CFD ANALYSIS OF MODULAR THRUSTERS PERFORMANCE

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ABSTRACT

The effective performance of modular thrusters in an aerospike configuration is difficult to determine. Standard analytical tools are applicable to conventional nozzle shapes, but are limited when applied to an aerospike nozzle (An aerospike nozzle is an altitude compensating external nozzle). Three baseline nozzle shapes are derived using standard analytical procedures. The baseline nozzles sizes are restricted to fill a volume envelope. The three shapes are an axi-symmetric round nozzle, a 2D planar square exit nozzle, and a super elliptic round to nearly square nozzle. The integrated (thruster /aerospike) performance of the three nozzles is determined through the use of 3-D viscous CFD calculations where complex features of the flowfield can be accurately captured. The resulting installed performance is then used to evaluate the efficiency of these nozzle shapes for aerospike applications.

The determination of effective performance of a thruster nozzle integrated into an aerospike nozzle requires the solution of the three dimensional turbulent Navier-Stokes equations. The model used in this study consisted of two zones; one of the upstream thruster cowl surface so freestream conditions can be accurately predicted, and two, the aerospike surface beginning with with thruster outflow and extending to the end of the aerospike surface. The numerical grid consisted of over 120,000 nodes and used symmetry on the thruster centerline and edge. A two species non-reacting chemistry model was used to capture the variation of fluid properties between the hot plume gas and freestream air.

From the results of the three baseline nozzle aerospike calculations, the effective performance of the nozzle was determined. The flowfield of these calculations do show some variation between the cases. Recirculation zones on the cowl surface is predicted for the 2D planar nozzle and a smaller one for the super elliptic nozzle. The recirculation is caused by the strong pressure gradient between the plume and freestream flows. The axi-symmetric nozzle results indicates recirculation zones on the thruster face. These recirculation zones smooth the pressure gradient between the plume and freestream flow limiting the formation of recirculation on the cowl surface. Thruster to thruster interaction is evident for the axi-symmetric and super elliptic calculation while the 2D planar nozzle did not have any lateral expansion in the nozzle so thruster to thruster interaction is limited. The integrated performance results, at the altitude choosen, shows very little variation between the three thruster shapes. This result allows for nozzle shape determination to based on additional considerations (thermal, structural, weight) besides performance.

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Performance Analysis and Applied Fluid Dynamics

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BASELINE COMPARISONS

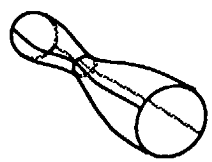
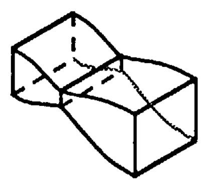
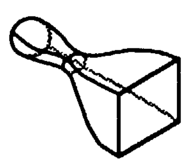
- **GOAL**
  - TO EVALUATE THE PERFORMANCE OF THREE BASELINE NOZZLE SHAPES INDIVIDUALLY AND INTEGRATED INTO AEROSPIKE

- **APPROACH**
  - USE MOC AND CFD CODES TO DETERMINE THE Isp OF THE INDIVIDUAL BASELINE NOZZLES
  - COMPARE THE MOC AND CFD RESULTS FOR CONSISTENCY
  - USE 3D CFD MODEL TO DETERMINE THE INSTALLED BASELINE NOZZLE / AEROSPIKE PERFORMANCE

BASELINE NOZZLE DEFINITIONS

- **3 UNIQUE SHAPES**
  - AXISYMMETRIC
  - 2-D PLANAR
  - 3-D SUPER-ELLIPSE
- **CONSTRAINTS**
  - SAME NOZZLE LENGTH
  - SQUARE EXIT
  - SAME MASS FLOW (THROAT AREA)
- **EACH SHAPE OPTIMIZED FOR Isp**

BASELINE NOZZLE DESIGNS

Baseline Thrust Cell Nozzle	Schematic	Throat Area (in2)	Nozzle Length (in)	Exit Dimension (in)	Nozzle Area Ratio
Axisymmetric		3.7688	11.585	D = 7.519	11.8
2-D Planar		3.7688	11.585	H = W = 7.519	15.0
3-D Super-Elliptic		3.7688	11.585	H = W = 7.519	14.8

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BASELINE COMPARISONS

BASELINE NOZZLE AND ANALYTICAL METHOD COMPARISON

- **MOC AND CFD CALCULATIONS WERE MADE OF EACH BASELINE NOZZLE SHAPE**

NOZZLE SHAPE	EXIT AREA RATIO	MOC INVISCID	CFD INVISCID	CFD VISCOUS
AXISYMMETRIC	11.8:1	409.0	410.6	406.1
2-D PLANAR	15.0:1	414.2	417.0	411.4
3-D SUPER ELLIPTIC	14.8:1	412.9	414.6	409.1*

* VALUE BASED ON LAMINAR CFD PREDICTION WITH SKIN FRICTION ESTIMATED BASED ON PREVIOUS CALCULATIONS AND WETTED SURFACE AREA

- **CONCLUSIONS:**
  - MOC AND CFD PREDICT CONSISTENT RESULTS
  - MOC CODES PROVIDE RAPID ANALYSIS CAPABILITY
  - CFD CODE PROVIDES RANGE OF ANALYSIS OPTIONS

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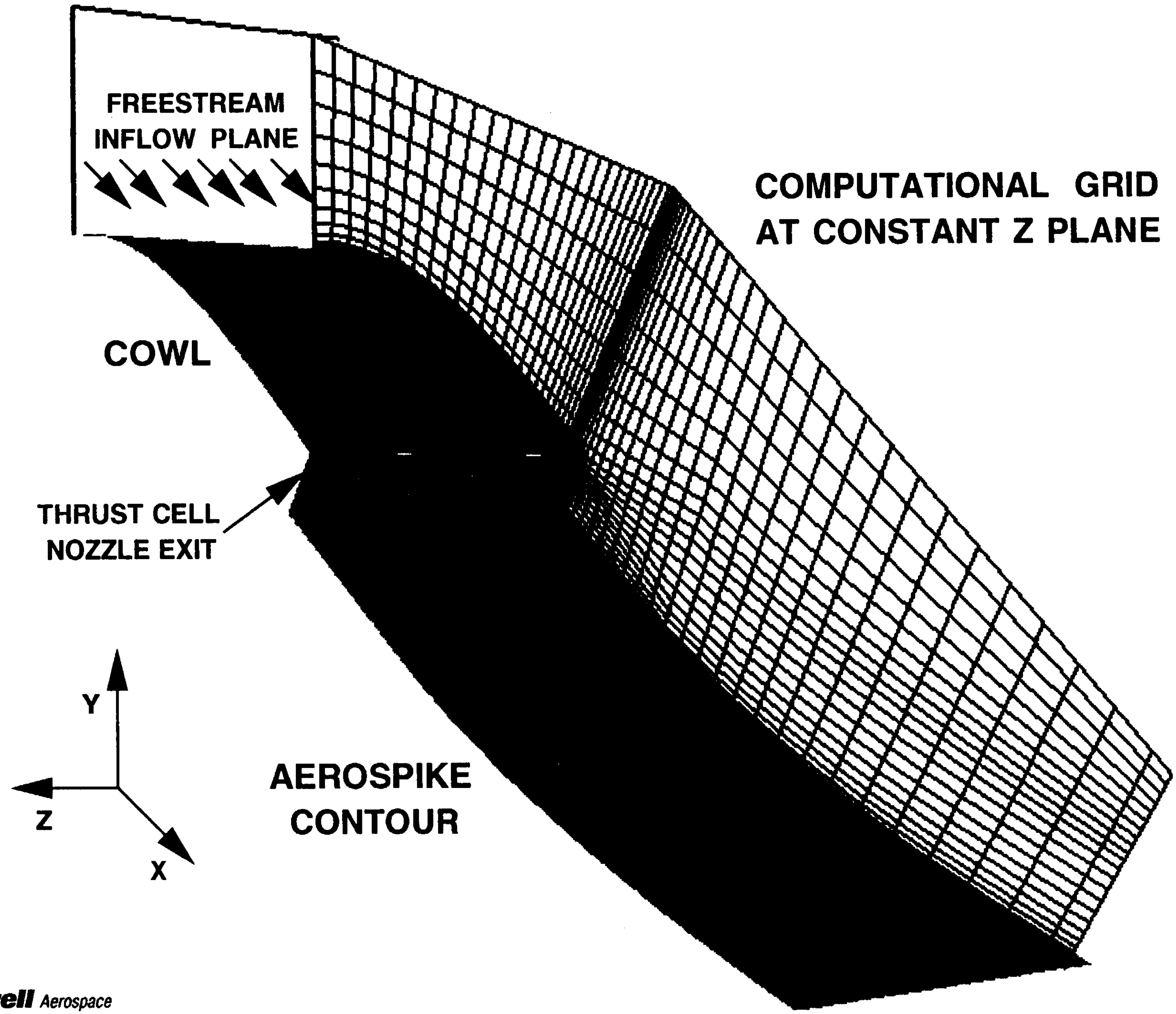
BASELINE COMPARISONS
3-D CFD MODEL

- **FULL NAVIER-STOKES SOLUTIONS**
- **BALDWIN-LOMAX TURBULENCE MODEL**
- **TWO SPECIES (FREESTREAM, PLUME) NONREACTING CHEMISTRY MODEL**
- **TWO ZONE, 125,350 NODE GRID**
  - ZONE ONE INCLUDES FLOW OVER COWL
  - ZONE TWO SIMULATES INFINITE ARRAY OF THRUSTERS AND AEROSPIKE SURFACE
- **FREESTREAM INLET CONDITIONS AT 50,000 FT (MACH NUMBER = 1.83), REPRESENTATIVE OF MIDPOINT OF FLIGHT ENVELOPE**

GEOMETRY OF INTEGRATED THRUST CELL MODEL



BASELINE COMPARISONS

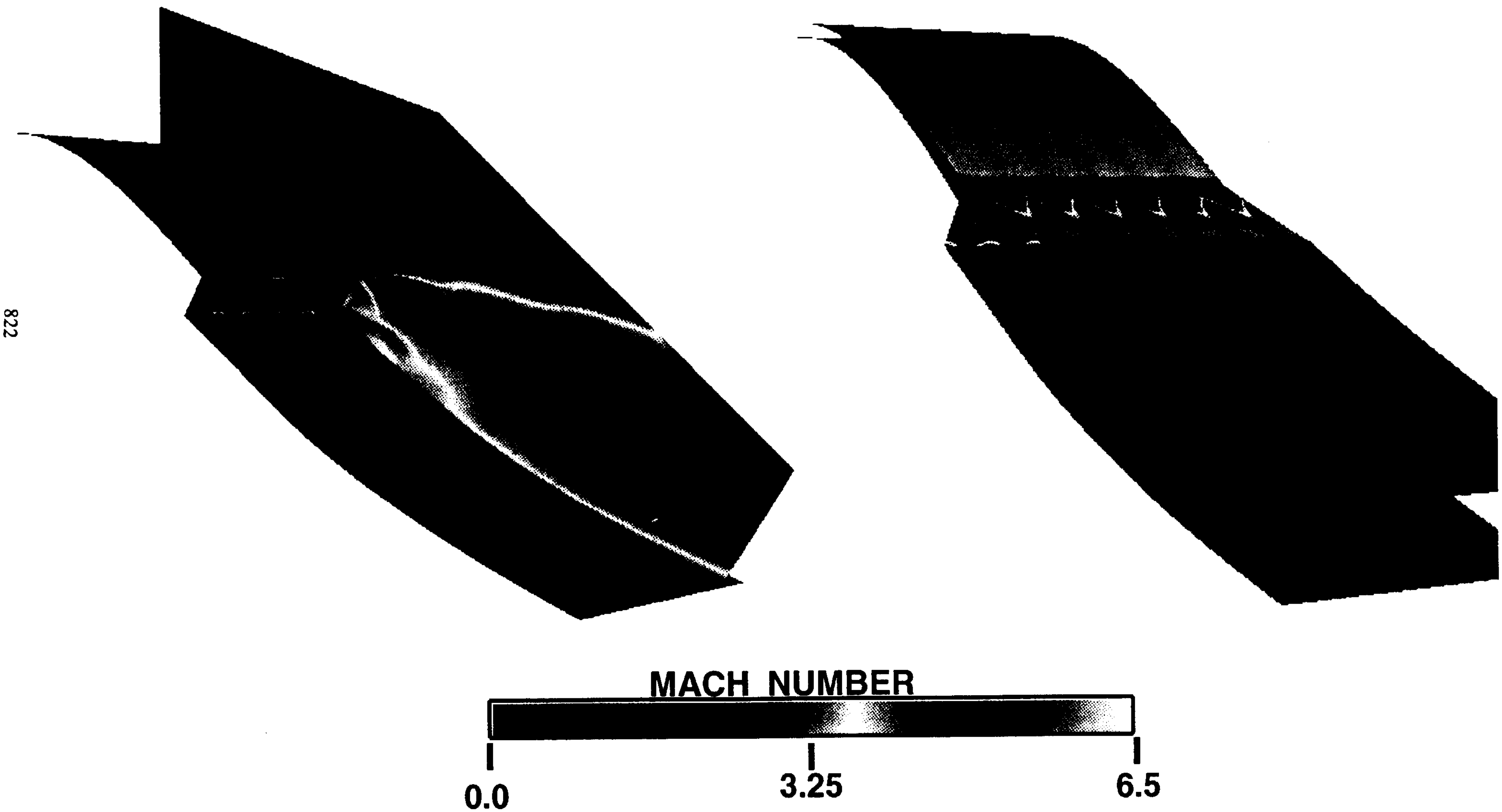
FLOW FEATURES COMMON TO ALL SOLUTIONS

- NORMAL SHOCK UPSTREAM OF THRUSTERS ON COWL SURFACE, DECREASING IN STRENGTH FROM COWL SURFACE
- MODULE TO MODULE INTERACTION CAUSES THREE DIMENSIONAL PLUME SHAPE
- RECIRCULATION REGIONS ON COWL SURFACE AND/OR ON THRUSTER FACE
- MODULE TO MODULE INTERACTIONS ON AEROSPIKE SURFACE
- AEROSPIKE EXPANDS FLOW TO SIMILAR PRESSURE VALUES

THRUST CELL TECHNOLOGIES: INTEGRATED THRUST CELL / AEROSPIKE ANALYSIS

BASELINE INTEGRATED SUPER ELLIPTIC NOZZLE RESULTS:

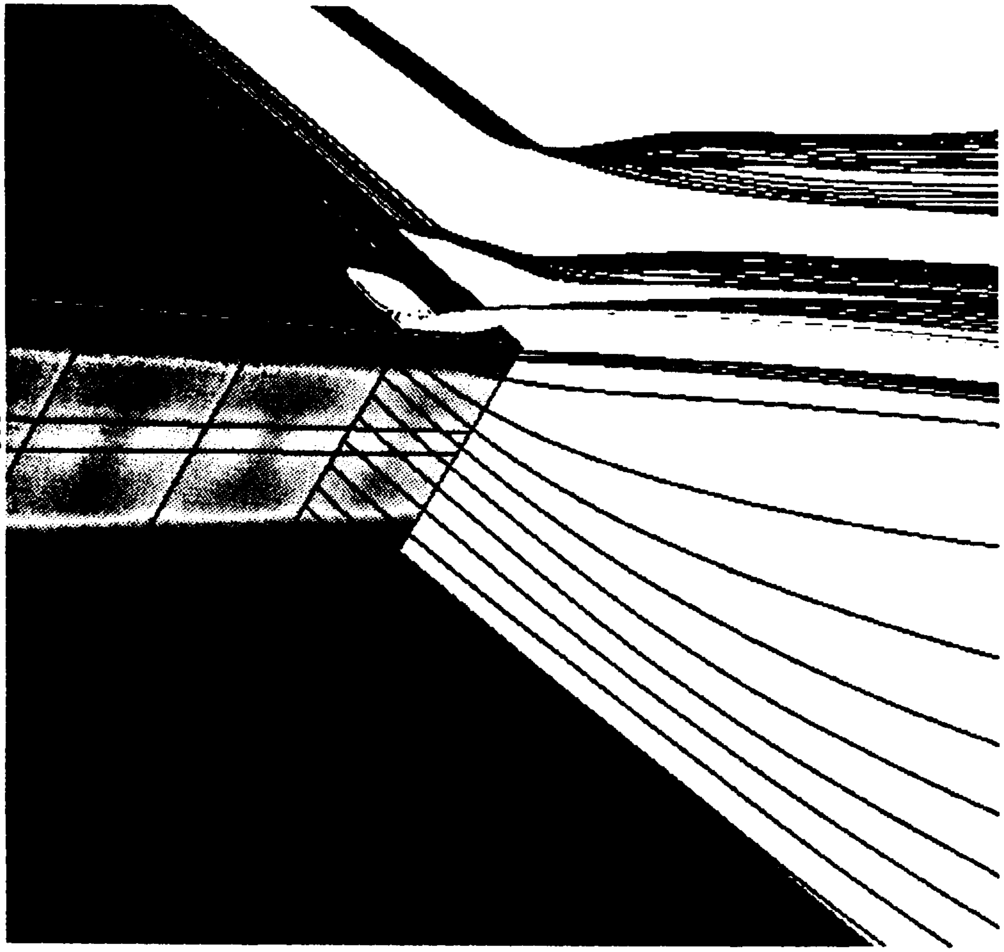
MACH NUMBER CONTOURS IN THE CROSS PLANES



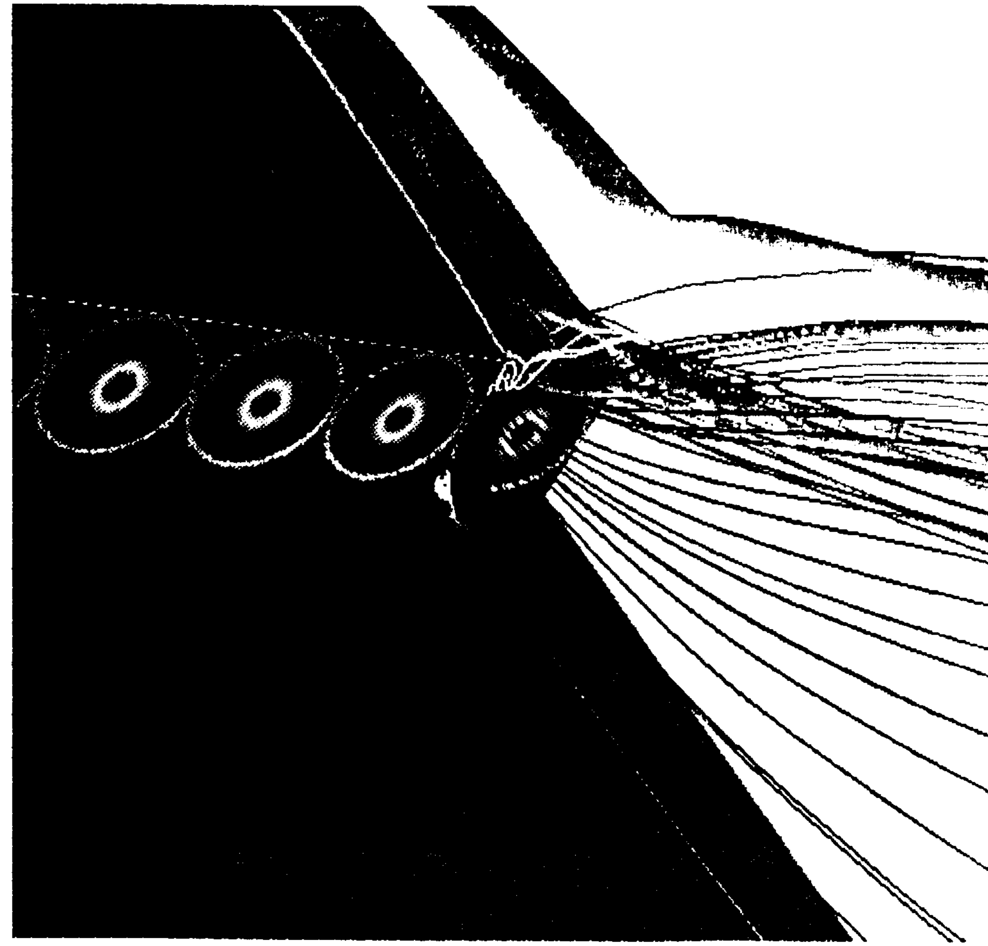
THRUST CELL TECHNOLOGIES: INTEGRATED THRUST CELL / AEROSPIKE ANALYSIS
BASELINE NOZZLE COMPARISON

PARTICLE TRACES

2D PLANAR THRUSTERS



AXISYMMETRIC THRUSTERS



RED: PLUME FLOW

LIGHT BLUE: FREESTREAM FLOW

: RECIRCULATION FLOW

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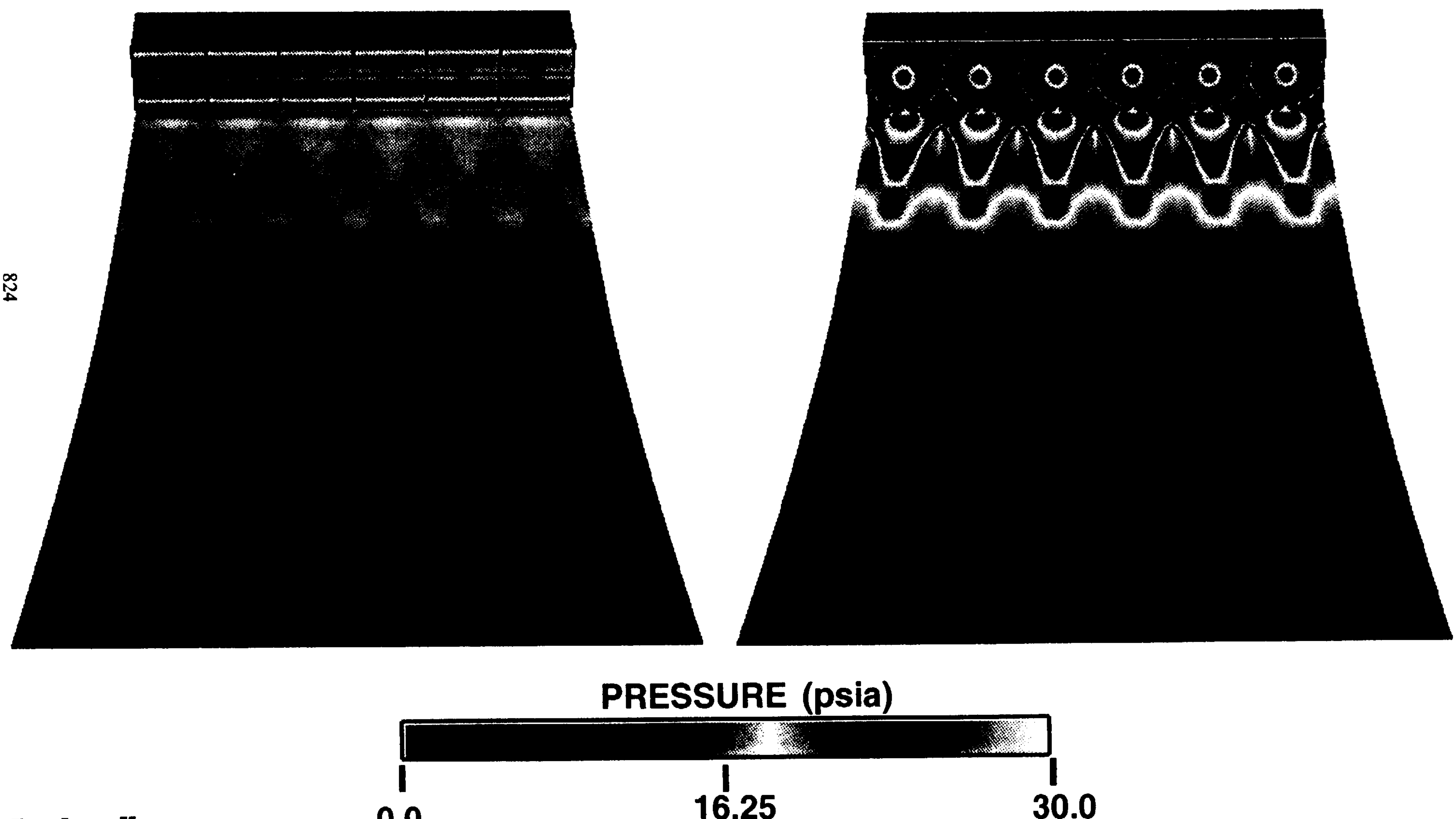
THRUST CELL TECHNOLOGIES: INTEGRATED THRUST CELL / AEROSPIKE ANALYSIS
BASELINE NOZZLE COMPARISON

PRESSURE CONTOURS ALONG AEROSPIKE SURFACE

2D PLANAR THRUSTERS

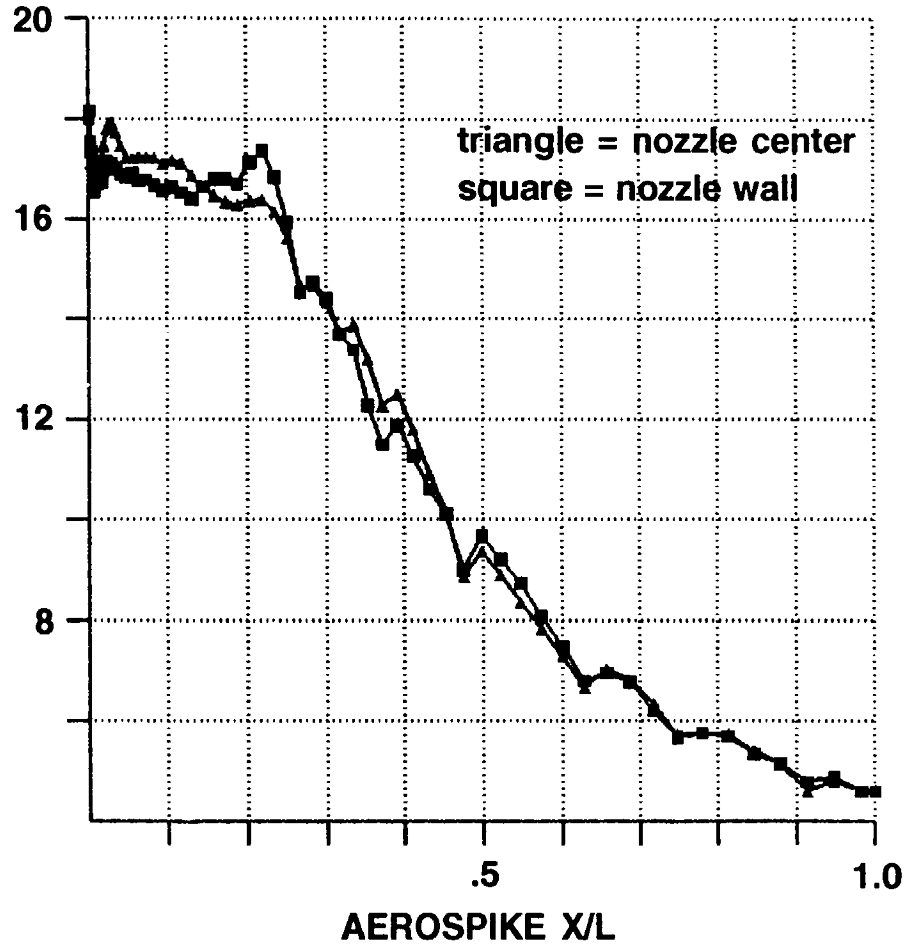
AXISYMMETRIC THRUSTERS



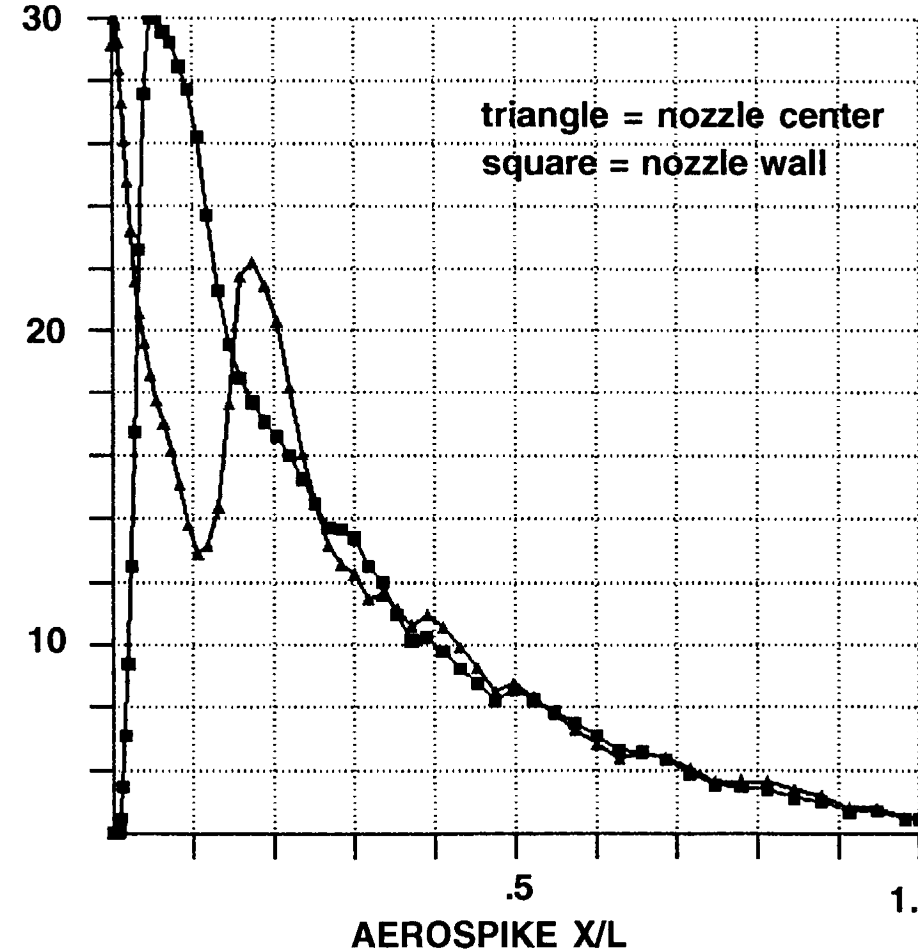
BASELINE NOZZLE COMPARISON

PRESSURE PROFILES ALONG AEROSPIKE SURFACE

2D PLANAR THRUSTERS



AXISYMMETRIC THRUSTERS



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BASELINE COMPARISONS

INSTALLED BASELINE NOZZLE / AEROSPIKE PERFORMANCE

BASELINE SHAPE	NOZZLE THRUST*	FACE PdA*	AEROSPIKE THRUST*	AEROSPIKE FRICTION*	TOTAL THRUST*	Isp (SEC)
AXISYMMETRIC	12403	15	3748	129	16037	**430.2**
2-D PLANAR	12566	--	3554	125	15995	**429.0**
3-D SUPER ELLIPTIC	12493	< 1.0	3660	129	16024	**429.8**

* ALL VALUES LBS

- **CONCLUSIONS:**
  - PREDICTED VALUES OF INSTALLED PERFORMANCE ARE EFFECTIVELY EQUIVALENT
  - SIMILARITY OF PERFORMANCE ALLOWS FOR OTHER DESIGN ASPECTS (EG. THERMAL, STRUCTURAL) TO BE CONSIDERED IN NOZZLE SHAPE SELECTION

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BASELINE COMPARISONS
TASK CONCLUSIONS

- CFD AND MOC PREDICT CONSISTENT RESULTS
- MOC CODES PROVIDE RAPID ANALYSIS CAPABILITY
- CFD CODE PROVIDE RANGE OF ANALYSIS OPTIONS
- INSTALLED BASELINE NOZZLE / AEROSPIKE PERFORMANCE PREDICTIONS FOR THREE NOZZLE SHAPES EFFECTIVELY THE SAME
- SIMILARITY OF PERFORMANCE ALLOWS FOR OTHER DESIGN ASPECTS (EG. THERMAL, STRUCTURAL) TO BE CONSIDERED IN NOZZLE SHAPE SELECTION

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