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Application of Optimization Techniques to Design of Unconventional Rocket Nozzle Configurations

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Abstract

Several current rocket engine concepts such as the bell-annular tripropellant engine, and the linear aerospike being proposed for the X-33, require unconventional three-dimensional rocket nozzles which must conform to rectangular or sector shaped envelopes to meet integration constraints. These types of nozzles exist outside the current experience database, therefore, application of efficient design methods for these propulsion concepts is critical to the success of launch vehicle programs.

The objective of this work is to optimize several different nozzle configurations, including 2-D and 3-D geometries. Methodology includes coupling CFD analysis to genetic algorithms and Taguchi methods, as well as implementation of a streamline tracing technique. Results of applications are shown for several geometry classes including: 3-D thruster nozzles with round or superelliptic throats and rectangular exits, 2-D and 3-D thrusters installed within a bell nozzle, and 3-D thrusters with round throats and sector shaped exits.

Due to the novel designs considered for this study, there is little experience base which can be used to guide the effort and limit the design space. With a nearly infinite parameter space to explore, simple parametric design studies cannot possibly search the entire design space within the time frame required to impact the design cycle. For this reason, robust and efficient optimization methods are required to explore and exploit the design space to achieve high performance engine designs. Five case studies which examine the applications of various techniques in the engineering environment are presented in this paper.

The first study uses two-dimensional CFD coupled to Taguchi methods to determine optimal design parameters for the D-1 test engine being built for the SSTO Advanced Propulsion Technology contract. The D-1 engine utilizes a ring of small thrusters within a larger bell nozzle. This study was used to determine the optimal value of four design variables to achieve the best overall performance during both low altitude (thrusters firing) and high altitude (thrusters not firing) operational modes. Two other case studies investigate the problem of using multidisciplinary techniques to optimize a 3-D thruster design with both genetic algorithms and Taguchi methods. The relative strengths and weaknesses of these two methods are apparent when using them to solve this problem using up to 21 design variables. This thruster is also designed using streamline tracing techniques for the fourth case study.

The final study uses Taguchi methods to determine the optimal 3-D thruster module design when installed in a bell nozzle. This requires full 3-D solutions of the thruster and bell nozzles to quantify module-to-module interaction effects.

Software which couples optimization techniques to CFD have tremendous potential as aerodynamic design tools. However, to function effectively in the engineering environment, the optimization algorithms must be robust and efficent. Several optimization techniques have been demonstrated for rocket nozzle design, and their performance on these real world applications has been assessed.

APPLICATION OF OPTIMIZATION TECHNIQUES TO DESIGN OF UNCONVENTIONAL ROCKET NOZZLE CONFIGURATIONS

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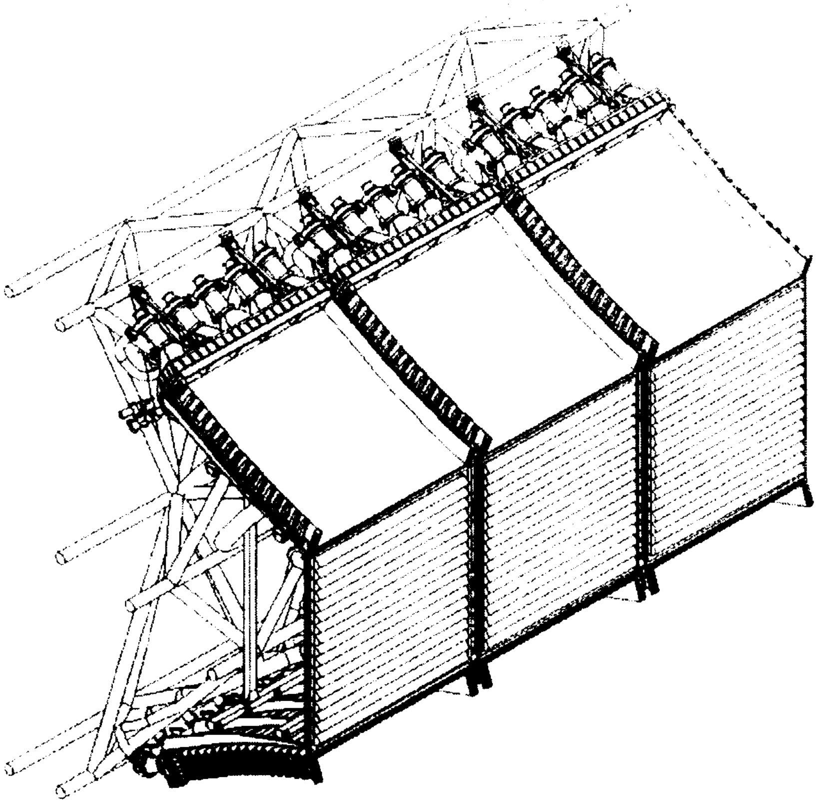
OPTIMIZATION OF UNCONVENTIONAL ROCKET NOZZLE CONFIGURATIONS

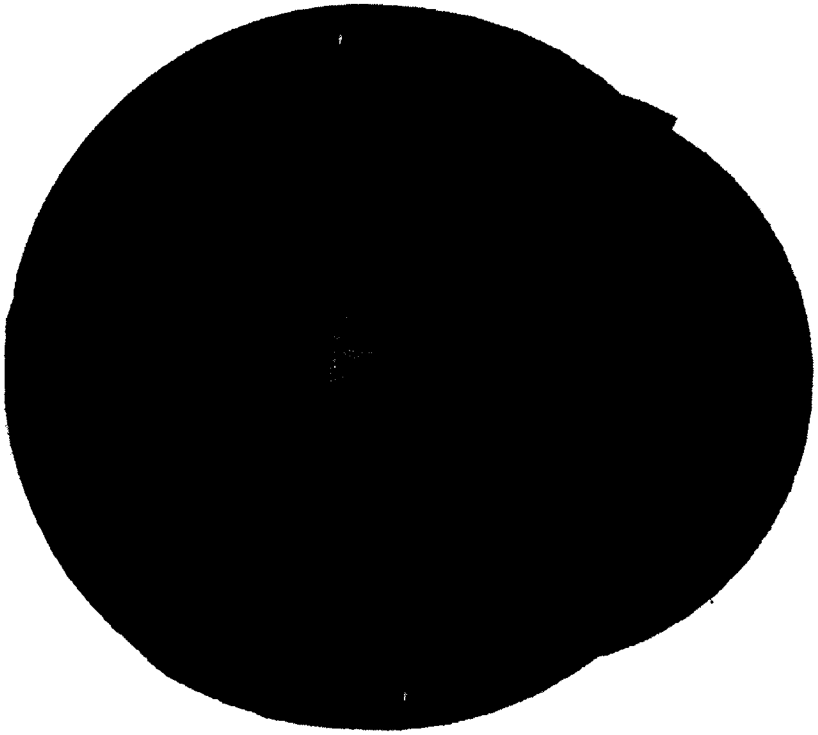
- **APPLICATIONS FOR NASA ADVANCED PROPULSION TECHNOLOGIES CONTRACT AND AIR FORCE MODULAR THRUST CELL CONTRACT**
- **GEOMETRY**
  - BELL-ANNULAR OR AEROSPIKE NOZZLES
  - 3-D THRUSTERS WITH RECTANGULAR OR SECTOR SHAPED EXITS
- **ANALYSIS METHODS**
  - 2-D AND 3-D CFD (EULER AND FNS)
  - 3-D MOC
- **OPTIMIZATION METHODS**
  - TAGUCHI, GENETIC ALGORITHMS, STREAMLINE TRACING

REPRESENTATIVE NOZZLE CONFIGURATIONS

AEROSPIKE



BELL-ANNULAR



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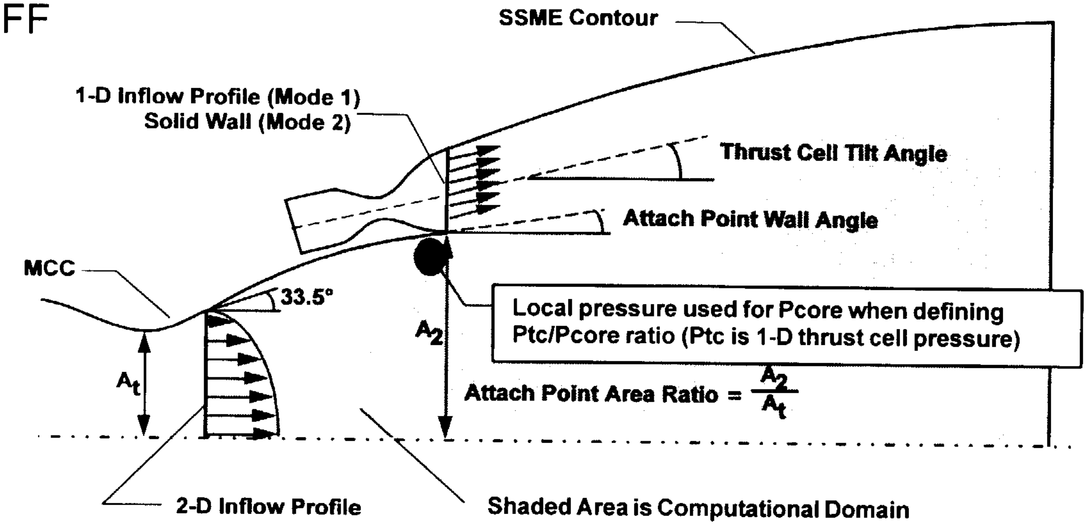
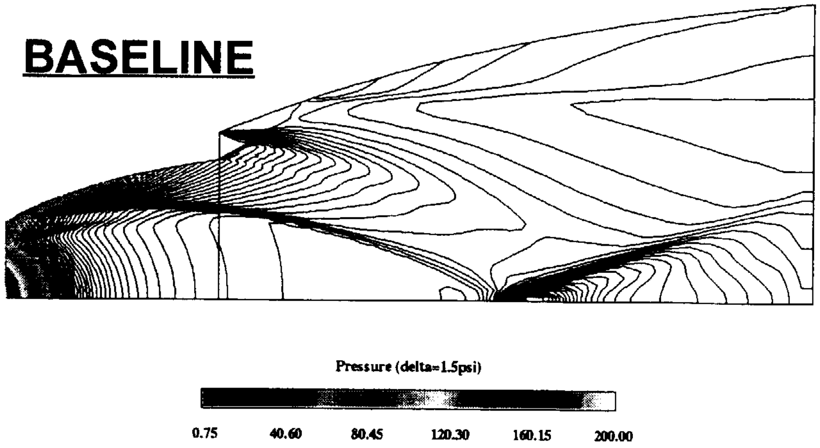
2-D BELL-ANNULAR D-1 TEST ENGINE DESIGN STUDY

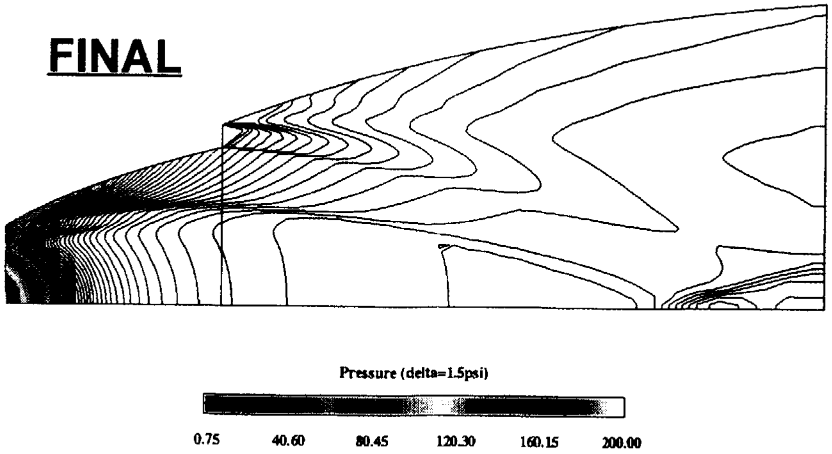
- **OBJECTIVE**
  - MAXIMIZE AVERAGE THRUST, ISP FOR THRUSTER ON AND THRUSTER OFF
- **OPTIMIZATION METHOD**
  - TAGUCHI L9 MATRIX
  - 4 DESIGN VARIABLES
  - 20 2-D CFD EVALUATIONS
- **IMPROVEMENT OVER BASELINE**
  - 1.2% IN THRUST & ISP



BASELINE



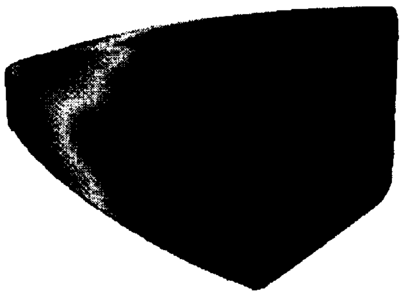
FINAL



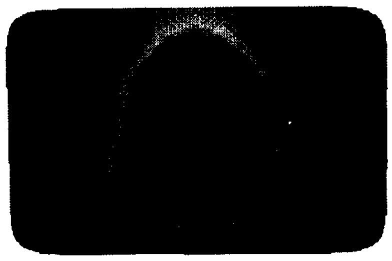
3-D THRUST CELL OPTIMIZATION

- **OBJECTIVE**
  - MAXIMIZE: $\frac{\text{THRUST(THRUSTER ONLY)}}{\text{SYSTEM WEIGHT}}$
  - MINIMIZE PEAK HEAT LOAD
- **OPTIMIZATION METHODS**
  - TAGUCHI L32 & L64 MATRICES
  - GENETIC ALGORITHM
  - 15-21 DESIGN VARIABLES
- **3-D MOC EVALUATIONS**
  - 460 FOR TAGUCHI
  - 1000 FOR GENETIC
- **IMPROVEMENT OVER BASELINE**
  - 4.6% IN THRUST / WEIGHT

Thrust Cell Taguchi Optimum
Mach Number Contours

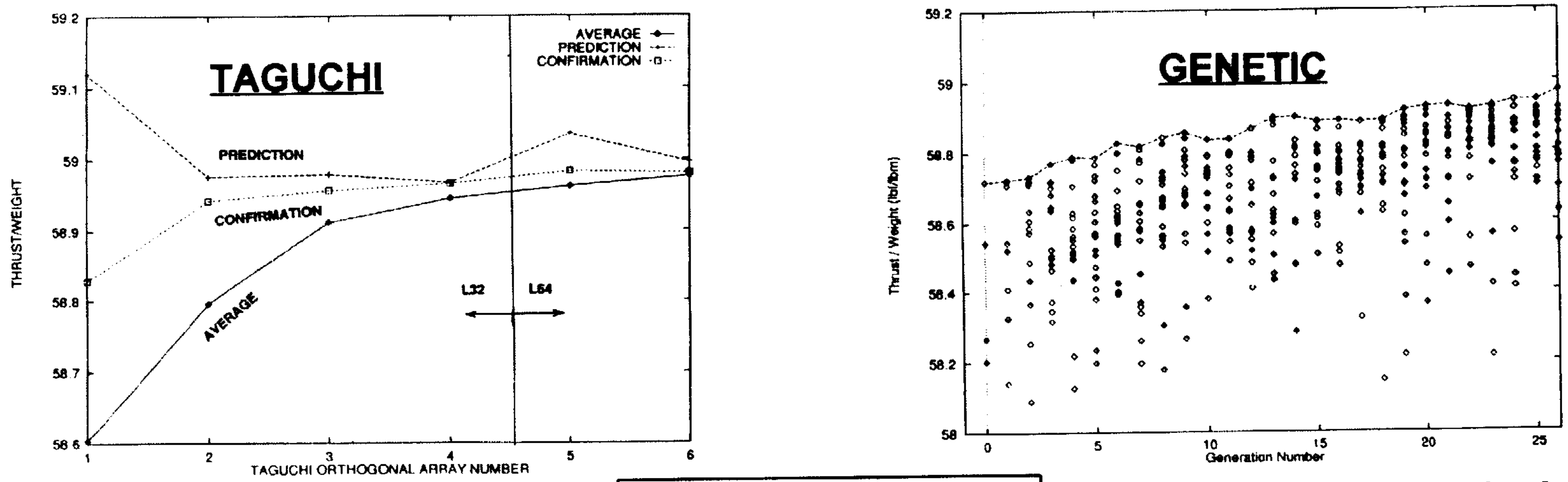


Mach Number Minimum = 1.0
Mach Number Maximum = 4.0



Mach Number Minimum = 3.0
Mach Number Maximum = 4.0

Min **Mach Number** **Max**



CONVERGENCE HISTORIES

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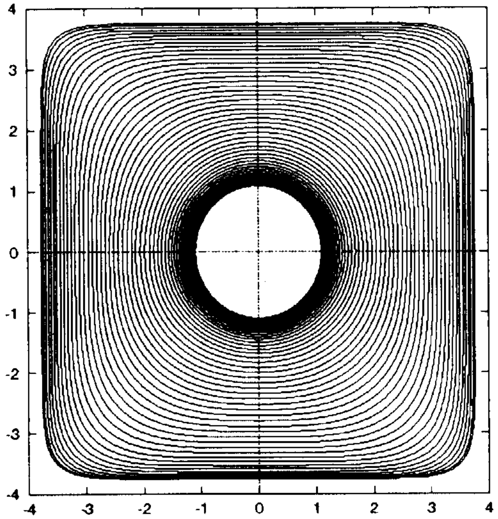
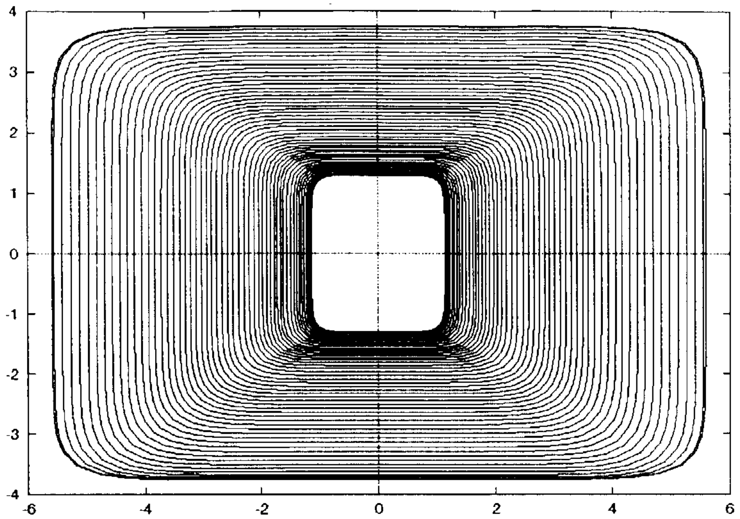
3-D THRUST CELL OPTIMIZATION

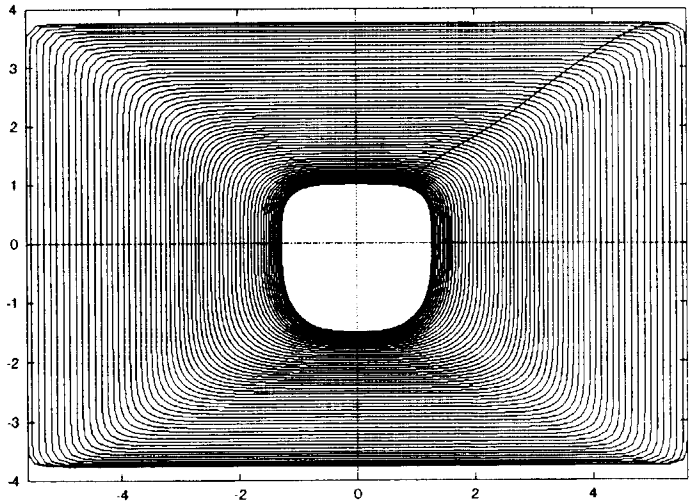
BASELINE
OPTIMIZED FOR AERO ONLY
T/W = 56.39



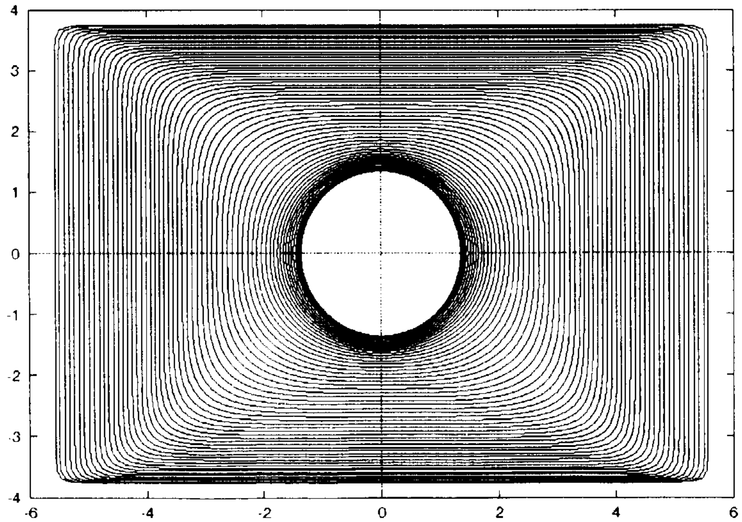
TAGUCHI OPTIMIZATION
T/W = 58.98



GENETIC ALGORITHM OPTIMIZATION
T/W = 58.97



TAGUCHI OPTIMIZATION
RESTRICTED TO ROUND THROAT
T/W = 58.92



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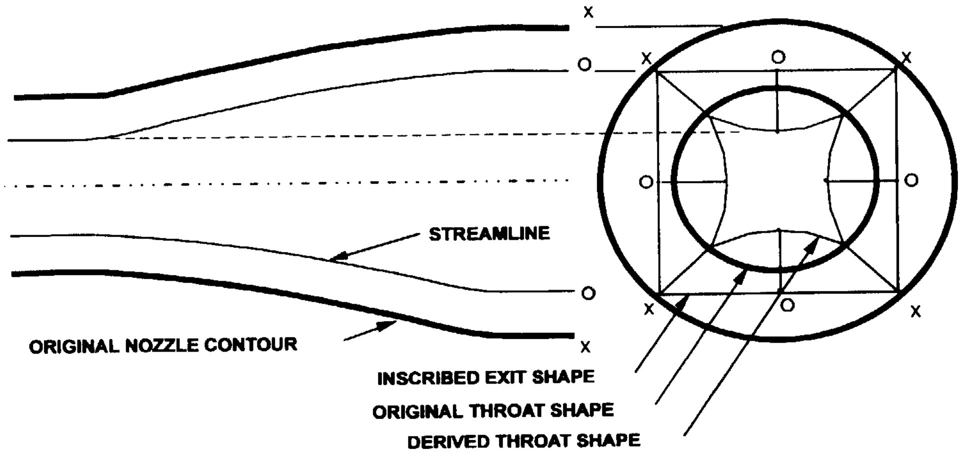
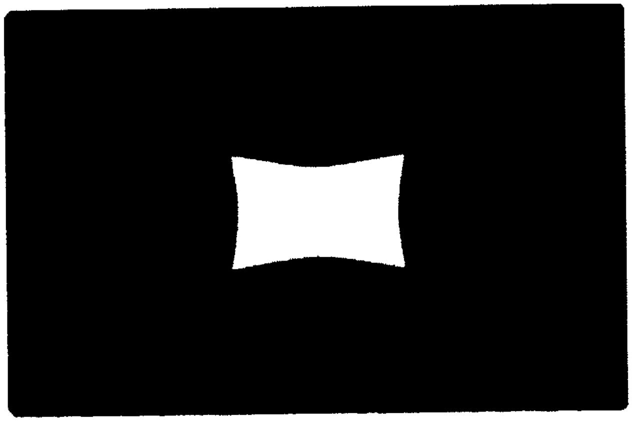
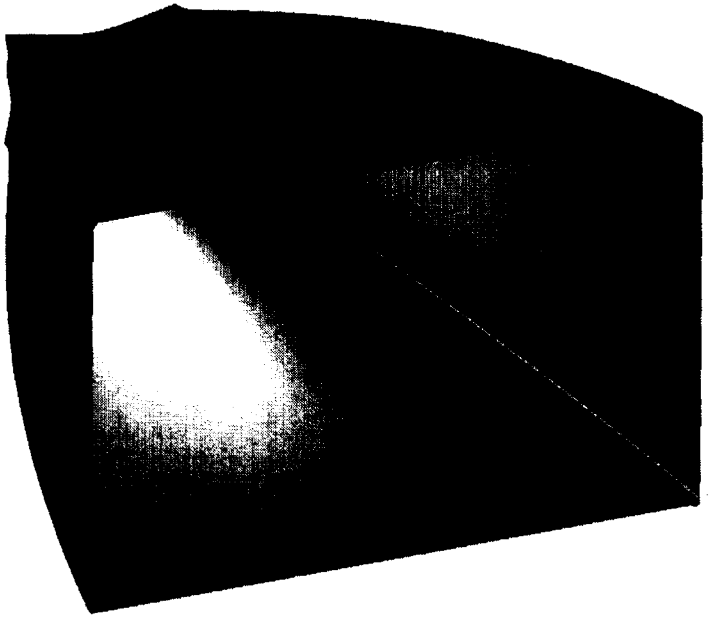
3-D STREAMLINE TRACING METHOD

- **OBJECTIVE**
  - MAXIMIZE THRUST, I_{SP} FOR STAND-ALONE THRUSTER
- **DESIGN METHOD**
  - STREAMLINE TRACING
  - RAO OPTIMUM NOZZLE-MODEL FLOWFIELD
  - THREE 2-D MOC EVALUATIONS
- **PERFORMANCE**
  - 0.15% LESS I_{SP} THAN TAGUCHI & G.A. OPTIMUMS

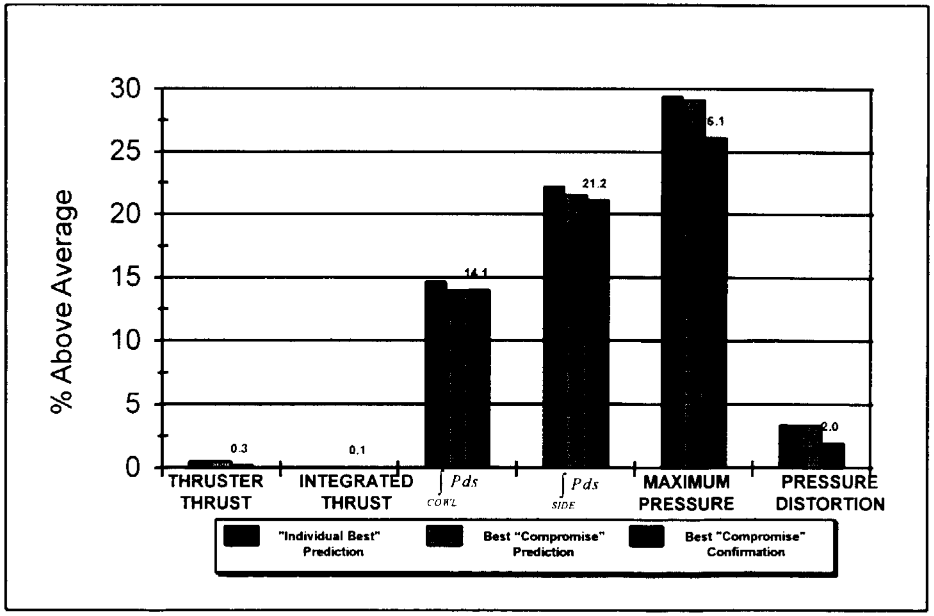




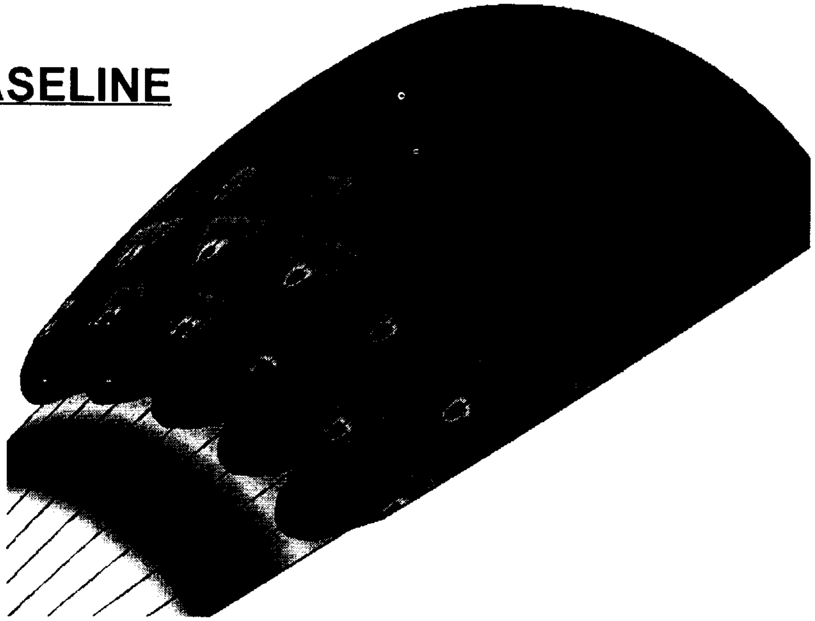


3-D BELL-ANNULAR D-1 INSTALLED THRUSTER DESIGN

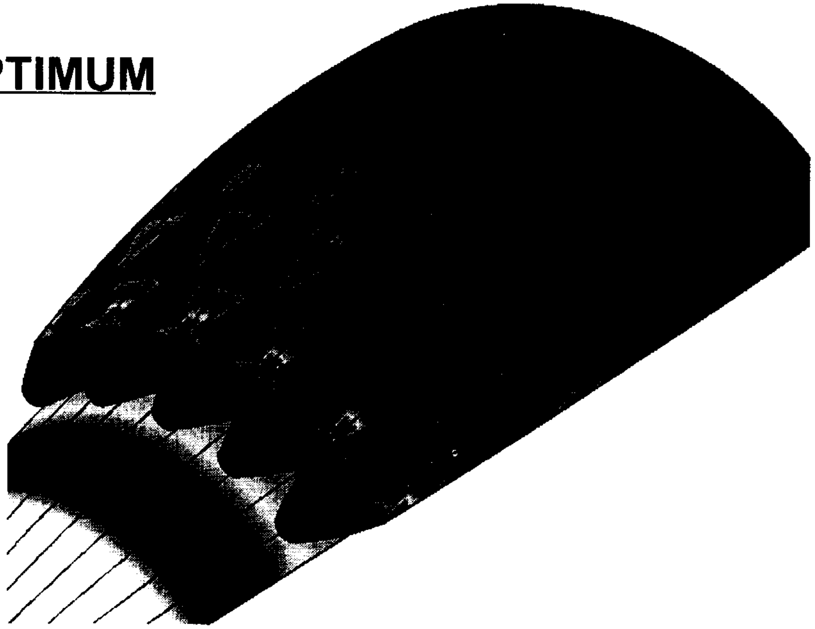
- **OBJECTIVES**
  - MAXIMIZE THRUST, ISP
  - MINIMIZE PEAK HEAT LOAD
- **OPTIMIZATION METHOD**
  - TAGUCHI L9 MATRIX
  - 4 DESIGN VARIABLES
  - 10 3-D CFD EVALUATIONS
- **IMPROVEMENTS OVER BASELINE**
  - 0.1% IN THRUST
  - 23% REDUCTION IN PEAK HEAT FLUX



BASELINE



OPTIMUM



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OPTIMIZATION OF UNCONVENTIONAL ROCKET NOZZLE CONFIGURATIONS

CONCLUSIONS

- **OPTIMIZATIONS METHODS ARE COMBINED WITH 3-D CFD ANALYSIS TO CREATE A VERY POWERFUL AERODYNAMIC DESIGN TOOL**
  - ALLOWS DESIGN IF COMPLEX CONFIGURATIONS WHICH WERE PREVIOUSLY INFEASIBLE
  - PROVIDES HIGH FIDELITY ANALYSIS EARLY IN THE DESIGN CYCLE
- **MULTIDISCIPLINARY OPTIMIZATION IS CRITICAL FOR ROCKET NOZZLE DESIGNS**
  - ROBUST AERO PERFORMANCE ALLOWS DESIGN FLEXIBILITY
  - OTHER CONCERNS (THERMAL, WEIGHT, MANUFACTURING) MAY BE MORE IMPORTANT FOR DELIVERING OPTIMAL “SYSTEM” PERFORMANCE