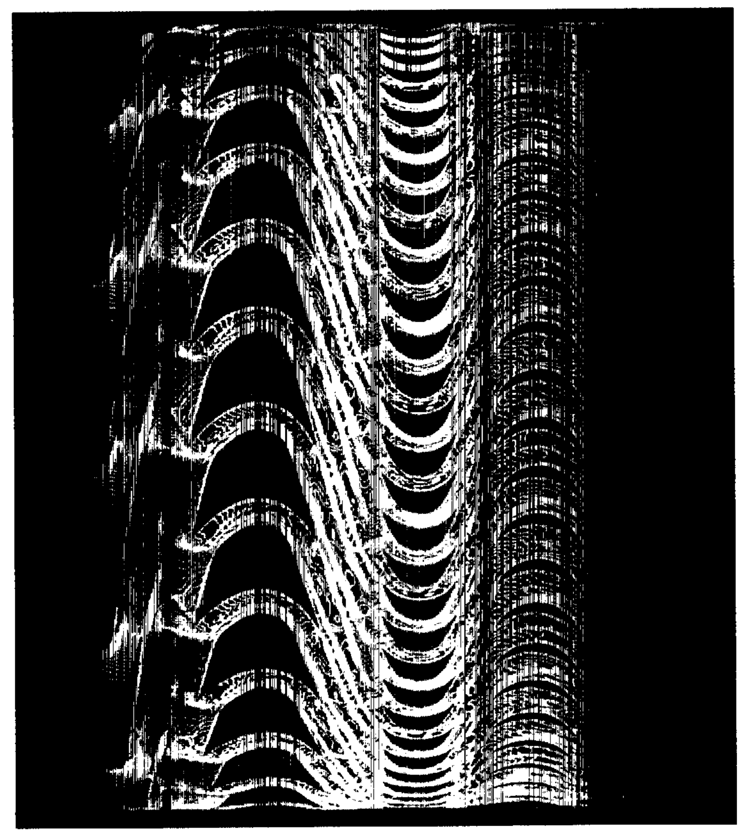
Turbine Performance Optimization Task Status



Presented by:
Lisa W. Griffin
Applied Fluid Dynamics Analysis Group
NASA/Marshall Space Flight Center

MSFC Fluid Workshop
April 4-5, 2001

Overview

- Introduction
- Goals and Objectives
- Team Members
  - MSFC
  - Industry and academia
- Approach
- Results
  - Preliminary design
  - Detailed design
- Lessons Learned
- Testing
- Summary and Conclusions

Introduction

- **Turbine performance optimization** → **Increased reliability**, **Higher Isp**, **Higher thrust-to-weight**

Turbine temperature
Engine Isp
Thrust-to-weight

are proportional to **Turbine efficiency**

- **Unsteady aero loads impact efficiency and life**

Capability to optimize for turbine performance and accurately predict unsteady loads will allow for increased reliability, Isp, and thrust-to-weight. The development of a fast, accurate aerodynamic design, analysis, and optimization system is required.

Example

- This task began in 1999, when the engine under consideration for the next generation RLV utilized a gas generator cycle.
- For a gas generator cycle, mass flow rate through the turbine must be minimized, and the power is produced predominately through work
- There are two options for achieving high work
  - Increasing available energy
  - Extracting energy more efficiently

Example

- **If option 1 is chosen**
  - High inlet temperatures required
  - Ceramic material needed

Viability of ceramic materials unproven for this application making the turbine one of the highest risk components in the engine

- **If option 2 is chosen**
  - Temperature can be reduced

    or
  - Mass flow rate can be reduced

An efficiency increase of 8 points reduces mass flow rate by ~ 10% which increases Isp by approximately 1.5 sec., corresponding to more than 1500 lbm of payload

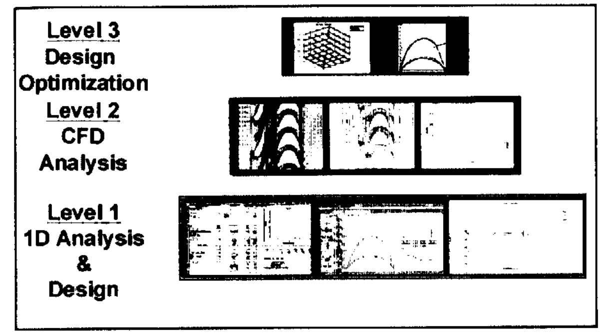
Goals and Objectives

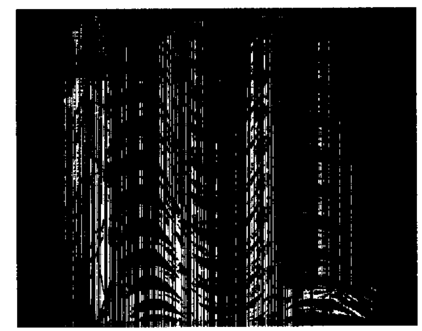
Goal: Develop and demonstrate advanced design and analysis tools for optimized turbine performance

- Develop advanced turbine aerodynamic design procedure
- Apply advanced design procedure to an RLV fuel turbine to improve efficiency

Baseline Efficiency → + 8 points (goal)

- Verify design and analysis with testing in air at MSFC





Team Members - MSFC

- **TD64**
  - Preliminary and detail aerodynamic design
  - CFD code enhancement
  - CFD analysis
- **TD62**
  - Rig mechanical design
- **ED21**
  - Rig structural dynamics
- **ED22**
  - Rig stress analysis
- **TD55**
  - Rig rotordynamics analysis
- **TD63**
  - Cold flow testing
  - Unsteady flows and acoustics
- **TD74**
  - Cold flow testing facility

Team Members - Industry and Academia

- **Rocketdyne**
  - Aerodynamic design
  - Systems analysis
  - Test support
- **Riverbend Design Services- Frank Huber**
  - Design code development
  - Aerodynamic design
  - Test support
- **University of Florida**
  - Optimization methodology development
  - Optimization application
- **Rig fabrication vendor - TBD**
- **Kulite/Oxford**
  - On-blade instrumentation and calibration

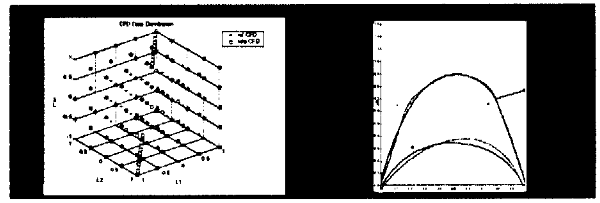
Approach

- **Determined what was missing from traditional design process**
  - Ability to efficiently explore large design space for both preliminary and detail design
  - Design optimization
- **Developed a plan to address requirements for an advanced design procedure**

Developed, enhanced, and assembled the pieces of the design process to enable the advanced aerodynamic design procedure

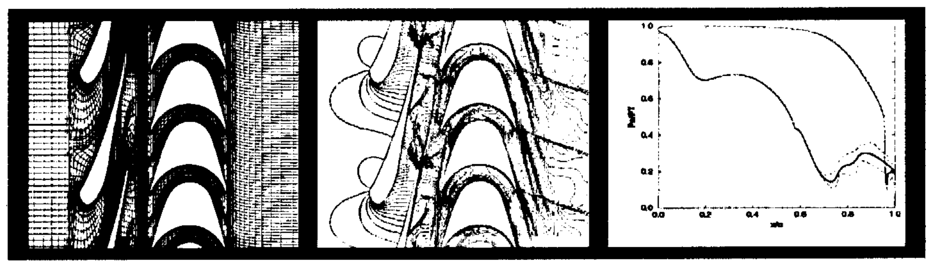
Turbine Aerodynamic Design

Level 3
Design Optimization



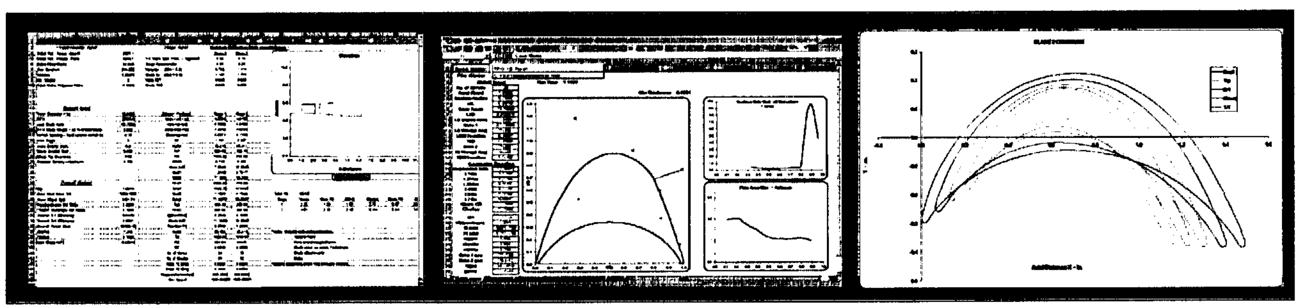
Design Space　　Optimized Design

Level 2
Detailed CFD Analysis



Grid Generation　　CFD Analysis　　Post-Processing

Level 1
1D Analysis & Design



Meanline Analysis　　Geometry Generation　　Radial Faring and Stacking

Optimization levies heavy requirements on lower levels.
Each level required development, enhancement, and integration to achieve an overall advanced aerodynamic design process

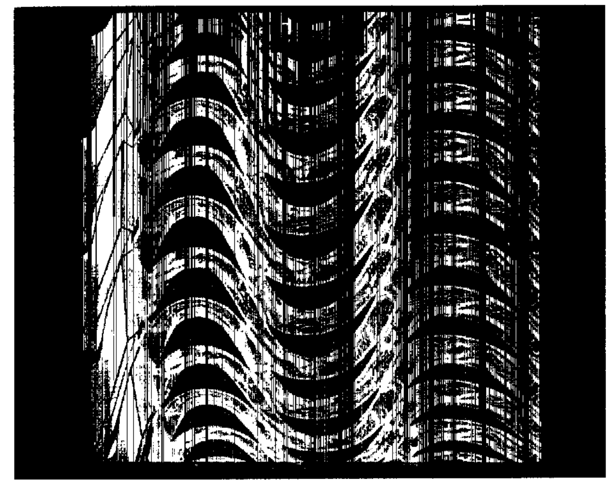
Approach

- **Requirements for advance design procedure**
  - Improve preliminary design tools
    - Improve performance modeling for rocket turbines
    - Improve flexibility to enable rapid predictions for large design space
    - Integrate with optimizer
  - Improve detail design tools
    - Improve flexibility to enable rapid generation of airfoil shapes for large design space
    - Increase efficiency of CFD calculations for a large design space
    - Integrate detail design pieces (geometry generation,grid generation, CFD, post processing)
  - Choose optimization procedures and develop methodology for application
    - DOE techniques for choosing points in design space
    - Response surface methodology
    - Neural Networks

Application

The hot gas path of the turbine for the RLV engine with the gas generator cycle will be redesigned with the goal of improving efficiency by 8 points

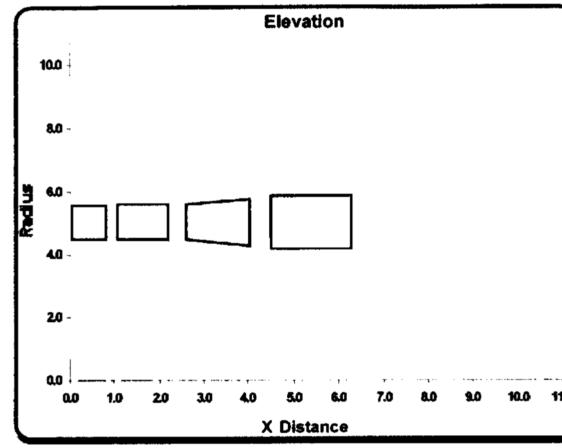
- **Baseline design features**
  - Supersonic turbine
  - 2 stages with ~ 85% of the work done in 1st stage
  - First stage nozzles with rectangular cross sections
  - First stage blades are of impulse type
- **Preliminary and detailed design considered**



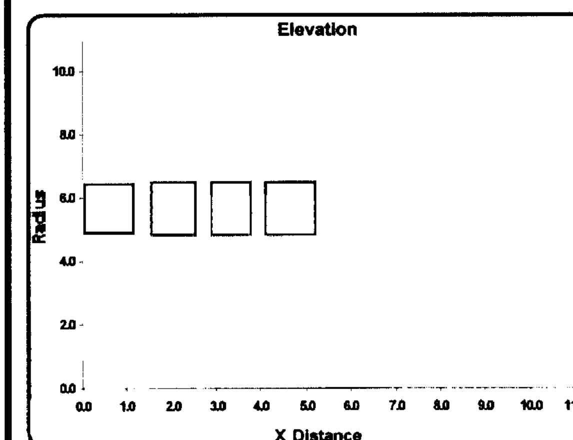
Baseline Turbine CFD Analysis

Preliminary Design Approach

- **Preliminary design**
  - Overall sizing (diameter, chords, etc.) and performance variables (speed, reaction, etc.)
- **Design process- systematic application of RSM computationally coupled to a meanline analysis**
  - Meanline Analysis
    - Predicts performance
    - Calculates gas conditions and velocity triangles
    - Generates flowpath elevation
    - Estimate of turbopump weight
    - Provides initial spanwise distribution of row exit angle
  - Meanline results used to populate the design space
    - DOE technique, FCCD, used to prescribe the set of design points
  - Second order polynomials used to approximate response surface
  - Equation describing the surface interrogated to find maximum or minimum of chosen variable



Baseline



Optimized

Flowpath Elevations

Results - Preliminary Design

Design Variables

(Normalized by Baseline Values)

Design Variable	Lower Limit	Upper Limit
Mean Diameter	0.5	1.5
Speed	0.7	1.3
Blade Annulus Area	0.7	1.3
Vane Axial Chord	0.4	1.7
Blade Axial Chord	0.3	1.1
Reaction	0.0	0.5

1 Stage

Design Variable	Lower Limit	Upper Limit
1^{st} Blade Height	0.9	1.5
2^{nd} Vane Axial Chord	0.3	1.8
2^{nd} Blade Axial Chord	0.2	1.1
2^{nd} Stage Reaction	0.0	0.5
Work Fraction(1^{st} Stg)	0.5	0.85

2 Stages

Design Variable	Lower Limit	Upper Limit
3^{rd} Vane Axial Chord	0.2	1.4
3^{rd} Blade Axial Chord	0.2	1.1
2^{nd} Stage Reaction	0.0	0.5
Work Fraction(1^{st} Stg)	0.4	0.8
Work Fraction (2^{nd} Stg)	0.1	0.3

3 Stages

Chose design variables with first order effects on performance

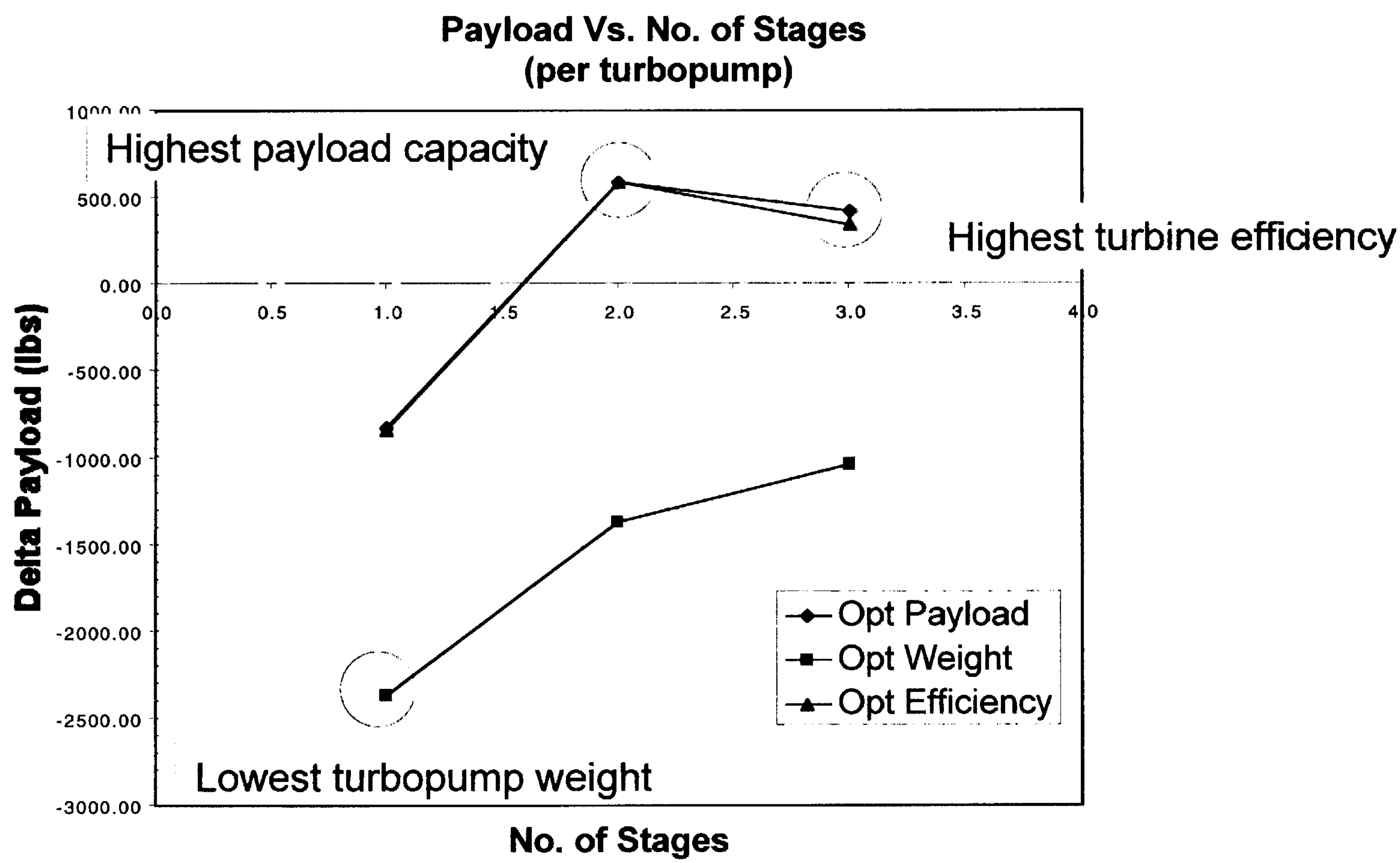
Results - Preliminary Design

- **Fixed parameters**
  - Inlet total pressure
  - Inlet total temperature
  - Total-to-static pressure ratio
  - Mass flow rate
- **Design Constraints**
  - Limit on AN^2
  - Limit on pitchline velocity
- **Three sets of optimizations performed**
  - Total-to-static efficiency
  - Turbopump weight
  - Payload capacity

Results - Preliminary Design

- **Approximately 1100 parametric preliminary design cases were analyzed using the advanced preliminary design code**
  - Each case required less than 1 second to run on an Apple Macintosh
- **System correlation developed for payload capacity as a function of the chosen design variables, efficiency, and turbopump weight**
- **Optimal design chosen as the one producing highest payload capacity (+700 lbs. per turbopump)**

Results - Preliminary Design Optimization

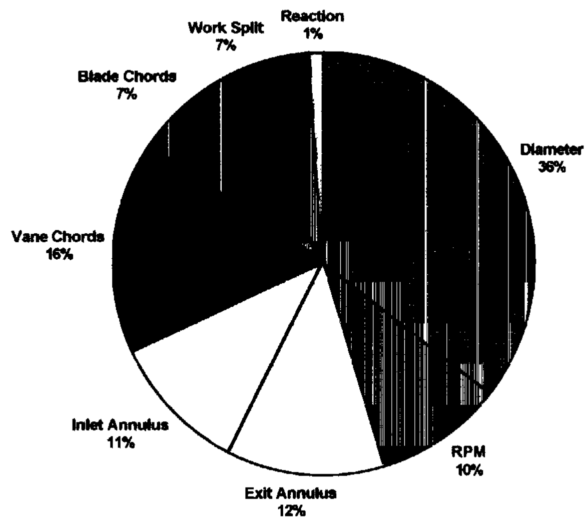


Neither highest efficiency nor lightest weight corresponds to highest payload

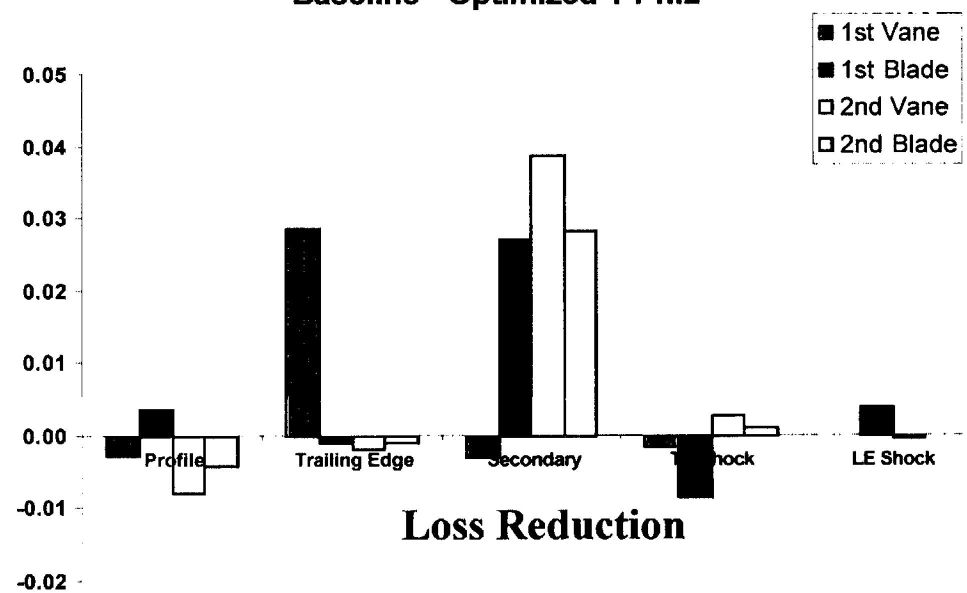
Areas of Performance Improvements

Design Variable	Value
Mean Diameter	1.12
Speed	1.02
Exit Annulus Area	1.08
1st Blade Height	1.50
1st Vane Axial Chord	1.30
2nd Vane Axial Chord	0.79
1st Blade Axial Chord	0.71
2nd Blade Axial Chord	0.62
Reaction (1st Stg)	0.10
Reaction (2nd Stg)	0.50
Work Fraction (1st Stg)	0.90

Optimized Design Variables



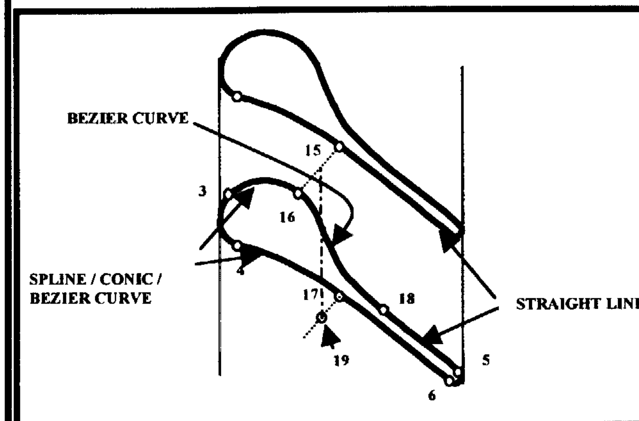
Design Variables



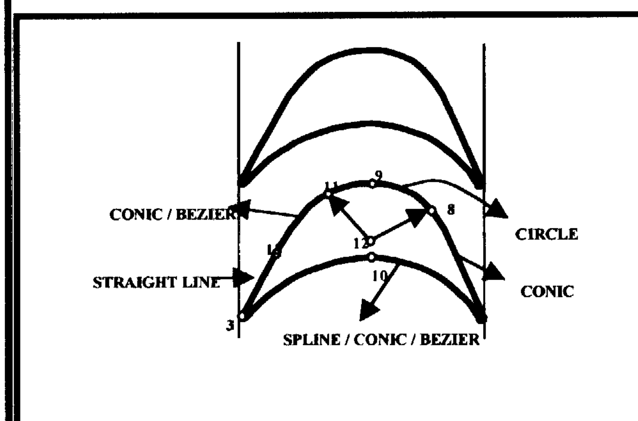
Loss Reduction

Detailed Design Approach

- **Detailed design**
  - Detailed vane and blade shapes, final sizing and performance, and clearances chosen
- **Design Process - CFD, RSM, and neural nets**
  - CFD
    - Wildcat (quasi 3D) and Corsair (3D)
      - Parallelized
      - Unsteady
      - Navier-Stokes
      - Moving grids
  - CFD results used to populate the design space
    - DOE technique, orthogonal array design, used to prescribe the set of design points
  - Neural nets trained with CFD results to augment number of points used to generate surface
  - Third order polynomials used to approximate response surface
  - Equation describing the surface interrogated to find maximum or minimum of chosen variable



Nozzle Design



Blade Design

Detailed Design of a Supersonic First Stage

Approach

- **Detailed design steps**
  - Generate and optimize the mean airfoil contours
    - Airfoils were generated using a geometry generator which can read the matrix of design variables, generate and plot the airfoil, and write a "first cut" input file for the grid generator
    - Because of the large amount of loss attributed to interactions between the first two rows, unsteady calculations were performed for the stage
      - Parametrics were performed for the vane first with the baseline blade
      - Parametrics were then performed for the first blade with the optimized blade
      - Stage efficiency chosen as objective function
  - Generate the 3D vanes and blades
    - As a start, vanes and blades had constant sections from hub to tip
    - Blades twisted according to meanline predicted spanwise angle distribution
    - Perform CFD analysis of 3D multistage turbine
    - Tweak angle distribution and sections for improved aerodynamics

Results - Baseline Design

- **Baseline geometry was analyzed using Corsair**
  - Flow features typical of supersonic turbine design
    - First stage nozzle with rectangular cross section
    - Strong leading edge shock
    - Strong interactions between first nozzle and blade
    - Separation on first blade

  Undesirable features, but generally unavoidable

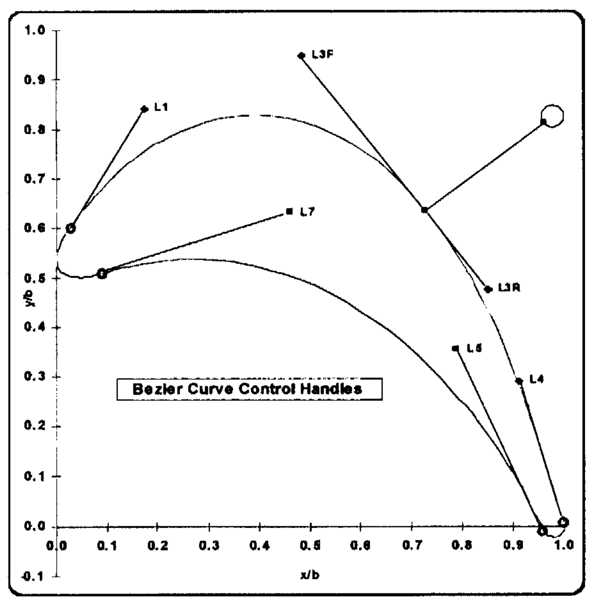
  - Baseline flow features kept in mind as design variables and ranges chosen
  - CFD predicted performance within 2 points of meanline performance

Results - Baseline Absolute Mach Contours

Results - Detailed Design Optimization

Design Variables

Design Variable	Lower Limit	Upper Limit
H/L	0.79	1.19
Uncovered Turning	-1.20	-0.20
L1	0.36	2.00
L3F	0.44	1.76
L3R	0.25	2.00
L4	0.05	1.25
L5	0.13	2.00

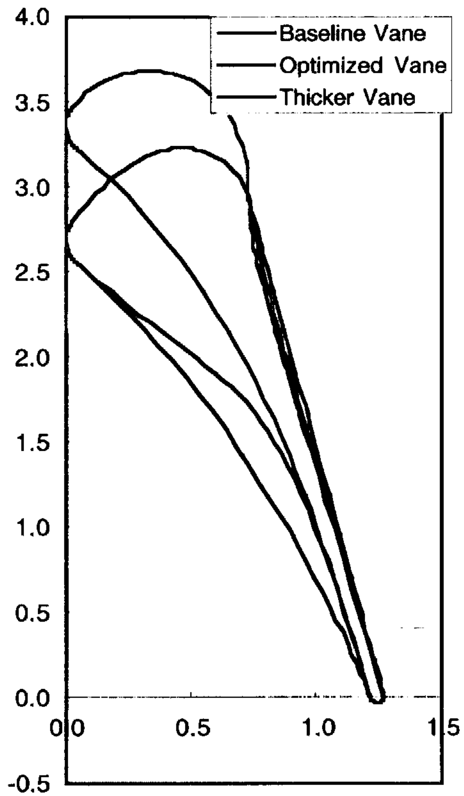


Detailed Design - Mean Contours

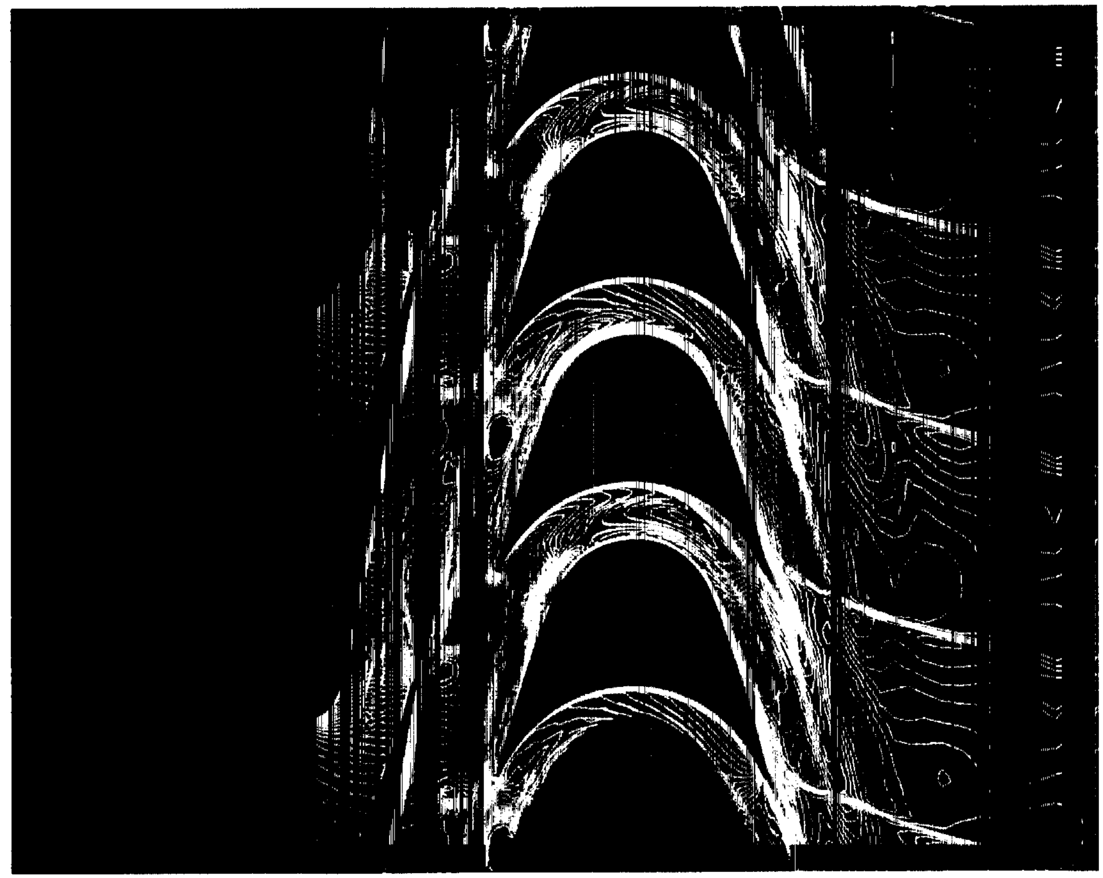
- **Approximately 3000 parametric cases used to populate detail design space**
- **Parametric analysis performed with quasi-3D, unsteady CFD code, Wildcat**
- **Grid densities and distributions chosen**
  - Average y^+ value of the first point off the wall less than 1
  - 15 points in the boundary layer
  - Wakes convected from one row to the next
- **Each case ran on one or two processors of an SGI (Origin 2000, Power Challenge, or Octane) at MSFC**
  - Completion of analysis of all design points required approximately 1 1/2 weeks per row
  - Times per calculation varied depending on which SGI computer had available processors

Results - Detailed Design Optimization

Optimized Vane Shapes



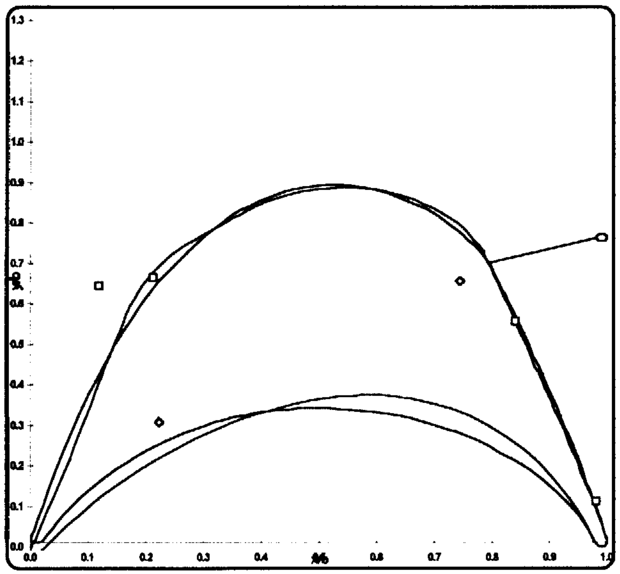
Optimized (Thicker) First Vane Mach Contours



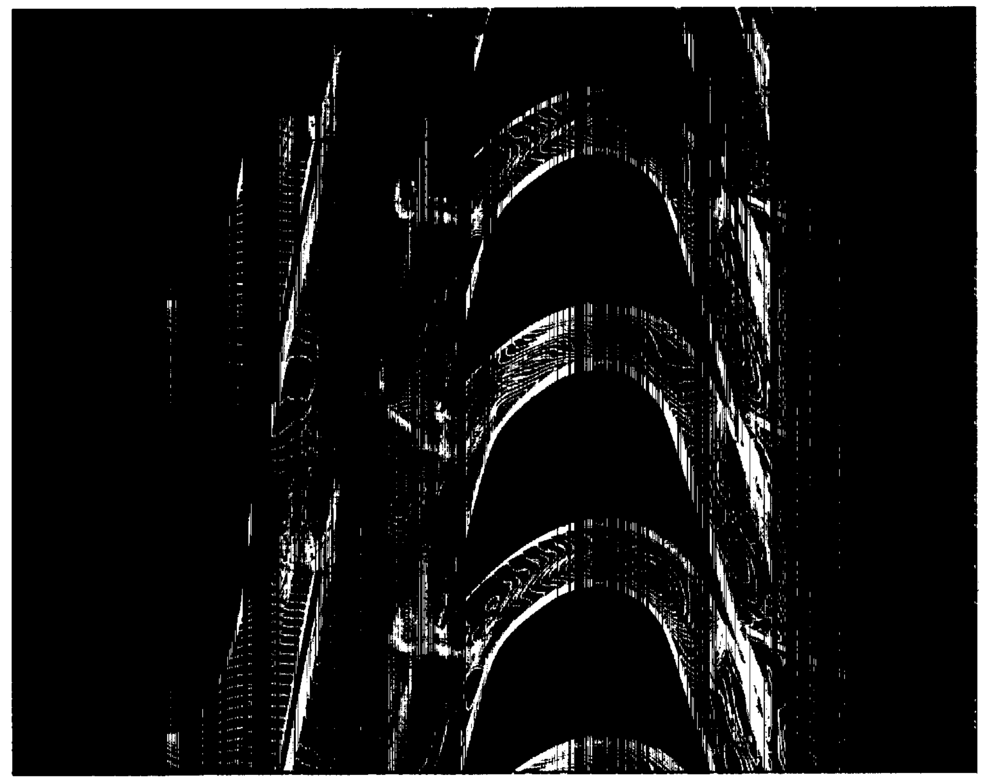
Results from CFD analysis indicated best performance with low H/L and high (less negative) uncovered turning trends in other variables not obvious

Results - Detailed Design Optimization

Optimized Blade Shape



Optimized First Blade Mach Contours

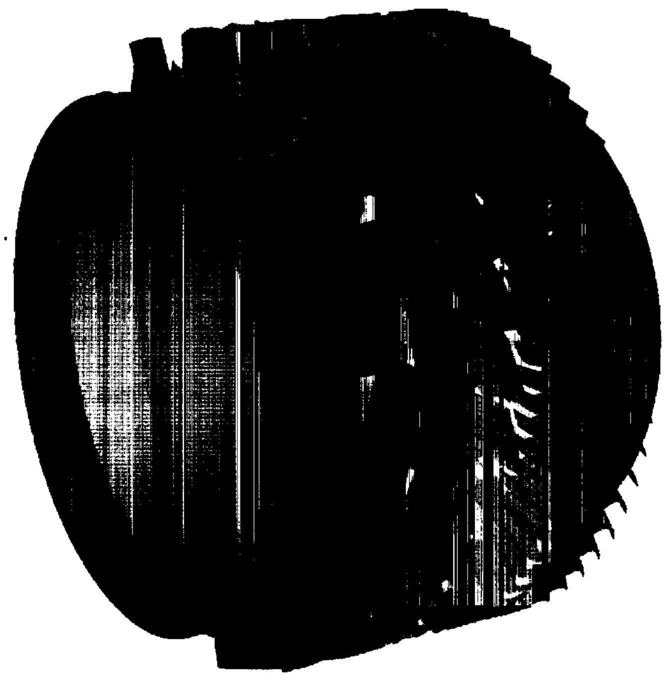


Change in suction side curvature mitigates leading edge shock effects

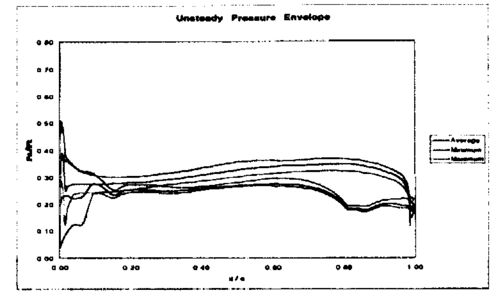
Detailed Design - 3D

- **Six 3D design cases used to populate detail design space**
- **Analysis performed with 3D, unsteady CFD code, Corsair**
- **Each case ran on 24 processors of an SGI Origin 2000 at ARC**
  - Completion of the six CFD analysis, run serially, were completed in 1 week
- **Modifications were made to the vanes and blades based on the analyses**
  - Added 3:1 elliptical trailing edge to 1st vane
  - 1st and 2nd blades twisted according to free vortex
  - 1st and 2nd blade root and tip sections were modified for good channel flow area distribution
  - 2nd blade incorporates a linear taper to reduce centrifugal stress

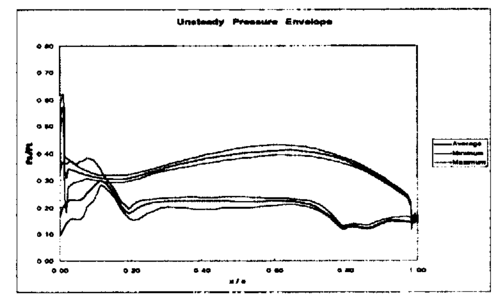
Detailed Design - 3D



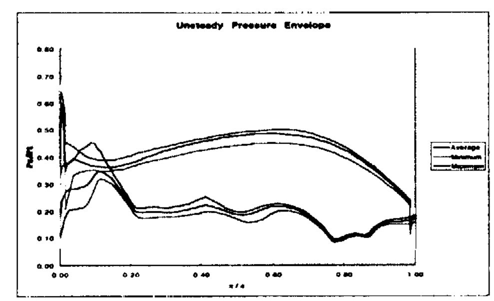
Absolute Mach Contours Near Surface



15% Span



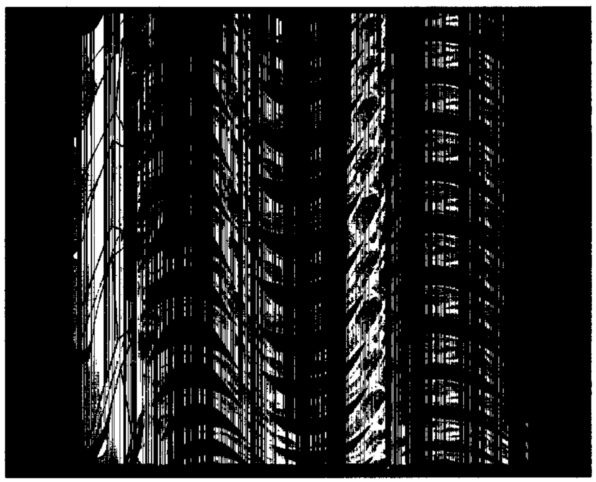
50% Span



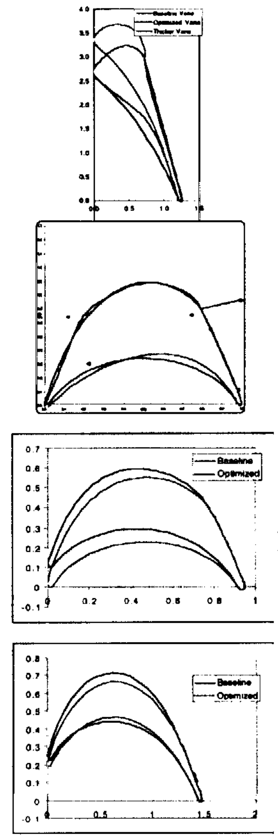
85% Span

Unsteady Pressure Envelopes
1st Blade

Application



Baseline CFD Analysis



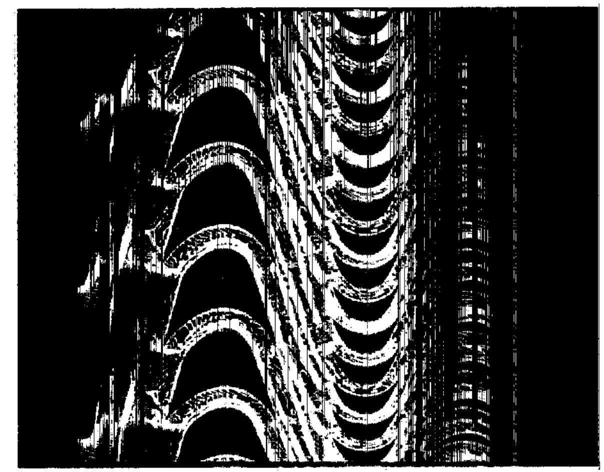
1st Vane

1st Blade

2nd Vane

2nd Blade

Optimized Blade Rows



Optimized CFD Analysis

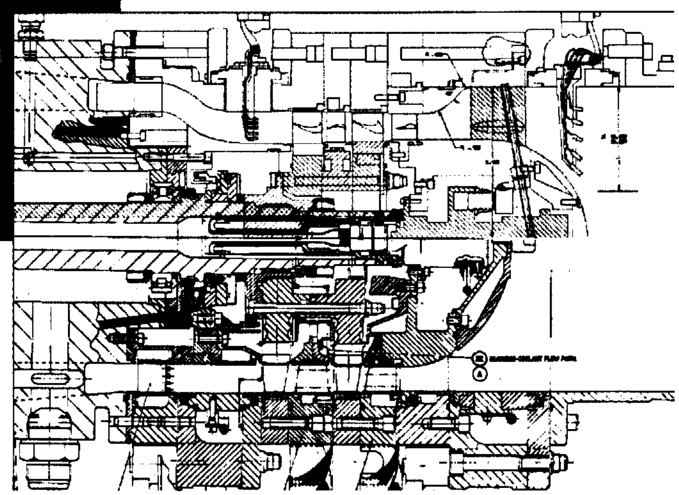
Current improvement in turbine efficiency is 11 points. This can be traded for approximately 230° R in turbine inlet temperature or ~2.25 seconds of Isp, or a combination of the two.

Lessons Learned

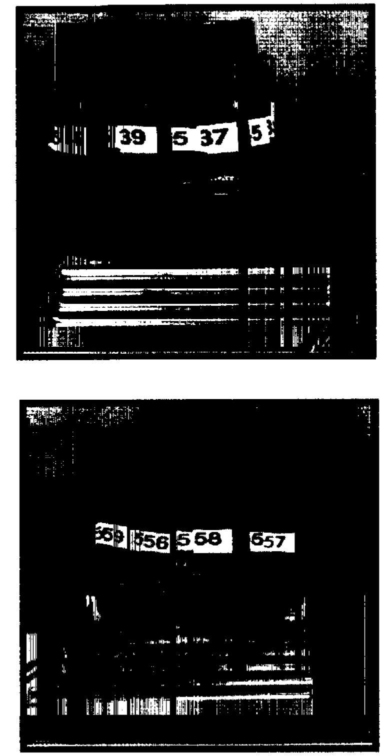
- **Amount of data needed to get a good response surface is VERY large**
  - Using neural nets to augment the data was useful
- **Integration of tools is absolutely necessary for an efficient process**
  - Take the time to integrate and automate. It will save time and misery later.
- **Develop grid templates that will cover the majority of the geometries**
  - In the case, it was impossible to have templates for all cases, but generating grids manually for only 15% of the cases saved a lot of time
- **Quasi-3D calculations should have been run as multistage, not single stage, even if only optimizing a row at a time**
  - Many iterations would have been saved if this had been done
- **Start looking a 3D effects early**

Turbine Air Flow Testing

MSFC Turbine Air Flow Facility



TPO Rig Mechanical Design



SSME HPFTP Turbine Test Article - Instrumented 1st Blades

Testing to be performed at MSFC not only for validation of design and analysis, but also to obtain unique supersonic turbine dataset. Unsteady data on the surface of the first blade will be taken

Summary and Conclusions

- **Task developed to improve turbine performance through application of advanced design and analysis tools**
  - Tools and techniques for preliminary design, analysis, and optimization have been developed
- **Advanced tools have been applied to the preliminary and detailed design of an RLV supersonic turbine with goal of improving efficiency by 8 points**
  - Aero design is complete
  - Efficiency goal has been exceeded
- **Improvements in the application of optimization techniques to detailed design will be explored**
- **Future work will include stronger integration of design and analysis tools**
- **Test rig is currently in mechanical design**
- **Verification testing is scheduled for the winter of 2001**