SIMULATION OF GAS TURBINE SECONDARY AND MAIN PATH FLOWS AND INGESTION

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Panel Title: OUTLINE

I will start with an overview of the objectives, followed by a brief discussion of the numerical methodology of SCISEAL code used in the simulations; the current version uses multi-block structured grids. I will then present results for two cavity-mainpath flow cases : UTRC Large Scale Rig, built to simulate the SSME high-pressure fuel turbopump turbine section, and the turbine section of the Allison T-56 engine. Finally a summary to conclude the talk.

Panel Title : OVERVIEW

Secondary flow management has become more important with the drive to improve gas turbine efficiency, especially in the turbine section. Coolant flow is necessary for cooling the components, at the the same time it represents a loss because expensive compressed air is used. Hence optimization of the cooling air is necessary, both in terms of the flow rates and injection locations.

Interaction between the primary or above blade platform and secondary flow or the below platform flows becomes more acute because optimization necessarily implies flow rate reduction. For adequate component life much more detailed information on the primary and secondary flow interaction under optimized conditions is needed.

Simulations can be performed at several stages of complexity. The first pass simulations are the steady-state or time-averaged flows in the machine and can be done using 2-D approximations for gross overall features of the flow field. The next step is to couple the energy equation between the flow and the solid parts to predict the thermal and structural changes in the solid parts such as turbine discs and seal supports. Further refinement can involve full time-dependent analyses. The time changes in the mainpath involve changes in gross flow due to engine setting change as well as the periodic changes generated due to the blade passing in multi-stage engines.

Panel Title : OVERVIEW (Contd.)

We have presented several studies in the past 3-4 years to show that modern computational analysis techniques can be used to provide such flow details. Some of the items we have looked at so far include single cavity and rim seals and interaction with the main path under flow and geometry changes; multiple-cavity multiple-mainpath flows where the interaction between cavity-mainpath as well as inter-cavity flows was considered. Finally, time-resolved analyses where the interaction under changing mainpath flows was done.

I'll show here the fluid and fluid-thermal analyses of two multiple- cavity multiple-mainpath flow configurations: one is the UTRC Large Scale Rig, experiments on which were conducted by Bruce Johnson and Bill Daniels of UTRC and the second is the Allison T-56 engine turbine section, geometries and flow conditions for which were supplied by Jim Forry and John Munson from Allison Engine Co.

Panel Title : NUMERICAL METHODOLOGY

I'll talk now about the numerical methodology that is used in the SCISEAL code as it stands now; we are in the process of shifting over to an unsrtuctured grid methodology. The current code is a 3-D CFD code, and has a finite-volume, pressure-based, implicit multi-domain structured grid capability. Pressure-based methodology allows treatment of both compressible and incompressible flows. We have incorporated a lot of features and physical models, for example high -order differncing schemes, a comprehensive set of boundary condition types, e.g. walls, inlets, a number of turbulence models including standard and low-Reynolds k-epsilon and 2-layer models useful in secondary flows; passive scalar transport, used in the UTRC rig simulations, and conjugate heat transfer where energy equation for flow and structural parts is coupled which is useful when predicting effects of the hot gas when in contact with the solid parts.

Panel Title: UTRC LARGE SCALE RIG

The first case we tried was the UTRC Large Scale Rig which was developed for the SSME high-pressure fuel turbopump turbine section. The configuration has four cavities. It has a pair of rotors (refer to Panel "LARGE-SCALE MODEL RIG"), four main paths, two inner cavities and a front and an aft cavity. The idea was to find out what happens to the flow inside the cavities. In the experiments, the flow was tracked using a tracer gas, CO2. A number of sensors were mounted on the cavity walls to measure the local gas concentrations. There were three purge flow locations: one each in the fore and aft cavities, and one in the central cavities. There were four mainpath flows shown by arrows.

The problem description (refer back to " UTRC LARGE SCALE RIG ") then is: four rim seals, four main paths, and three purge flow locations. The CFD model had 52 domains: I'll show the grid in a minute where you can see the complexity of the flow domain and this is one of the reasons for switching to an unstructured grid methodology which will simplify the grid generation and setting up of the problem. In any case, the current grid had over 19K cells.

The flow model had central differencing for convective fluxes, standard k-epsilon model for turbulence and the passive scalar transport for tracking the tracer gases. The computed flow rates and tracer concentrations were compared with the experimental data. The experiments were done at several different mainpath and purge flows and rotational speeds, but we simulated three cases in all and I'll quickly show the results for one of them.

Panel TITLE "FLOW DOMAIN"

This is what the grid looks like. The problem has four main paths as shown with different tracer gas compositions, three rim seals, and purge flows at three locations as shown. The central block represents the slots that are present in the actual rig that connect the inner cavities.

Two Panels titled "Streamfunction Plot" put together.

These panels show the predominant flow thread in the flowfield of the four cavities. The design of the cavities was such that mainpath ingestion was expected in seal 1. Seal 2 was also expected to ingest mainpath gas and then the flow moved across the central support. The (central) purge bifurcates and mixes with the flow thread in the central cavities. The flow then moves along the upper wall of cavity 3, part of the flow exits through Seal 3 and the remaining flow then mixes with the purge flow in the aft cavity and exits through Seal 4.

Panel Title : SEAL MMASS FLOW RATES

The designed ingestion in seals 1 and 2 was found correctly. I'll quickly show the comparison of the computed flow rates and experimental values through all four seals, and good correlation is seen.

Panel Title : LARGE SCALE RIG RESULTS

We also compared the tracer gas concentrations at several spots in the cavities and found good correlation with experimental data except a few regions such as the blade shanks. The test rig had blades in this region which could not be modeled exactly using the 2-D axisymmetric flow which may be one of the reasons for this.

Panel Title : ALLISON T56 ENGINE TURBINE SECTION

Moving on to the second case, thanks are due to Jim Forry and John Munson for providing the geometry and flow details of the problem. The problem involves the disc cavities in the T56/301D engine. It has four rotor stages, three pairs of inner cavities, and one cavity each ahead of the first stage and aft of the last stage. (Refer to Panel "Allison T56 Engine Turbine Cavities"). The interstage labyrinth seals were modeled exactly. Over the time we have performed several stages of simulations. One study involved the stage 1-2 cavities. This shows the geometry with the rotor stages and the turbine cavity sets. The rotor stages are marked 1 to 4 and stages 1 and 4 have external single cavities that were not considered here. The present work stayed with the inner cavities: stage 1-2, stage 2-3 and stage 3-4 cavities.

Starting (Refer back to Panel "ALLISON T56 ENGINE TURBINE SECTION") with the 1-2 cavities, variations in the laby seal clearance and purge flow rates were considered, and laby seal clearance was found to be important when gas ingestion was concerned.

We also did conjugate heat transfer calculations in individual pairs of cavities to see the effects on the structural parts and finally put the whole thing together to simulate the entire turbine drum.

Panel Title : ALLISON T56 ENGINE TURBINE SECTION

All of the inner cavities, rotors, laby supports and laby seals were modeled exactly and are shown in this figure. We have a total of six cavities, six mainpath conditions, e.g. exiting the first rotor, exiting the fist stator row etc. Dark shaded regions are solids and are parts of the solution domain for the energy equation; the open areas have gas flow and heat transfer. You can see the laby seals in the three pairs of cavities and several purge flow locations. The overall flow geometry was split into several subdomains and the red lines indicate the outer boudaries of the subdomains.

Panel Title : FLOW AND BOUNDARY CONDITIONS

Model involved specifying inlet boundaries at the six mainpaths and specified purge flow rates at appropriate locations. Walls in contact with flow were congugate walls, all other walls were treated as adiabatic. Usually the wall boundary conditions for energy equation are a problem because one has no idea of the heat flux or temperature distribution. Solving the conjugate problem avoids the necessity of imposing external conditions on at least the conjugate walls.

Panel Title: RESULTS

For the given flow conditions, some of the results I am going to show include flow streamlines to show flow threads, and temperature distributions in the flow field. Flow streamlines (Refer to panel "Allison T56 Engine Turbine Cavities, Stream Function") show the complex complex vortical structures that exist in the cavities, and also can be used to infer ingestion of mainpath gases, which is not seen in any of the six rim seals.

Flow rates (refer to "COMPARISON OF ANALYSIS AND DESIGN DATA") and gas temperatures at the rim seals were compared with Allison designs and fair to good comparison was seen. Strong temperature gradients were seen in all solid supports (refer to "Allison T56 Engine Turbine Cavities, Temperatures") which will be of interest, since they will affect the labyrinth seal clearances. Additionally, we also found that the inclusion of the conjugate heat transfer had the effect of increasing the rim seal flow temperatures.

Panel Title : "ADDITIONAL SIMULATIONS"

Some additional simulations that we performed on this geometry were to consider the effects of the laby seal clearance which showed that the Stage 1 rim seal ingested gas when the laby seal clearance was increased from 12 to 24 mils; these results are consistent with design data.

We also presented last July some results on time dependent behavior of the Stage 1-2 cavities when the main-path flow setting was changed from fast idle to takeoff. The analysis showed no ingestion during this change.

Panel Title: "ADDITIONAL SIMULATIONS (CONTINUED)

Finally, we took some runs to see what happens to the rim seal flows as the purge flows in the cavities were reduced. This is of interest, since optimization of the secondary flows will result in such reductions. For the simulations, keeping all other parametres for the stage 1-2 cavities constant, the purge flow rates were reduced in steps from the baseline values to 50% of the baseline. No ingestion was seen till about 60% of the design coolant flow rate, and there was clear evidence of ingestion at 50%.

Panel Title : "Allison T56 Stage 1-2 Cavity Results"

This behavior is clearly seen in these plots of temperature in the cavities which are relatively cool till 65% design coolant flow. At 50% purge flow, cavity 1 temperatures increase near the rim seal, and the shape of the contour lines clearly indicates ingestion; this was also seen from the streamline plots not shown here.

Panel Title : "SUMMARY"

To conclude, gas turbine engine have multi-cavity multi-mainpath environments in the compresor and turbine setions with very complex flow-fields. As shown in the two examples, current CFD tools can be used to obtain detailed flow-fields that are reasonably accurate and can be used to great advantage. The simulations show that the interaction between primary and secondary flowpaths is important and with the current drive for optimization of secondary flows, knowledge of this can become critically imporant for adequate component life. Finally, the 2-D analyses provide only the steady steady fields, and the numerical methodology needs to be extended further. In particular, the effects of time-transient flows near the rim seals, due to blade passing and other reasons, need to be evaluated at the design stage. The local flow variations could lead to pockets of ingestion along the rim seal periphery that may not show up in a steady analysis. This effect may become worse with modern turbine stages with opimized coolant flows and high stage loadings. Other areas that need attention are the coupled thermal solutions for gas and solid parts to generate the temperture information in the solids to calculate the thermal deformations and their effects on critical cavity dimensions such as labyrinth seal clearances.

OUTLINE

CFDRC

- Overview
- Numerical Methodology
- Multistage Cavity Problem Description and Results
  - UTRC Large-Scale Rig
  - Allison T-56 Turbine Cavities
- Summary

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OVERVIEW

CFDRC

- Secondary Flow Management Important in Overall Engine; In Turbine Section
  - Necessary for component cooling
  - Represents an efficiency loss
  - Optimization of the coolant flow rates and locations

- Interaction Between Mainpath and Secondary Flows Becomes More Acute with Optimization Efforts

- Need Much More Detailed Information on Primary-Secondary Flows and Their Interaction Under Optimized Conditions:
  - “Steady State” response
  - Coupled fluid-thermal analyses, structural as well
  - Response to time-dependent/periodic changes in mainstream

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OVERVIEW (Continued)

CFDRC

- Computational Analysis Techniques Could Be Used to Provide Such Details
  - Single cavities/rim seals, and interaction with mainpath
  - Multiple cavities/multiple mainpath interactions
  - Time resolved analyses
- Presented Herein Are Fluid and Fluid-Thermal Analyses of Multiple Cavity and Mainpath-Cavity Flow Interaction
  - UTRC large-scale rig
  - Allison T56 engine turbine section

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NUMERICAL METHODOLOGY

CFDRC

- Calculations Performed with SCISEAL, 3D CFD Code Developed for Flow Analysis In Turbomachinery Seals
- SCISEAL Description
  - Finite volume, pressure-based, implicit multidomain
  - Incompressible and compressible flows
  - High-order differencing, comprehensive set of boundary types
  - Turbulence models, passive scaler transport, conjugate heat transfer

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UTRC LARGE-SCALE RIG

CFDRC

- 2-Rotor, 4-Cavity Configuration in UTRC Large-Scale Rig
  - Simulate SSME HPFTP turbine section
  - 4 rim seals, 4 mainpaths, 3 purge locations
  - Tracer gases used to track fluid movement
- CFD Model
  - Multidomain (52 domains), 2-D axisymmetric geometry, 19k grid
  - Central differencing, standard k-ε model
  - Passive scalar transport used for tracer gases
  - Simulations at different purge flow rates and rotation speeds

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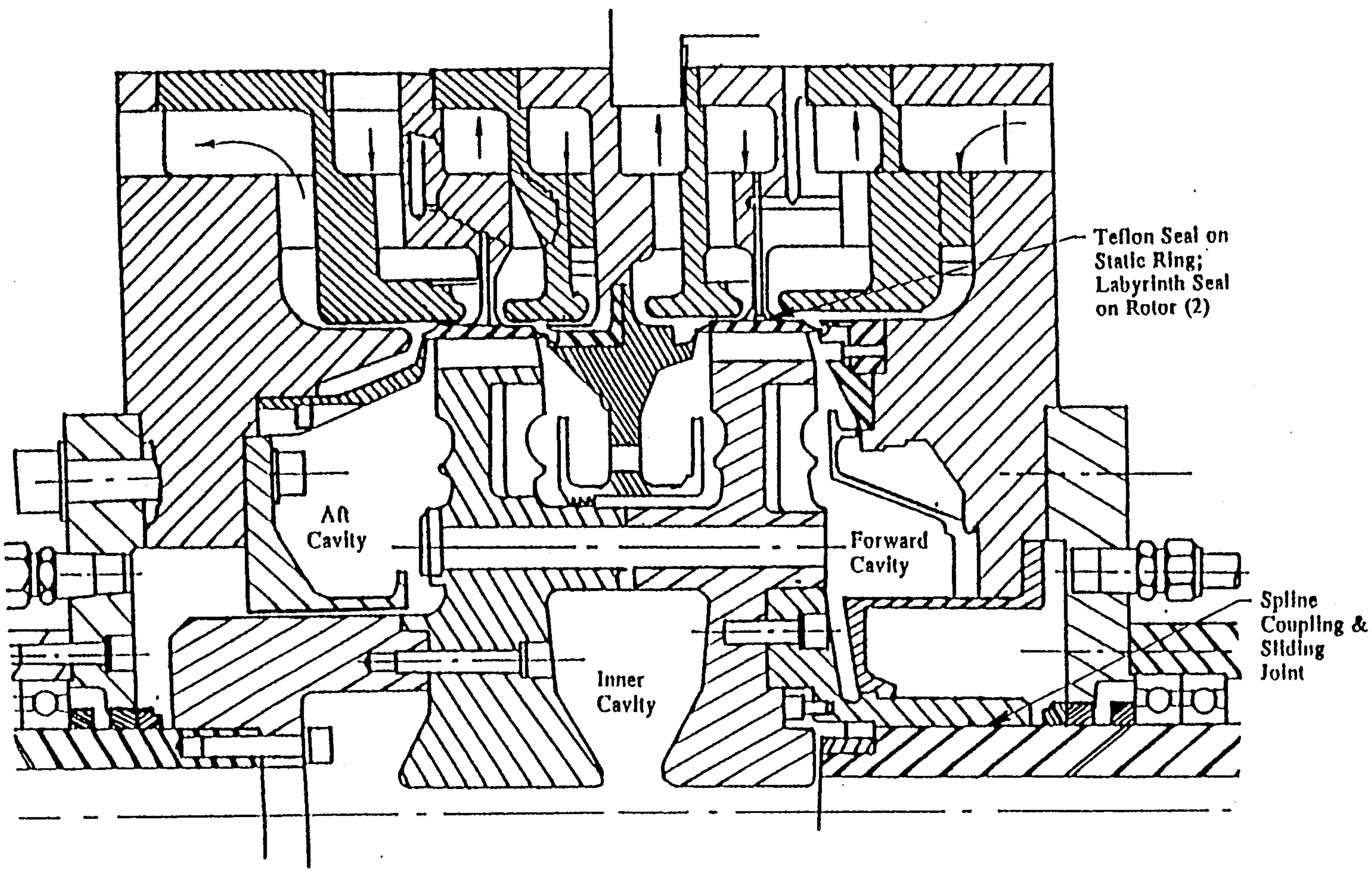
LARGE-SCALE MODEL RIG

CFDRC



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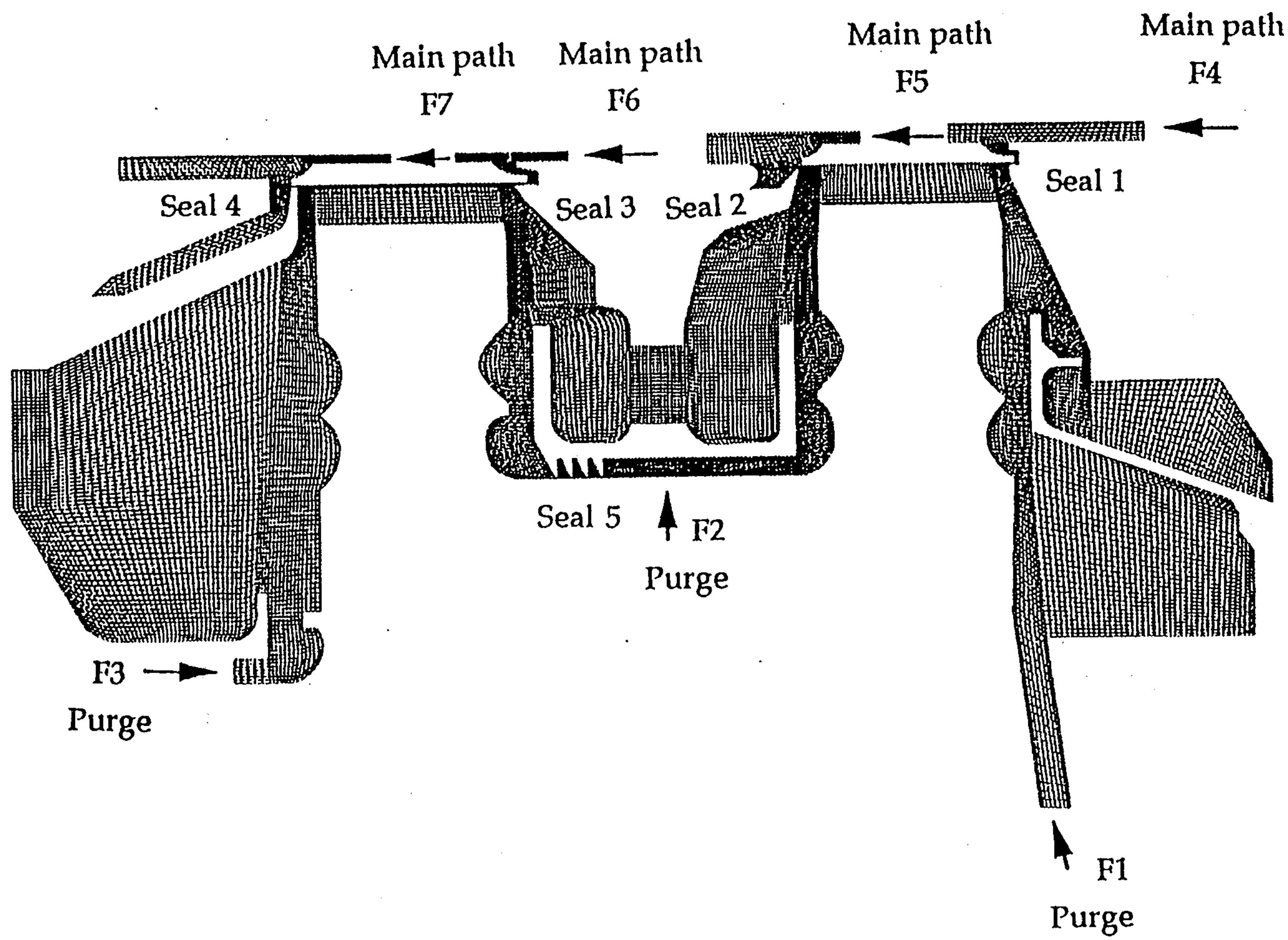
FLOW DOMAIN



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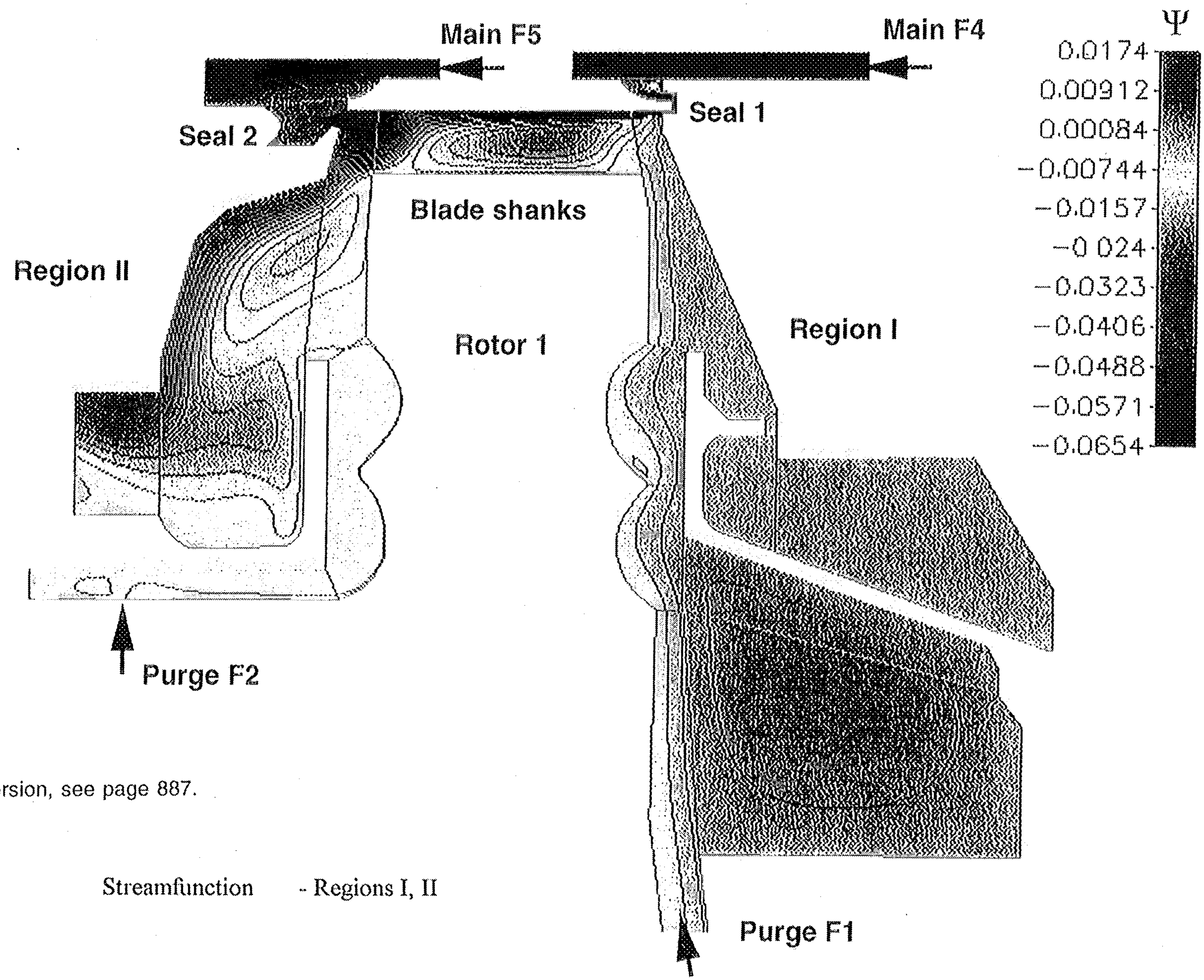
Streamfunction Plot

CFDRC

Regions I, II and Blade Shanks, Run No. 202



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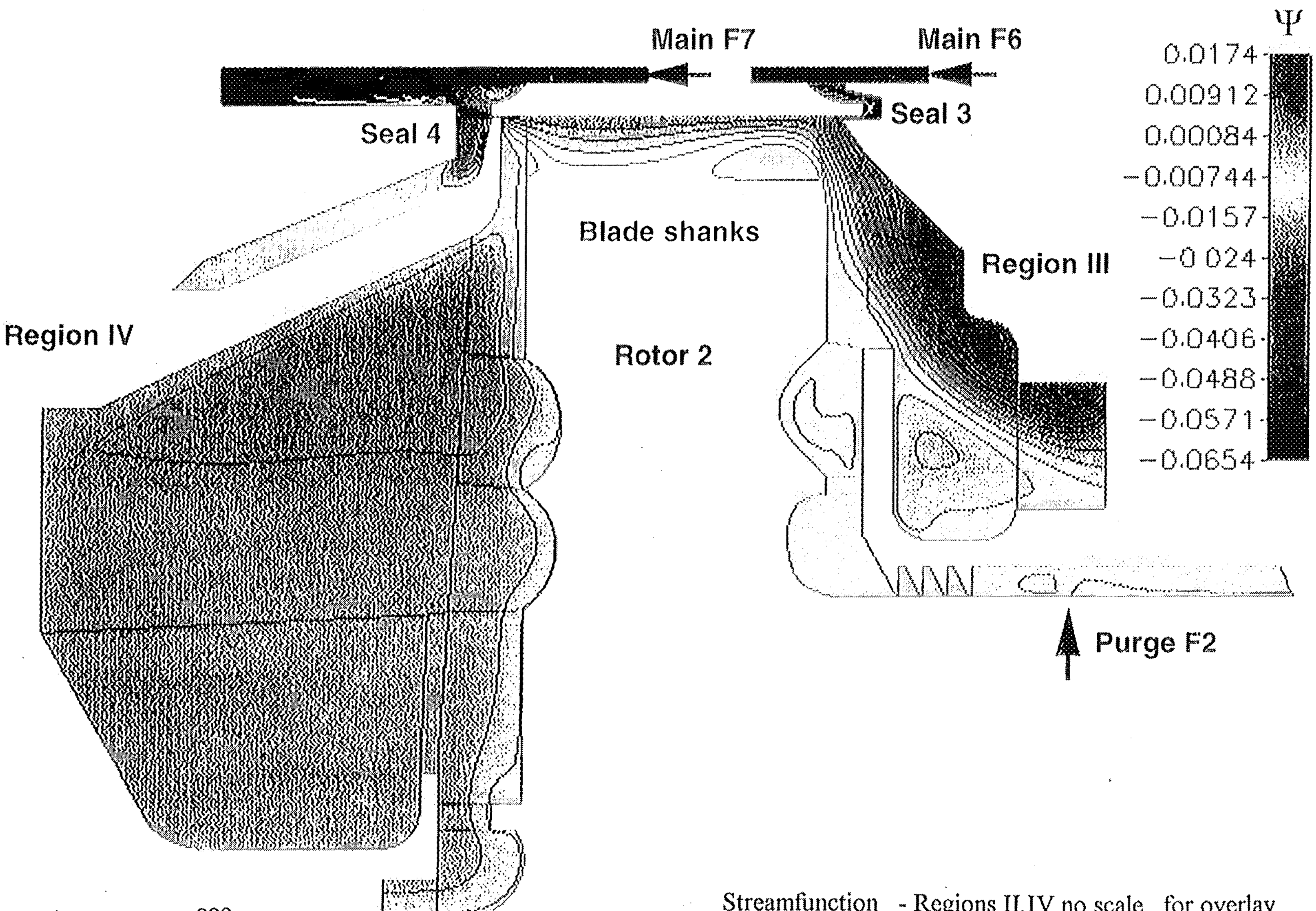
Streamfunction - Regions I, II

Streamfunction Plot

CFDRC

Regions III, IV and Blade Shanks, Run No. 202

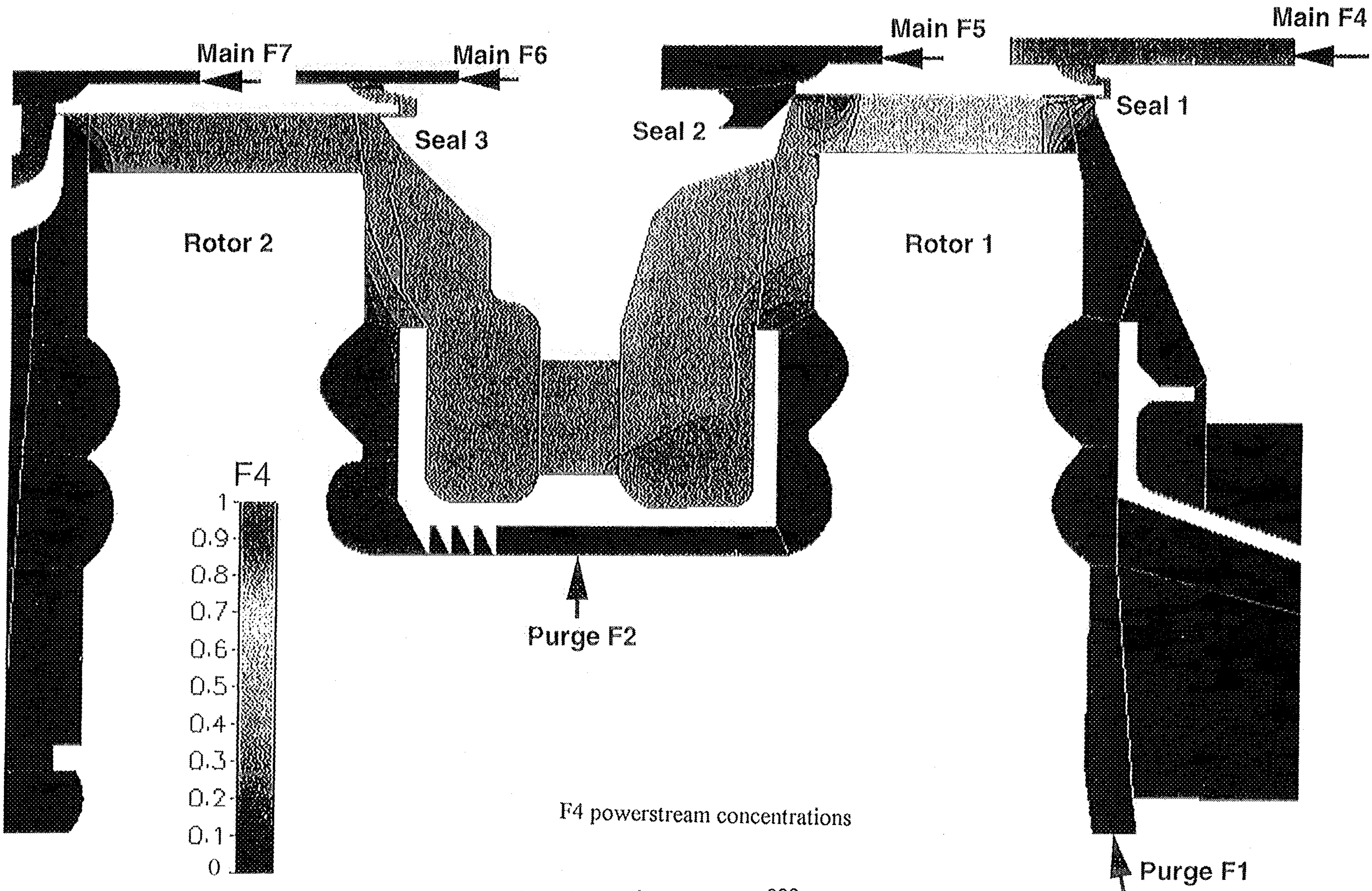


For color version, see page 888.

Streamfunction - Regions II,IV no scale, for overlay

Mixture Fraction (Concentrations) CFDRC

Computed Values of F4 Concentrations, Run No. 202



F4 powerstream concentrations

For color version, see page 889.

SEAL MASS FLOW RATES

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- **Rim Seal Ingestion Flow Rates is an Important Parameter**
- **Computed and Experimental Values Given Below**

(Mass Flow rates in lbs/s)

Run No.	Rim Seal Flows				Specified Purge Flows				
	Seal 1	Seal 2	Seal 3	Seal 4	Forward Cavity	Center Cavity	Aft Cavity	Net, in $\dot{m}$	Net, out $\dot{m}$
102									
numerical	-0.150	-0.072	0.233	0.260	0.1425	0.0637	0.064	0.4923	0.4928
experimental	-0.126	-0.094	0.265	0.208	0.143	0.062	0.066	0.491	0.473
(exp-num)/exp	.19	-.23	.12	-.25	0	-.03	.03	.003	-.04
202									
numerical (18K grid)	-0.236	-0.139	0.286	0.353	0.1168	0.0552	0.0904	0.6374	0.639
numerical (30K grid)	-0.237	-0.126	0.283	0.33	0.1168	0.0552	0.0904	0.6374	0.639
experimental	-0.224	-0.154	0.257	0.271	0.115	0.057	0.087	0.637	0.528
(exp-num)/exp	.05	-.10	-.11	-.30	-.02	.03	.04	0	-.21
205									
numerical	-0.223	-0.1025	0.357	0.381	0.208	0.103	0.0985	0.7351	0.738
experimental	-0.186	-0.113	0.302	0.302	0.208	0.105	0.095	0.707	0.604
(exp-num)/exp	.20	.09	.18	.26	0	.01	.04	.04	.22

Net $\dot{m}_{in}$ = |seal 1| + |seal 2| + |all purge flows|

Net $\dot{m}_{out}$ = |seal 3| + |seal 4|

$\Delta\text{-}\dot{m} = (\dot{m}_{in} - \dot{m}_{out})$

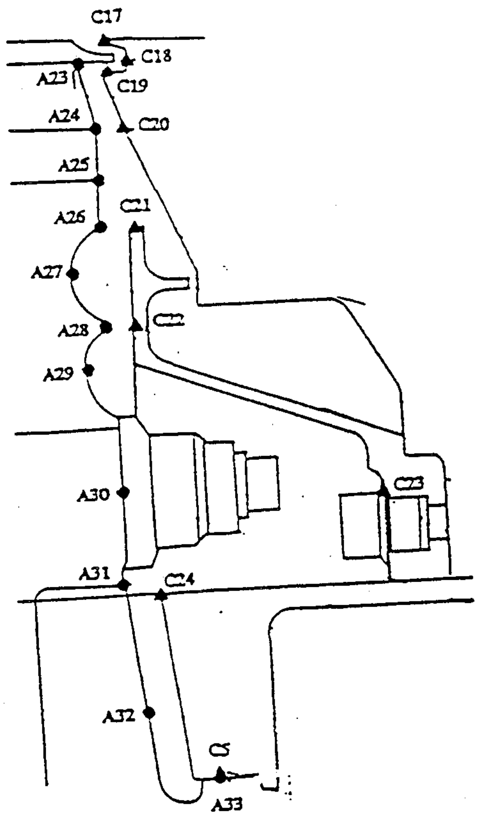
$\Delta\text{-}\dot{m} > 0$ implies net mass accumulation in apparatus

$\Delta\text{-}\dot{m}$

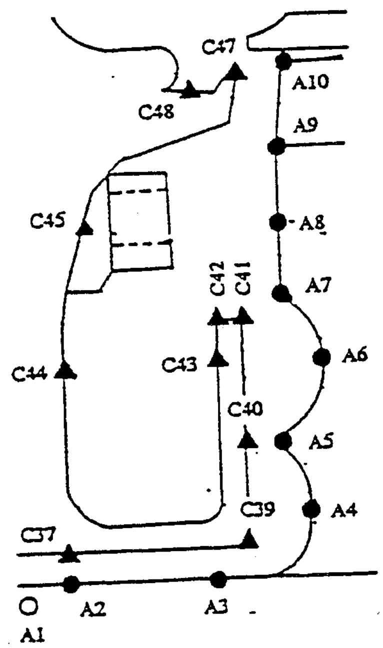
Run No.	102	202	205
experimental	+ 0.018	+ 0.109	+ 0.103
numerical	- 0.005	- 0.0006	- 0.0029

CONCENTRATION MEASUREMENTS
Location of Probes

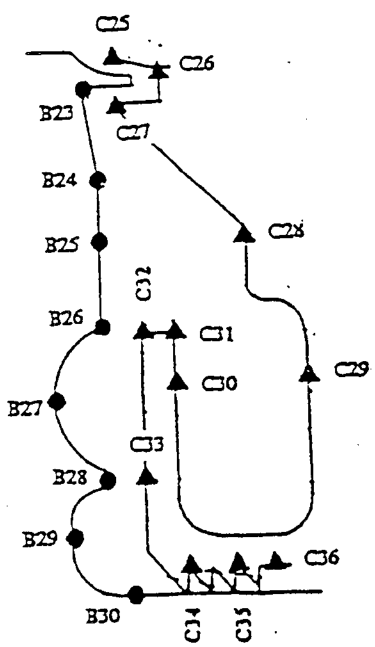
CFDRC



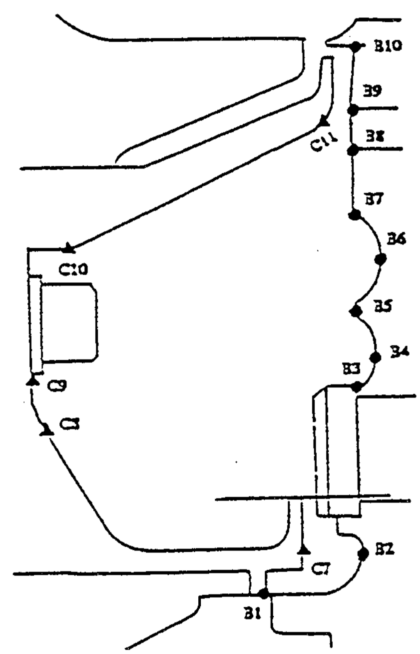
a. Region 1 and Rotor 1



b. Region II and Rotor 1



c. Region III and Rotor 2



d. Region IV and Rotor 2

COMPARISON OF ANALYSIS AND EXPERIMENTS

CFDRC

	ϕ_{12} F1	ϕ_{13} F2	ϕ_{14} F3	ϕ_{01} F4	ϕ_{03} F5
Region I - Forward Cavity					
A23 - numerical experimental	0.278 0.09	4E-5 0	0 0	0.721 0.93	0.001 0
A24 - numerical experimental	0.978 0.96	1E-4 0	0 0	0.021 0.09	2E-4 0
Region II - Center Cavity and Rotor I					
C44 - numerical experimental	0.232 .24	0.03 .12	0 .03	0.465 .32	0.273 .28
C42 - numerical experimental	0.150 .22	0.378 .18	0 .03	0.299 .31	0.173 .22
A8 - numerical experimental	0.194 .09	0.194 .67	0 0	0.388 .13	0.223 .11
A5 - numerical experimental	0.003 .03	0.987 .9	0 0	0.006 .05	0.004 .04
C39 - numerical experimental	0.002 .07	0.992 .71	0 .03	0.004 .1	0.002 .04

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COMPARISON OF ANALYSIS AND EXPERIMENTS

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Region III - Center Cavity and Rotor II					
B30 - numerical experimental	0.039 .06	0.838 .77	0 .03	0.078 .08	0.045 0
B26 - numerical experimental	0.070 .22	0.708 .22	0 .03	0.140 .29	0.082 .22
B23 - numerical experimental	0.216 .24	0.102 .12	0 .03	0.431 .33	0.251 .26
C25 - numerical experimental	0.218 .24	0.091 .11	0 .02	0.436 .33	0.254 .25
C33 - numerical experimental	0.097 .2	0.598 .19	0 .03	0.193 .31	0.112 .23
C29 - numerical experimental	0.223 .23	0.068 .11	0 .02	0.447 .33	0.261 .25
Region IV - Aft Cavity and Rotor II					
C11 - numerical experimental	0.006 .05	0.012 .03	0.956 .77	0.011 .07	0.007 .07
B10 - numerical experimental	0.213 .21	0.109 .12	0.004 .06	0.425 .34	0.248 .3

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LARGE-SCALE RIG RESULTS

CFDRC

- Computed Rim Seal Mass Flow Rates Compared with Experiments, Good Agreement
- Concentrations of the Various Tracer Gases at Several Locations Compared with Experiments, Good in Regions I and IV, Portions of Regions II and III
- Concentration Plots of Various Passive Scalars and Streamlines Show Fluid Movement/Thread in the Overall Rig

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ALLISON T56 ENGINE TURBINE SECTION

CFDRC

- Flow and Heat Transfer Calculations in the Turbine Section of the Allison T56/501D Engine
  - 4 rotor stages, 3 pairs of inner cavities considered
  - Interstage labyrinth seals modeled exactly
- Several Different Runs Completed
  - Stage 1.2 cavities: Variation in laby seal clearance, variation in purge flow rates
  - Flow and conjugate heat transfer for individual pairs of stage 2-3 and stage 3-4 cavities
  - Flow and conjugate heat transfer for all inner cavities, rotors and laby seals

P-4117-5/8

FLOW AND BOUNDARY CONDITIONS

CFDRC

- For All Runs Mainpath Conditions at Appropriate Rim Seals Specified
- Purge Flows Applied at Appropriate Locations
- All Walls Considered Adiabatic When <u>Not</u> Treated as Conjugate Surfaces
- 140 Domain, 91K Cell Grid for the Complete Inner Cavity Set

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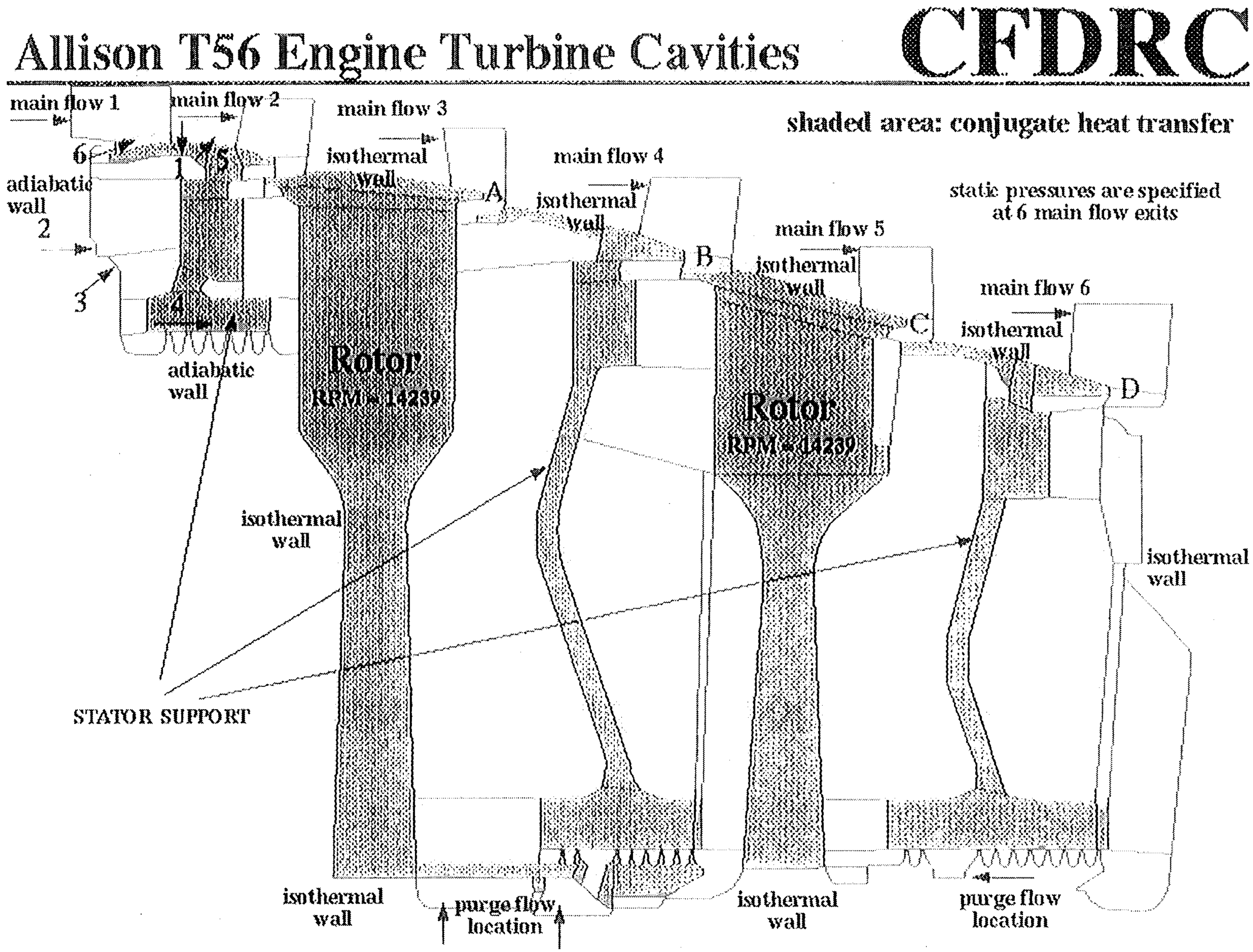

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RESULTS

CFDRC

- Flow Streamlines, Temperatures
- Mass Flow Rates and Gas Temperatures at Various Seal Locations Compared with Allison Design Data
  - Fair to good comparison with design numbers
- Stator Supports for Labyrinth Seal Honeycomb Surfaces Show Strong Temperature Gradients
- Inclusion of Conjugate Heat Transfer Allows Heat Conduction in Stator Support and Rotors $\Rightarrow$ Increased Gas Temperatures at Rim Seals

P-4117-5/11

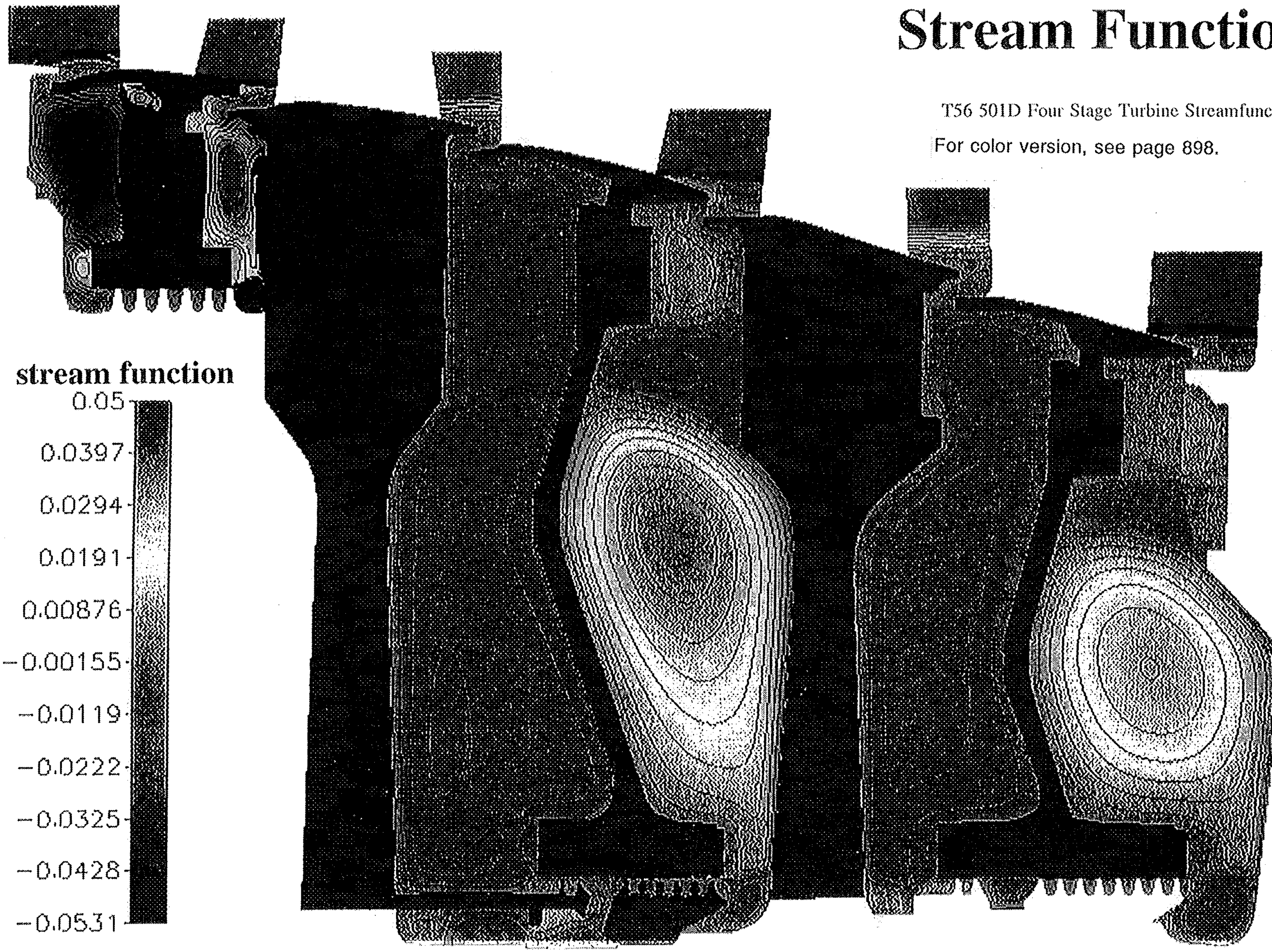
Allison T56 Engine Turbine Cavities

CFDRC

Stream Function

T56 501D Four Stage Turbine Streamfunction

For color version, see page 898.



Allison T56 Engine Turbine Cavities

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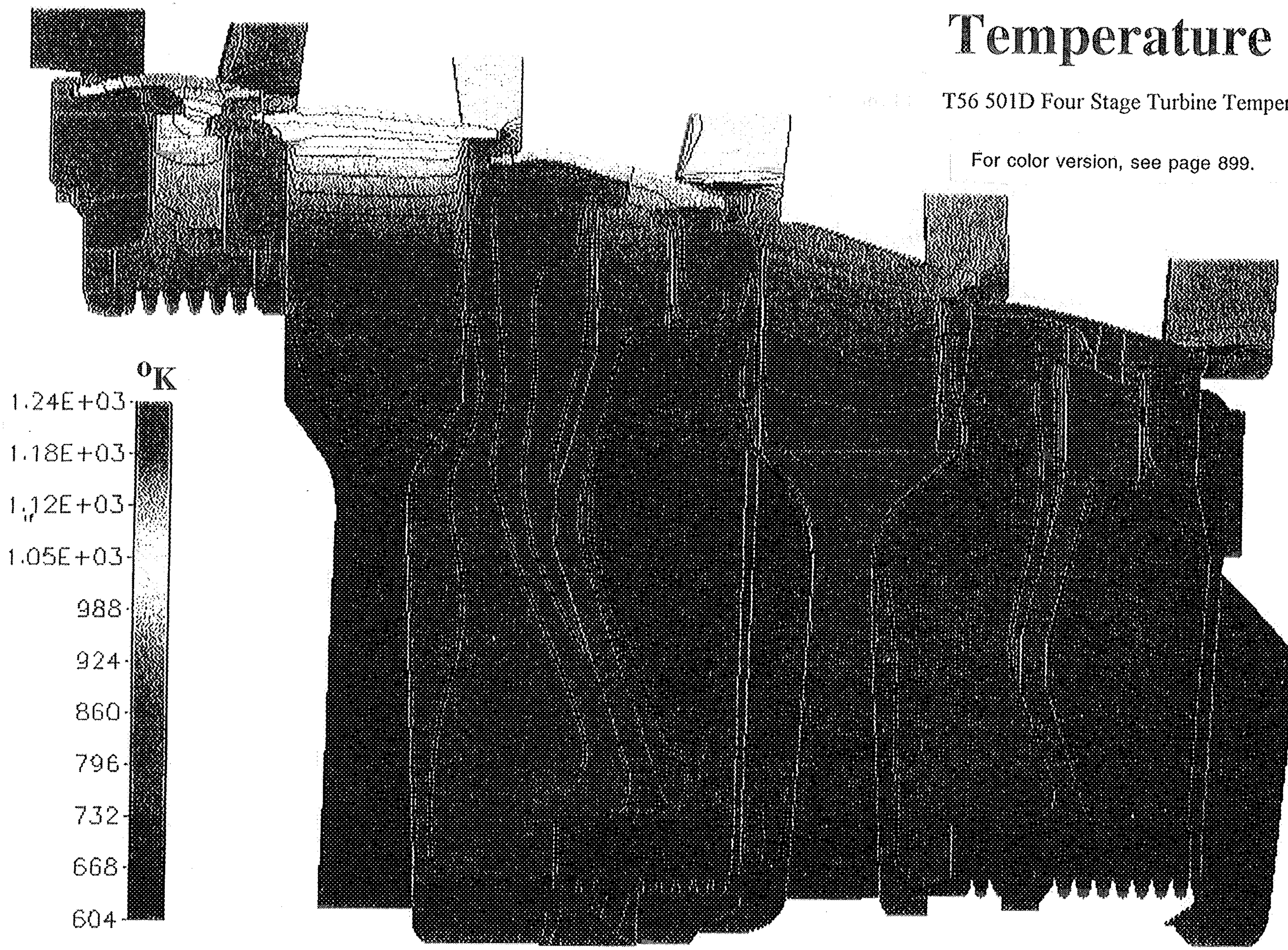
Temperature

T56 501D Four Stage Turbine Temperature

For color version, see page 899.



COMPARISON OF ANALYSIS AND DESIGN DATA

Stage 1-2 Cavities

Path No.	Design		Prediction (include conjugate heat transfer for solid parts)		Previous Prediction (without conjugate heat transfer for Stage 1-2 and rotors , Ref. 12)	
	Massflow (kg/s)	Temperature (K)	Massflow (kg/s)	Temperature (K)	Massflow (kg/s)	Temperature (K)
4	0.1129	843	0.1284	870	0.1397	829
5	0.0186	843	0.0249	984	0.0136	827
6	0.0449	843	0.0481	893	0.0431	866

COMPARISON OF ANALYSIS AND DESIGN DATA

CFDRC

Stage 2-3 and 3-4

Locations	Design			Prediction (include conjugate heat transfer for all solid parts)			Previous Prediction (without conjugate heat transfer for Stage 1-2 and rotors, Ref. 12)		
	Mass (kg/s)	Pressure (Pa)*x10^5	Temperature (K)	Mass (kg/s)	Pressure (Pa)*x10^5	Temperature (K)	Mass (kg/s)	Pressure (Pa)*x10^5	Temperature (K)
A	0.0567	3.309	741	0.0390	3.282	790	0.0376	3.275	786
B	0.0376	2.137	698	0.0522	2.089	794	0.0540	2.068	716
C	0.0340	1.724	705	0.0249	1.682	769	0.0240	1.689	700
D	0.0209	1.103	703	0.0263	1.082	732	0.0272	1.069	666

* Values at the center of the cavities.

ADDITIONAL SIMULATIONS

CFDRC

- Stage 1-2 Cavities Only Were Considered for Additional Simulations

1. Effect of labyrinth seal clearance on rim seal flows
   - Showed ingestion in stage 1 rim seal when labyrinth seal clearance was increased from 0.012″ to 0.024″
   - Predictions match with design data
2. Transient conditions that occur during changes in engine mainpath setting
   - Fast idle-to-takeoff condition change
   - Time-accurate simulations showed no evidence of ingestion

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ADDITIONAL SIMULATIONS (CONTINUED)

3. Some runs to see the effect of lowering purge flow rates

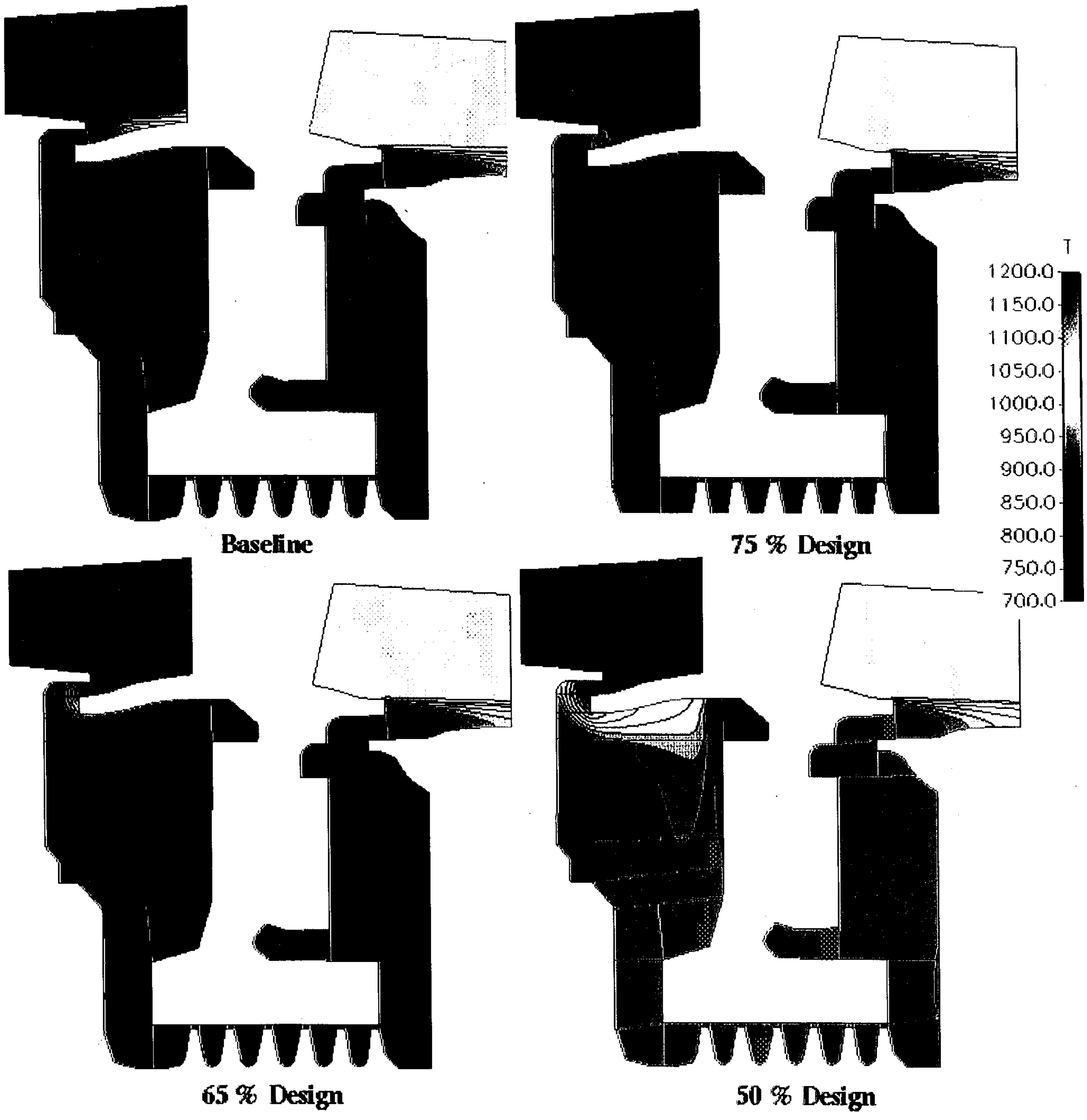
   – All purge flows reduced by same fraction

   – Estimate the fraction at which ingestion through stage 1 rim seal occurs

   – Computations show no ingestion up to about 60% of design purge flow rates

Allison T56 Stage 1–2 Cavity Results **CFDRC**

Effects of reduction in the purge flows.



SUMMARY

CFDRC

- Flow Fields Are Very Complex in Multi-Cavity, Multi-mainpath Environments
- CFD Tools Can Be Used to a Great Advantage for Obtaining Detailed, Reasonable Predictions
- Interaction Between the Mainpath and Secondary Flow Systems Is Important and Can Become of Critical Importance for Optimized Coolant Management
- 2-D Axisymmetric Runs Provide Very Detailed Numbers and a Good Start, but Need to Extend it Much Further
  - Time accurate interaction simulations (3-D), at rim seals: consider blade passing effects, etc.
  - Thermal information in solid parts can be used with a structures code for predictions of deformation, and influence on flow, e.g., at rim and labyrinth seals

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