table 1. Entrance Loss Coefficients, Radius/Clearance = 50

Entrance Gap/Clearance = 50			Entrance Gap/Clearance = 100		
u_{ax} m/s	Re_{ax}	ξ	u_{ax} m/s	Re_{ax}	ξ
10.814	10377	0.471	10.82	10384	0.490
16.232	15484	0.431	10.24	15584	0.488
21.619	20746	0.414	21.66	20785	0.482
26.942	25854	0.406	27.06	25970	0.48

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Table 2. Entrance Loss Coefficients, Radius/Clearance = 100

Entrance Gap/Clearance = 50			Entrance Gap/Clearance = 100		
u_{ax} m/s	Re_{ax}	ξ	u_{ax} m/s	Re_{ax}	ξ
10.80	5181	0.562	10.797	5167	0.567
16.56	7945	0.54	16.176	7761	0.558
21.595	10361	0.526	21.55	10339	0.55
26.67	12796	0.51	26.934	12664	0.54
32.27	15484	0.493	32.24	15469	0.537
43.062	20667	0.478	42.533	20408	0.524

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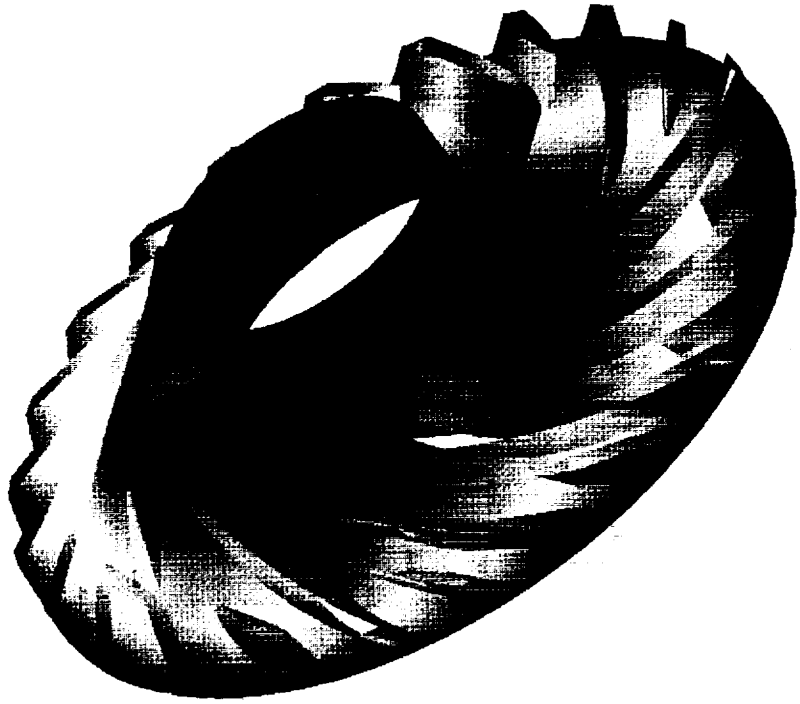
Table 3. Entrance Loss Coefficients, Radius/Clearance = 150

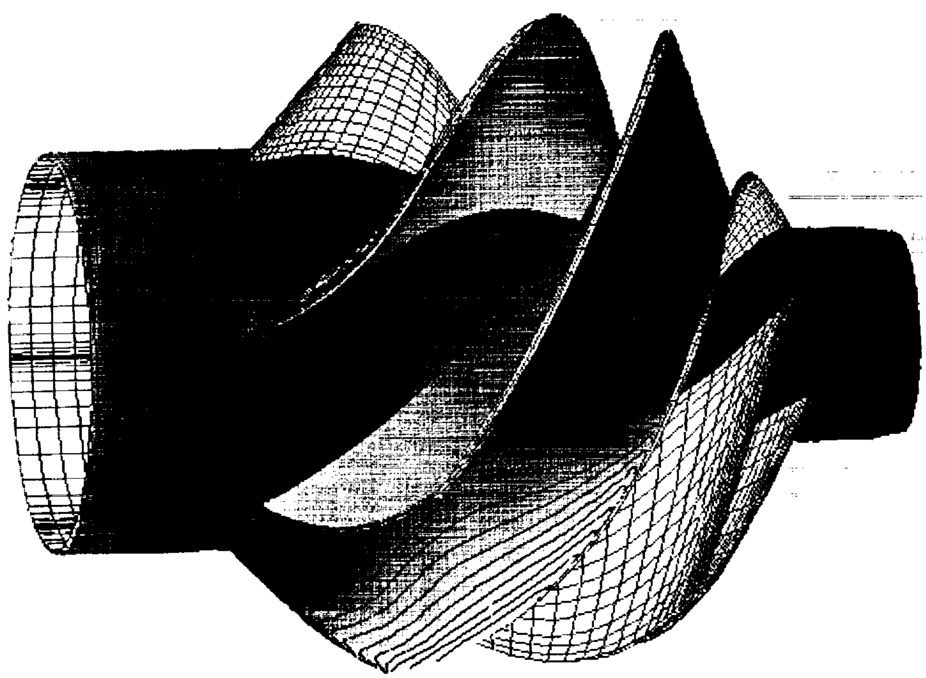
Entrance Gap/Clearance = 50			Entrance Gap/Clearance = 100		
u_{ax} m/s	Re_{ax}	ξ	u_{ax} m/s	Re_{ax}	ξ
10.82	3461	0.66	10.75	3438	0.68
16.19	5178	0.65	16.09	5146	0.66
21.49	6874	0.647	21.47	6874	0.65
26.74	8553	0.637	26.81	8553	0.648
32.25	10315	0.628	32.176	10292	0.64
48.33	15461	0.606	47.87	15315	0.63
64.487	20630	0.595	64.165	20630	0.624

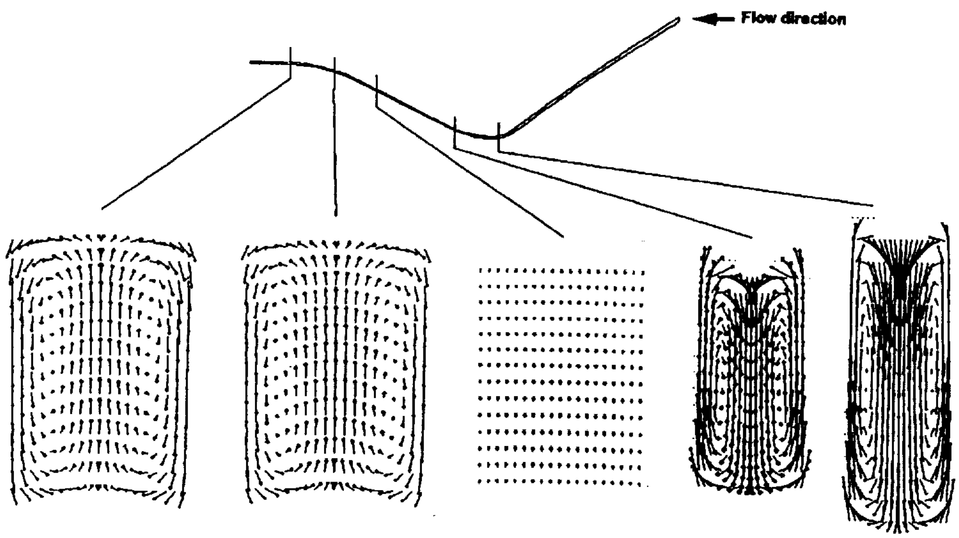
RELATED CFD RESULTS

- **REFLEQS-3D Used for Rotating Flows**
  - **Flows in Inducer & Centrifugal Impeller (For MSFC Pump Consortium)**
  - **REFLEQS-3D & SCISEAL have Similar Numerical Techniques**

- **SCISEAL in Narrow, Long Channels**
  - **Suitable for Cooling Channels in Rocket Nozzles**
  - **Heat Transfer & Flow Calculations**







Secondary flow patterns in a long, narrow channel

(Velocity vector size and cross-section sizes not to scale)

CONCLUDING REMARKS

- A 3D CFD Code, SCISEAL, Being Developed and Validated
    - Current Capabilities Include Cylindrical Seals
- State-of-the-Art Numerical Methods
    - Colocated Grids
    - High-Order Differencing
    - Turbulence Models, Wall Roughness (in progress)
- Seal Specific Capabilities
    - Rotor Loads, Torques, etc
- Rotordynamice Coefficient Calculations
    - Full CFD Based Solutions - Centered Seals
    - Small Perturbations Method - Eccentric Seals
- Extensive Validation Effort

WORK PLANS FOR NEXT YEAR

- Consolidate Current Models

- Include Multi-Domain Solution Methodology

  - Efficient Solutions for Complicated Flow Geometries
    - -- entrance region & seal clearance
    - -- stepped and straight labyrinth seals
    - -- face seals
    - -- tip seals
    - -- conjugate heat transfer

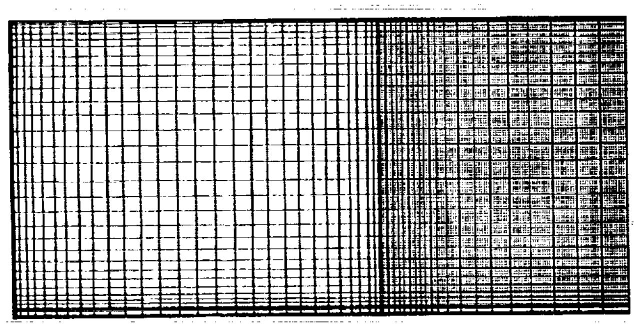
  - Increases Code Flexibility

  - Technology Already Developed but Requires Adaptation and Testing for Seals

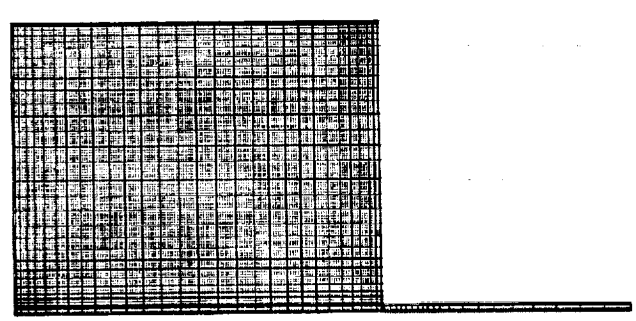
- Continue Work on Labyrinth Seals

- Validation/Demonstration for Practical Seal Configurations

Entrance Loss Calculations

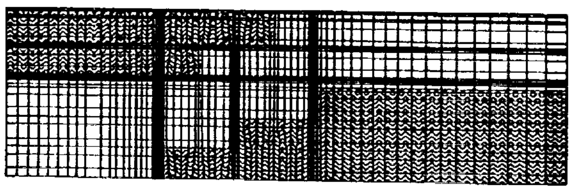


Single Domain Grid

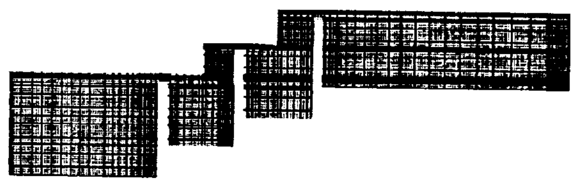


Multidomain Grid

Stepped Labyrinth Seal grids



Single Domain grid



Multidomain grid