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COMPUTATIONAL FLUID DYNAMICS (CFD) ANALYSES IN SUPPORT OF SPACE SHUTTLE MAIN ENGINE (SSME) HEAT EXCHANGER (HX) VANE CRACKING INVESTIGATION

R. Garcia, T. Benjamin, and J. Cornelison
NASA/Marshall Space Flight Center, Alabama

A. J. Fredmonski
Pratt & Whitney, West Palm Beach, Florida

Integration issues involved with installing the alternate turbopump (ATP) High Pressure Oxygen Turbopump (HPOTP) into the SSME have raised questions regarding the flow in the HPOTP turnaround duct (TAD). Steady-state Navier-Stokes CFD analyses have been performed by NASA and Pratt & Whitney (P&W) to address these questions. The analyses have consisted of two-dimensional axisymmetric calculations done at Marshall Space Flight Center and three-dimensional calculations performed at P&W. These analyses have identified flowfield differences between the baseline ATP and the Rocketdyne configurations. The results show that the baseline ATP configuration represents a more severe environment to the inner HX guide vane. This vane has limited life when tested in conjunction with the ATP but infinite life when tested with the current SSME HPOTP. The CFD results have helped interpret test results and have been used to assess proposed redesigns. This paper includes details of the axisymmetric model, its results, and its contribution towards resolving the problem.

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AXISYMMETRIC CFD ANALYSIS IN SUPPORT OF THE SSME HEAT EXCHANGER (HX) VANE CRACKING INVESTIGATION

R. Garcia
T. Benjamin
J. Cornelison
NASA/MSFC

A. J. Fredmonski
Pratt & Whitney/West Palm Beach, FL

11th Workshop for CFD
Application in Rocket Propulsion
Huntsville, AL
April 20-22, 1993

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OVERVIEW

- **Introduction/objective**
- **Approach:**
  - Testing
  - CFD analysis
- **Results**
  - Axisymmetric analysis
- **Conclusion/future work**

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OVERVIEW OF MSFC CFD SUPPORT OF HX VANE CRACKING INVESTIGATION

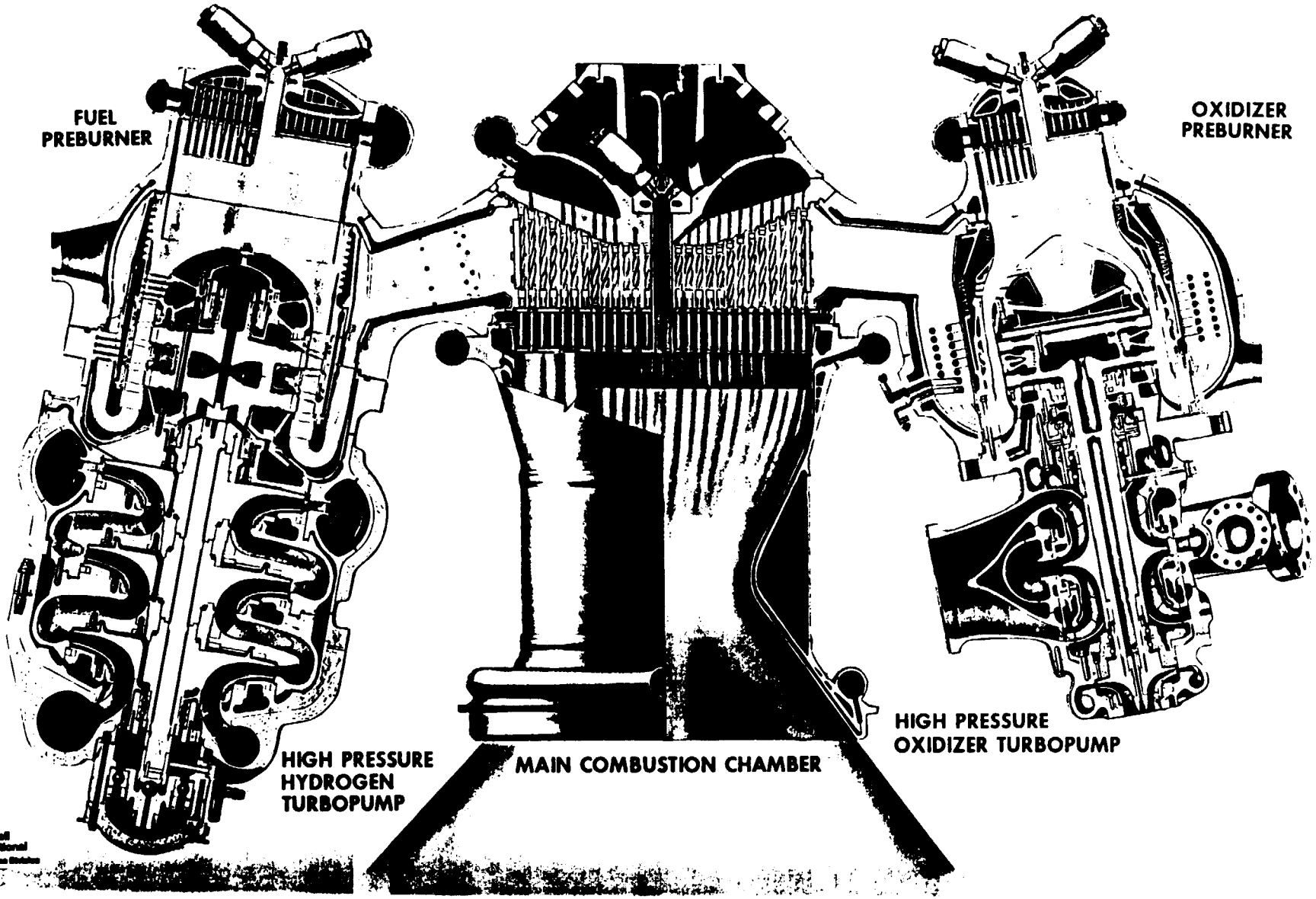
INTRODUCTION

- **The inner Heat Exchanger (HX) guide vane cracks when tested with the Pratt & Whitney oxygen turbopump**
  - Flow environment about the vane varies with turbopump used (Pratt & Whitney vs. Rocketdyne)
  - HX vanes have not cracked when tested with Rocektdyne's oxygen turbopump
  - Inspection of cracked vanes indicates failure due to high cycle fatigue

OBJECTIVE

- **Identify potential sources of vane unsteady loading**
  - Differences between Rocketdyne and Pratt & Whitney configuration
- **Identify configurational changes to the turbopump to reduce unsteady loading**

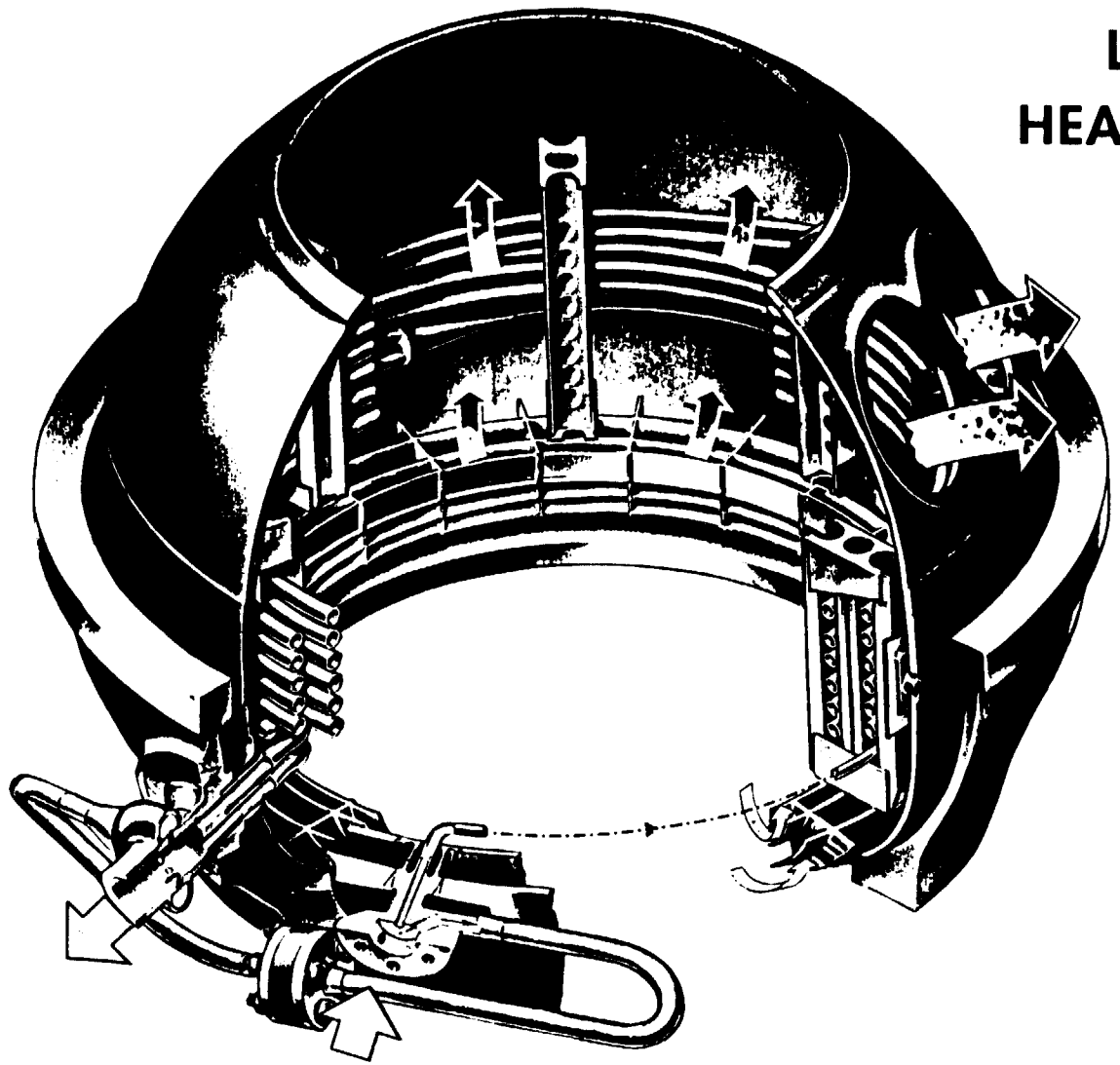
SSME POWERHEAD COMPONENT ARRANGEMENT



LC300-266N

Rockwell International

LOX TANK PRESS HEAT EXCHANGER ASSY



- INCOLOY 903
- 316L
- HAYNES 188
- INCONEL 625
- INCONEL 718
- HOT GAS
- HOT OXYGEN
- COLD OXYGEN

Rocketdyne Division
Rockwell International

LC301-3940

OVERVIEW OF MSFC CFD SUPPORT OF HX VANE CRACKING INVESTIGATION

APPROACH: TESTING

- **2D Water-flow rig (Rocketdyne and Pratt & Whitney)**
  - Used for flow visualization and qualitative CFD results validation

- **2D air-flow rig (Rocketdyne)**
  - Provides turbulent pressure fluctuations and preliminary evaluation of potential fixes

- **3D air-flow rig (MSFC)**
  - Full simulation of duct geometry
  - Provides unsteady pressure levels and vane strain levels

- **Hot fire testing (Pratt & Whitney and SSC)**
  - Actual environment, duration testing
  - Provides HX vane strain levels

OVERVIEW OF MSFC CFD SUPPORT OF HX VANE CRACKING INVESTIGATION

APPROACH: CFD ANALYSIS

- **Modified Euler, multi-stage turbine analysis (Pratt & Whitney)**
  - Provided duct inlet velocity field for both baseline geometries
- **Single stage Navier-Stokes turbine analysis (Rocketdyne, REACT3D)**
  - Verified modified Euler predictions
- **Axisymmetric steady CFD analysis (MSFC, REFLEQS)**
  - Provided two day turnaround capability
  - Used to identify differences between baseline configurations
  - Used to evaluate all proposed fixes, and test rig configurations
- **3D symmetric discharge CFD analysis (Pratt & Whitney)**
  - Included effect of axial strut on flowfield
- **Axisymmetric, unsteady CFD analysis (Rockwell, USA)**
  - Used to identify unsteady flow features not captured by the steady analysis

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APPROACH: AXISYMMETRIC, STEADY ANALYSIS

- **Assembled a three member team: grids, codes, and post-processing**
- **Geometries to be analyzed generated at Pratt & Whitney or at MSFC**
- **Grids generated using GENIE**
  - Typical grid size: 175 X 51
- **Model included splitter vanes, HX vanes, and the first five HX coils**
  - Axial struts and asymmetric discharge not included
- **CFD code REFLEQS with the K-ε turbulence model**
  - Pressure based, finite volume method
  - Fully implicit formulation
  - SIMPLEC solution algorithm
  - On YMP: 118 μsec/point/iteration, 136 words/point

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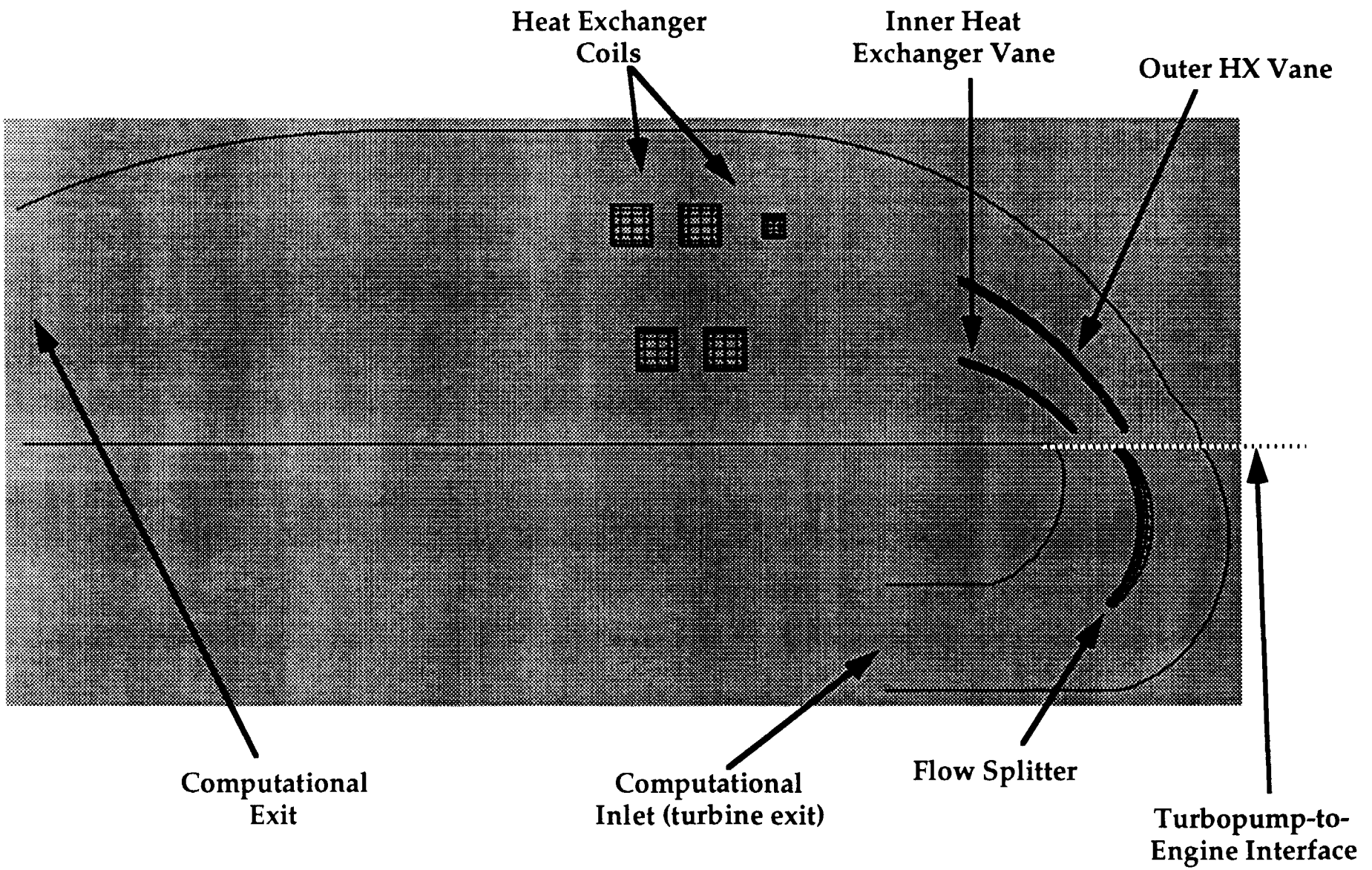

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OVERVIEW OF MSFC CFD SUPPORT OF HX VANE CRACKING INVESTIGATION

APPROACH: AXISYMMETRIC, STEADY ANALYSIS

- **Full-upwind formulation used to obtain solutions**
- **Fixed inlet velocity field, fixed exit pressure**
- **Solution process initiated with inlet condition, "empty" flowfield, heavy under-relaxation**
- **Engineering solution typically obtained with 1,500 iterations**
  - Always continued to run to at least 3,000 iterations
- **Sensitivity of solution to various parameters assessed**
  - Grid spacing, differencing scheme, inlet turbulence levels
- **Solutions qualitatively compared to 2D test rigs**
- **Code solutions used to obtain relative comparisons between configurations**
  - Absolute quantities treated with caution
- **Goal was to try to match the Rocketdyne velocity and turbulence fields**

OVERVIEW OF MSFC CFD SUPPORT OF HX VANE CRACKING INVESTIGATION

RESULTS

- **Primary difference between Rocketdyne and Pratt & Whitney baseline flowfields due to turbine exit flow**
  - Rocketdyne has radially inward flow, Pratt & Whitney radially outward
- **Turbine exit flow difference leads to higher velocities in the inner HX vane region for the Pratt & Whitney configuration**
  - Higher dynamic pressure, more severe turbulence buffeting
- **Approximately 45 cases modeled to date**
  - Approximately half were of different configurations
- **Solutions have been evaluated for:**
  - Flow split across the splitter
  - Velocity and turbulence intensity profile at the turbopump-to-engine interface
  - Velocity and turbulence intensity profile at the HX coils

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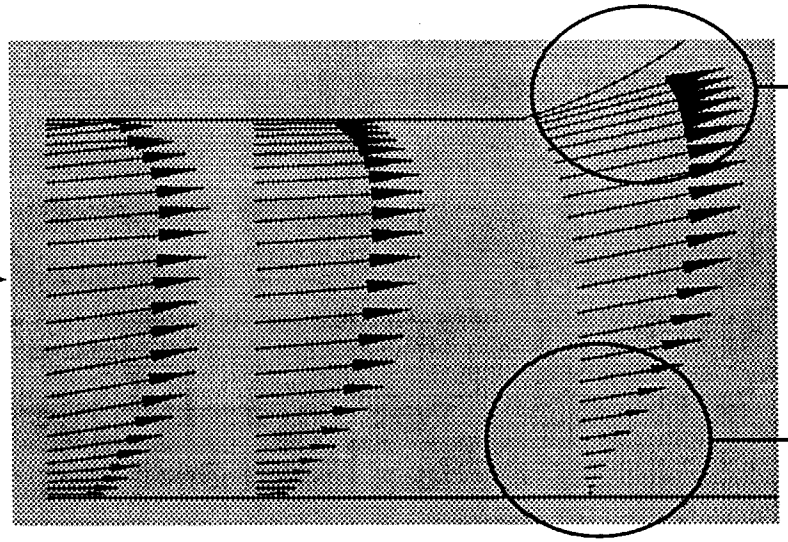
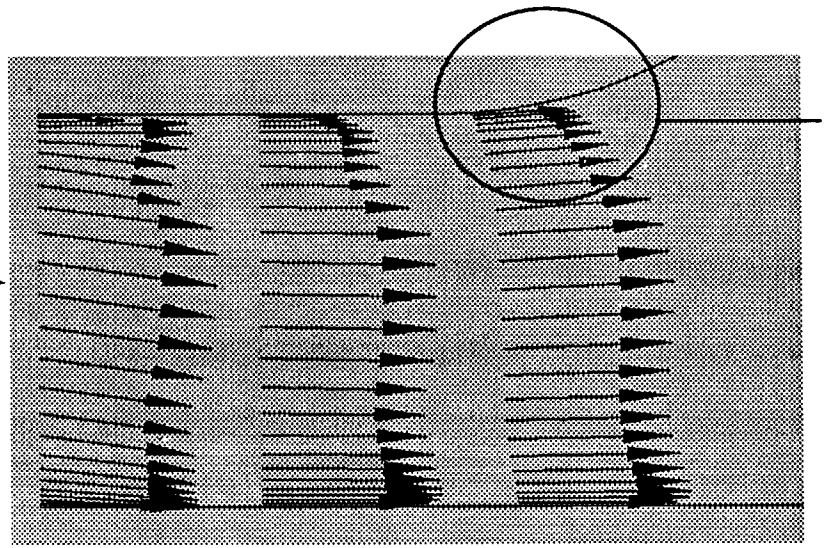
OVERVIEW OF MSFC CFD SUPPORT OF HX VANE CRACKING INVESTIGATION

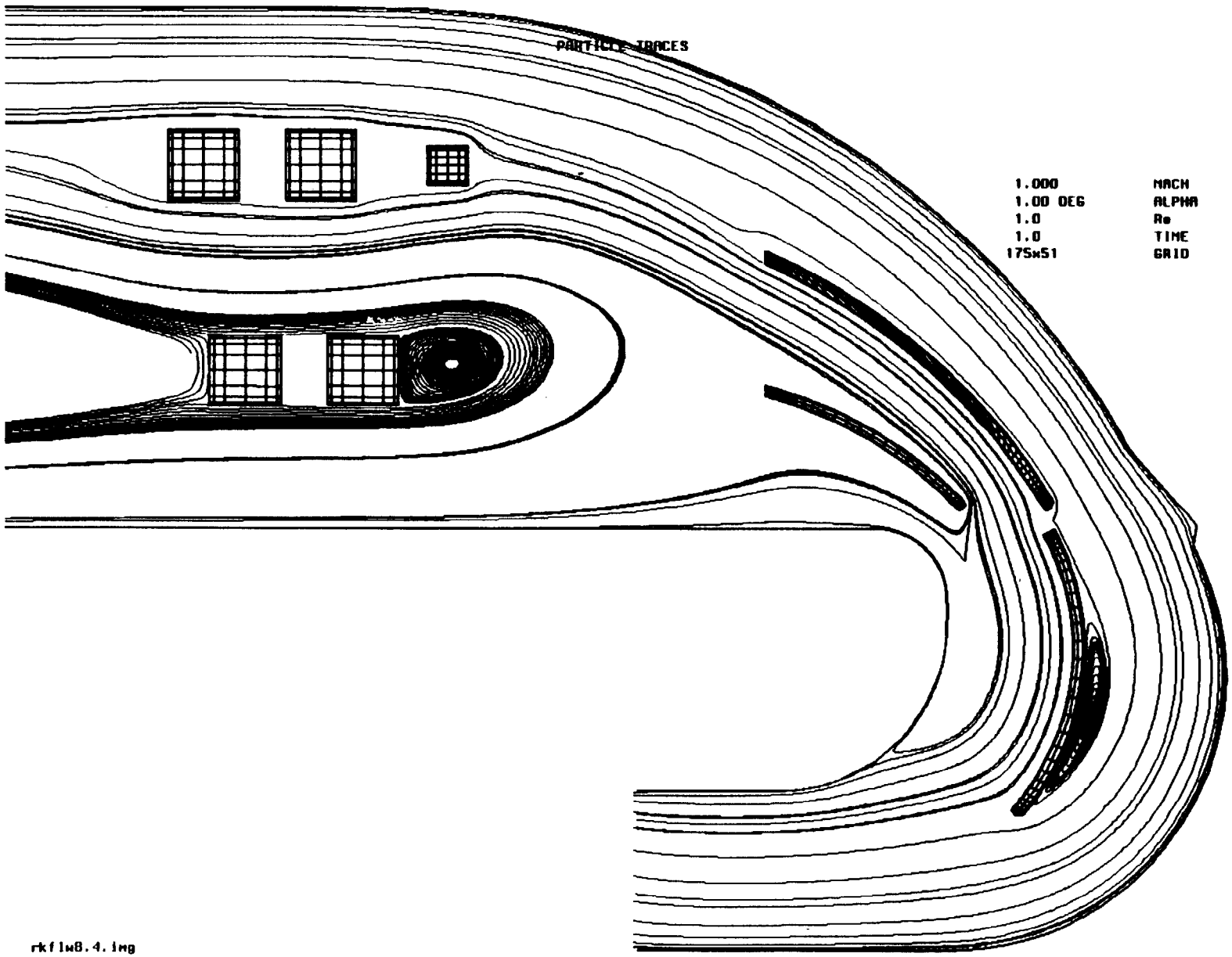
Turbine Exit Profiles:

ATD: Radially outward flow vector



Rkdn: Radially inward flow vector

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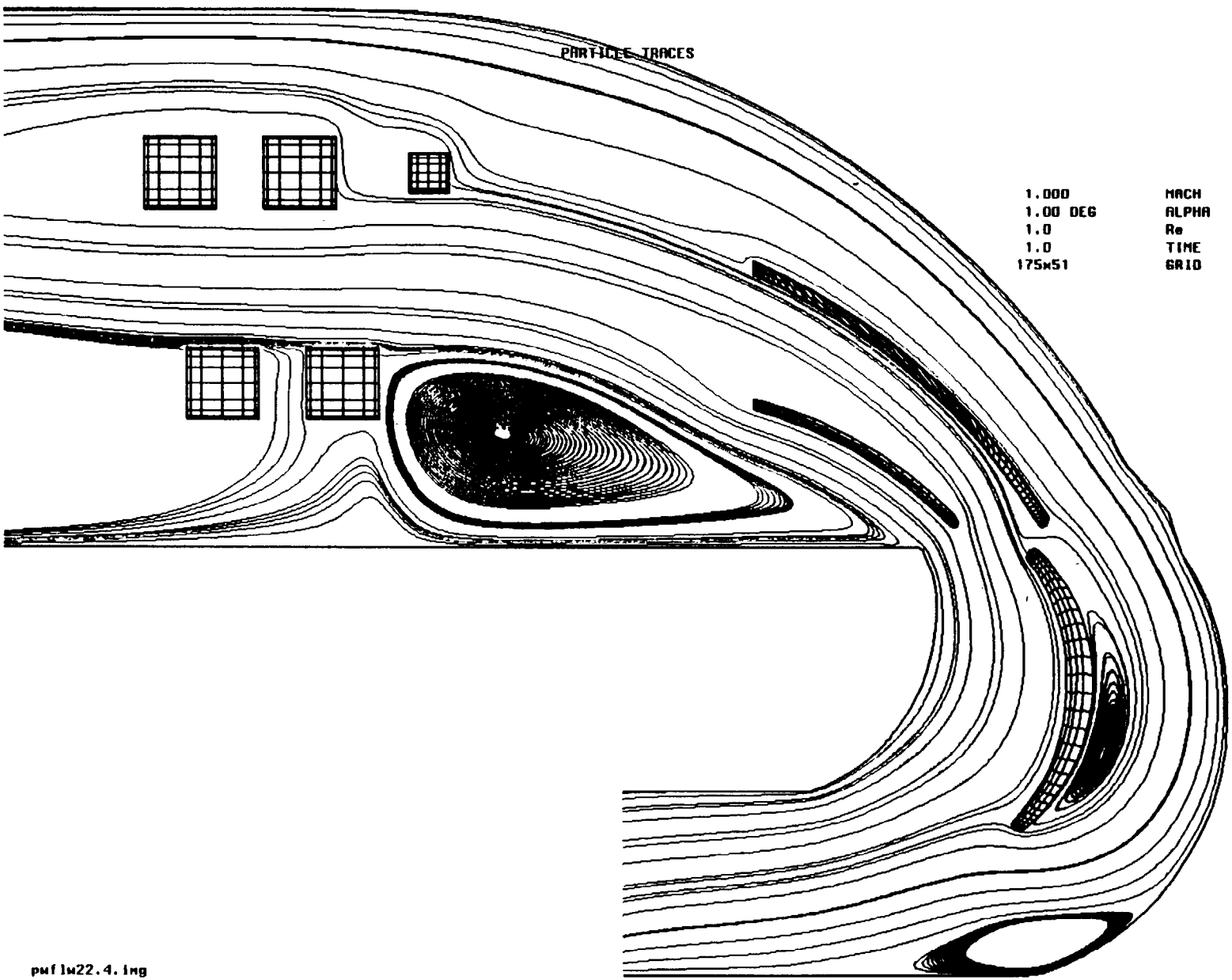
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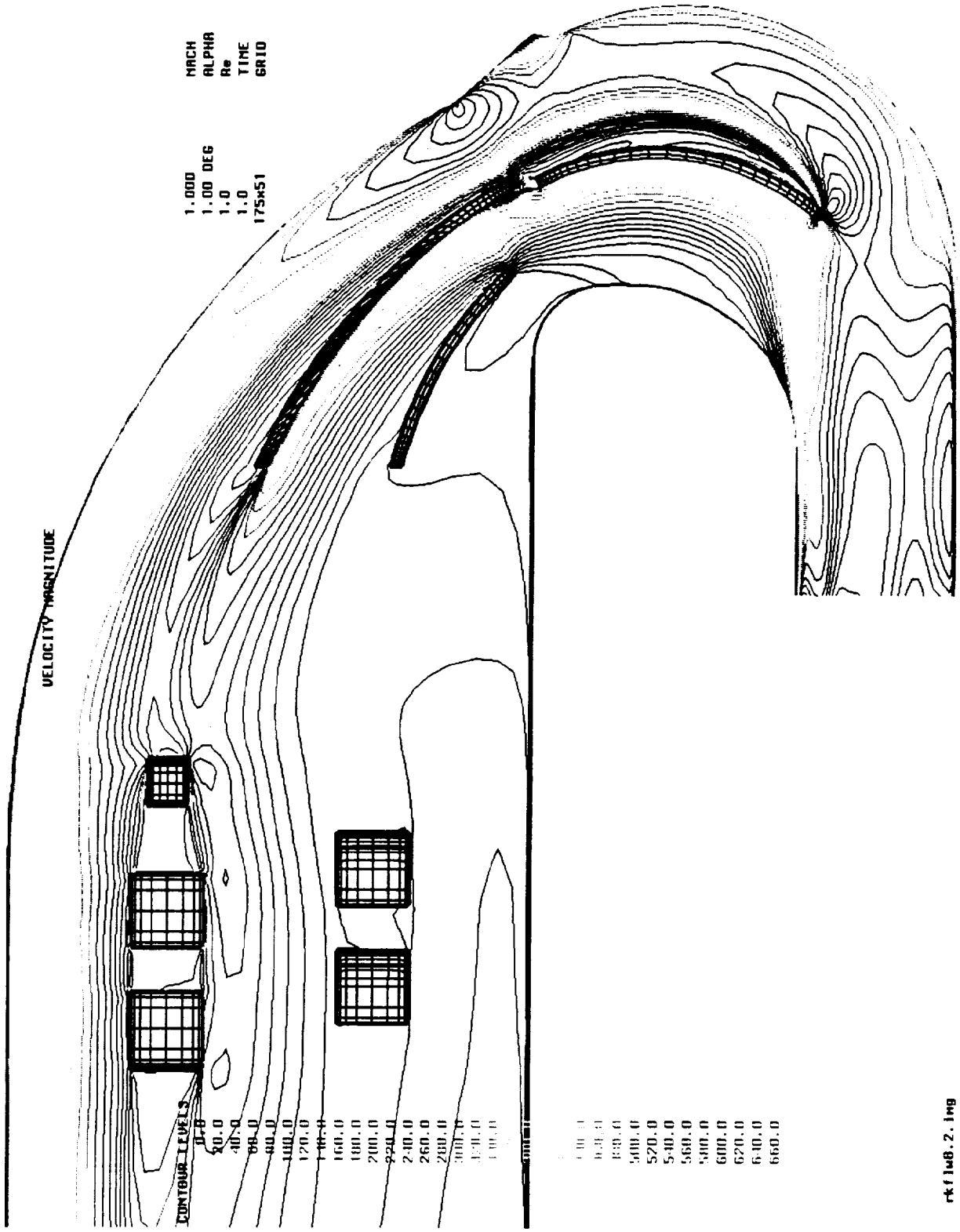

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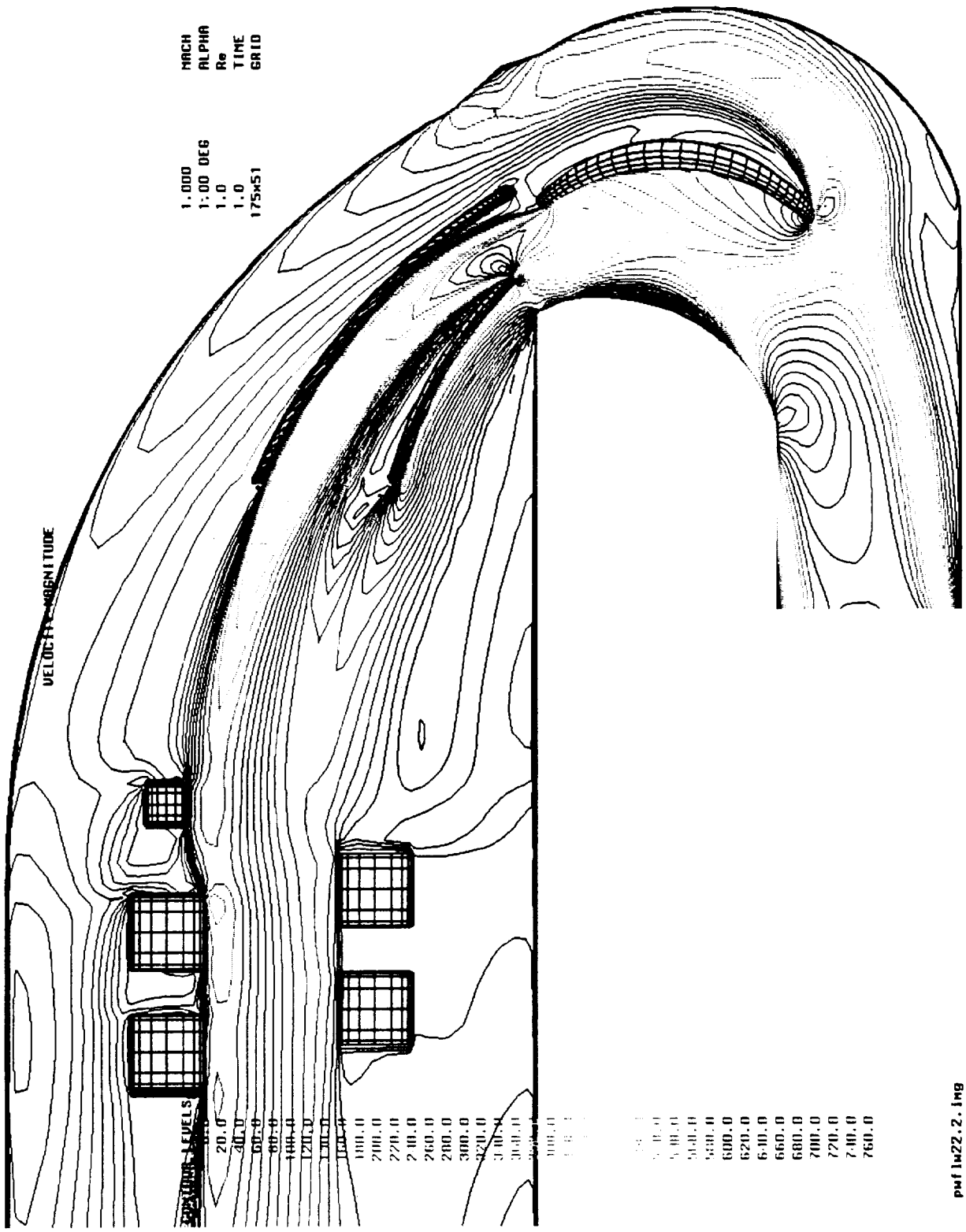

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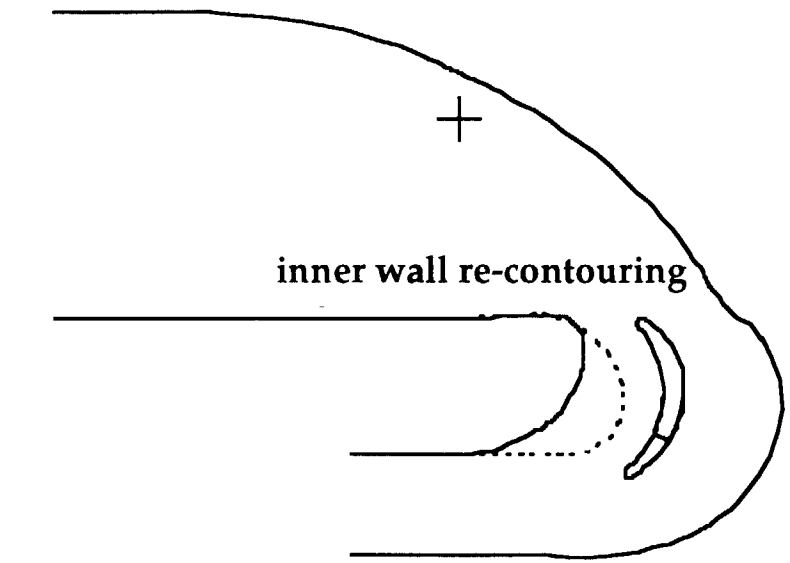
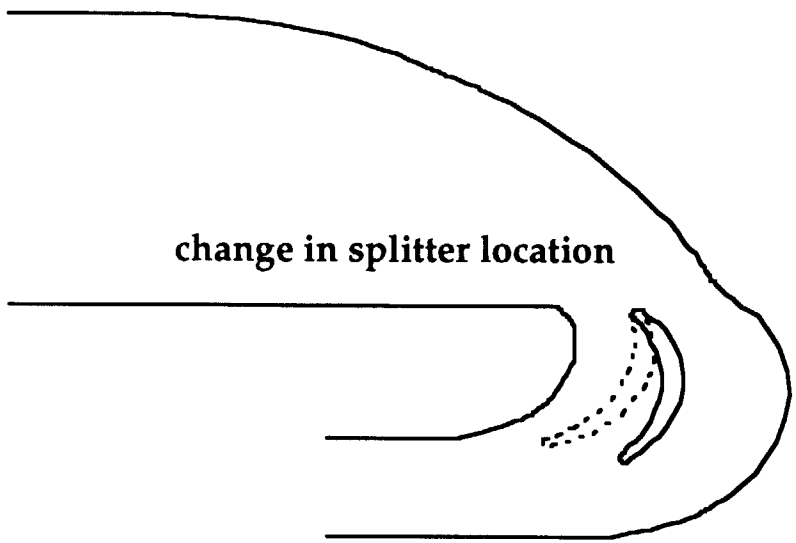
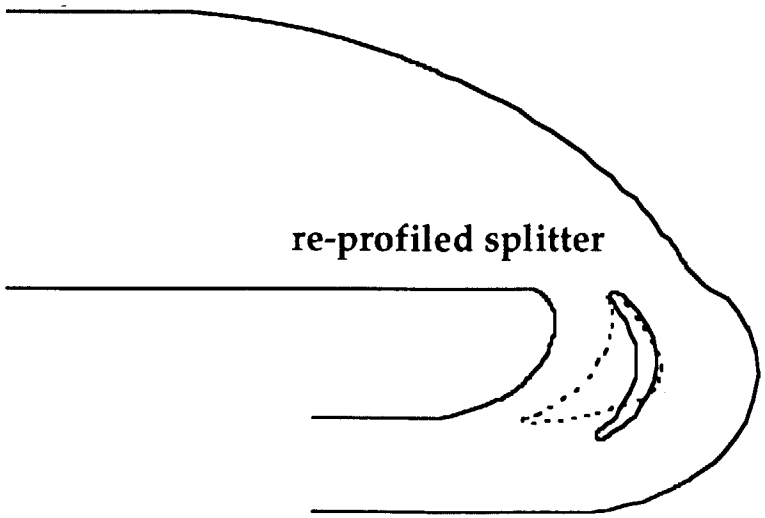
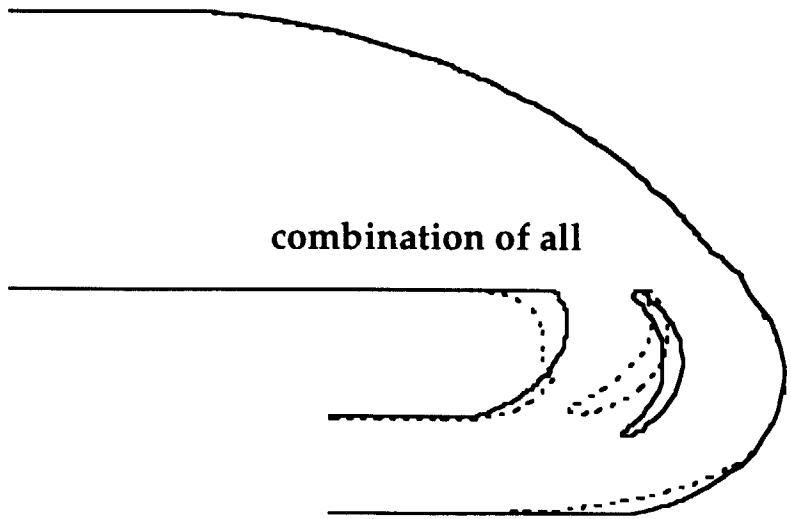
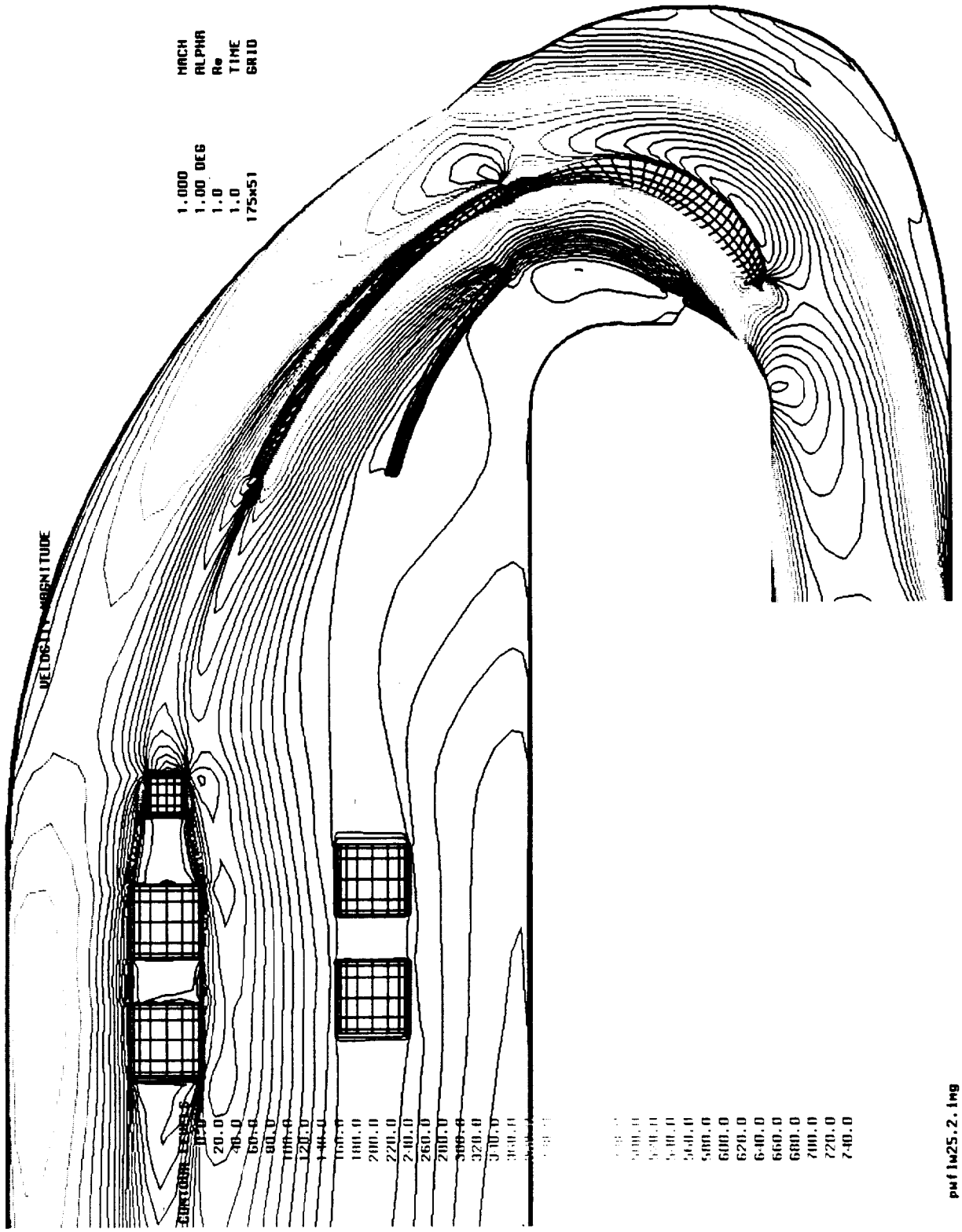
Examples of Geometries Modeled











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OVERVIEW OF MSFC CFD SUPPORT OF HX VANE CRACKING INVESTIGATION

RESULTS

- **Configuration identified that closely matches the Rocketdyne baseline velocity profile at the engine interface**

- **Predicted turbulence intensity similar to Rocketdyne configuration**
  - Peak turbulence intensity near the vane surfaces reduced ~ by a factor of 2

- **Environment in the HX coils region similar to or better than Rocketdyne baseline**

OVERVIEW OF MSFC CFD SUPPORT OF HX VANE CRACKING INVESTIGATION

CONCLUSION/FUTURE WORK

- **Quick turnnaround CFD capability demonstrated**
- **Potential source and fix to the problem identified**
- **Increased sensitivity among analysts to turbulence field**
  - K prediction, shear layer strengths
- **Presently generating full 3D grid**
  - To identify circumferential variation that may intensify turbulence levels
  - To assure that the proposed fix is not impaired functionally by 3D effects

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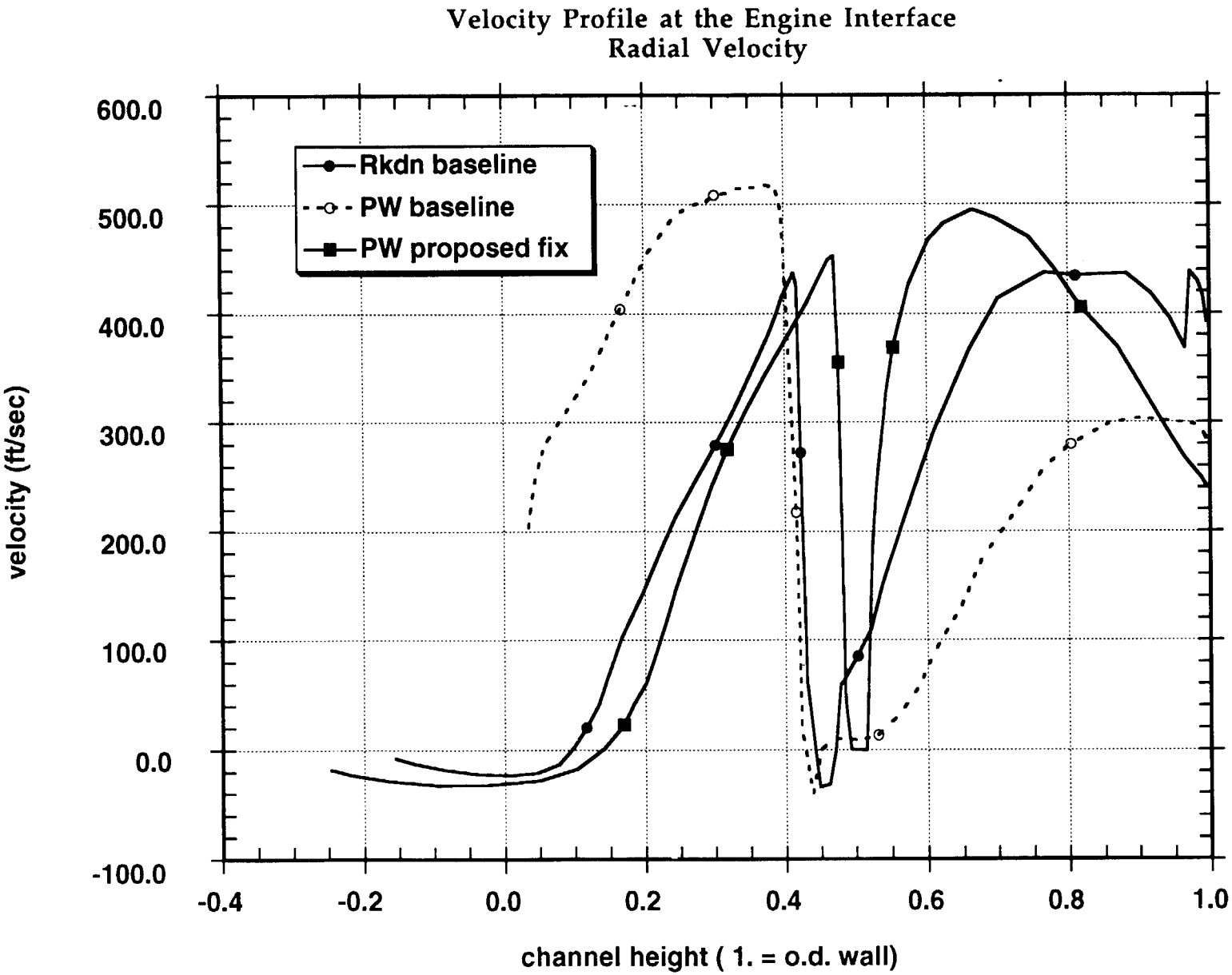

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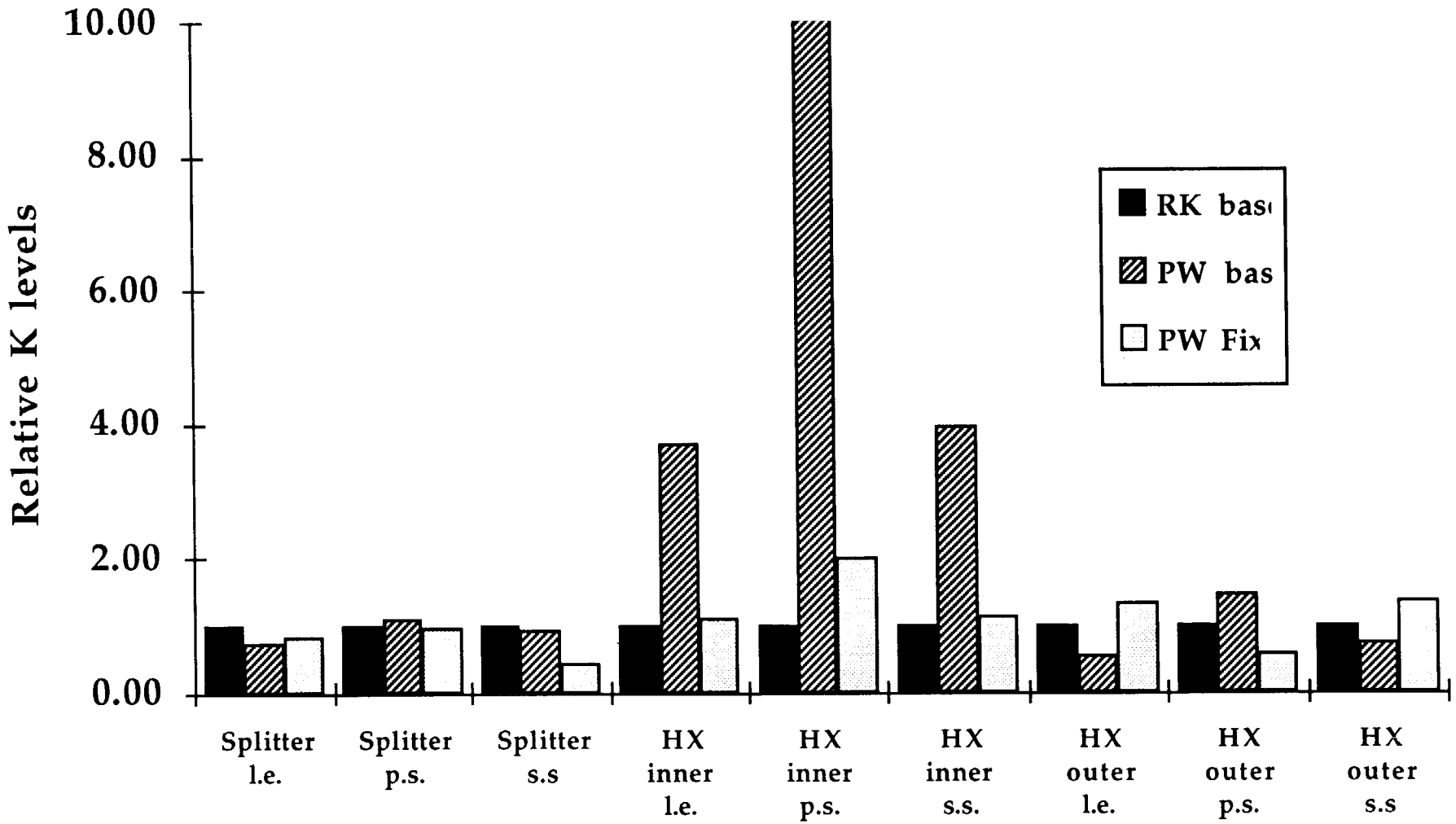
Relative Peak Turbulence Intensity

(Rkdn levels used as reference at each loca



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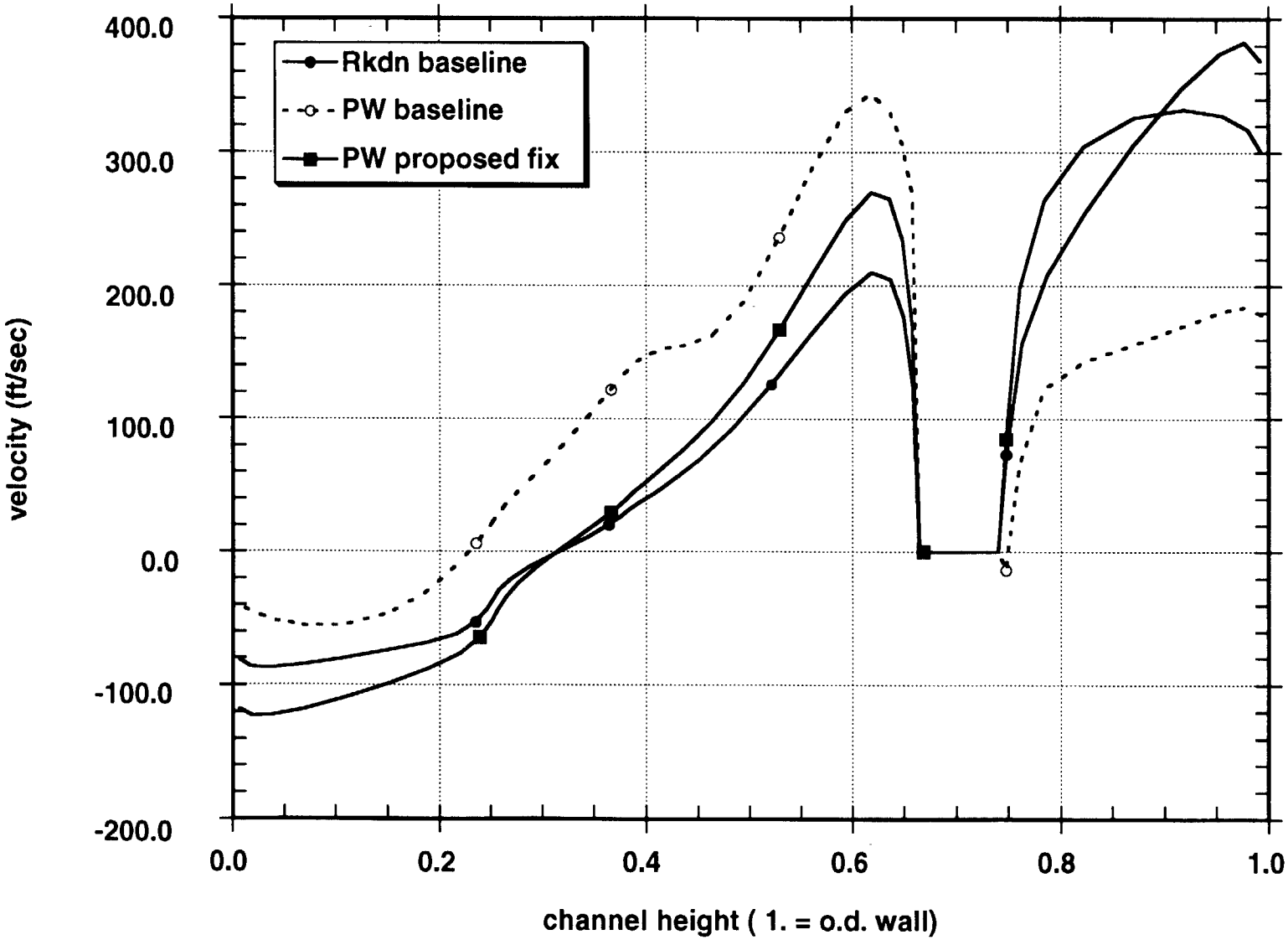
Velocity Profile at the HX Coils
Axial Velocity