Rolls-Royce Low Noise Highly Variable Cycle Nozzle for Next Generation Supersonic Aircraft

Dr. Jack S. Sokhey, LibertyWorks®
Matthew Kube-McDowell, Grad. Student, Purdue University

Presented at Fundamental Aeronautics 2008 Annual Meeting
Re: NRA NN06ZEA001N, Contract NNL08AA29C, COTR – Brenda Henderson

Abstract:
An overview of the work performed by Rolls-Royce under contract NNL08AA29C is presented. The work includes computational fluid dynamic (CFD) analysis for, and design of, a highly variable cycle exhaust model for the Supersonic project (NRA NN06ZEA001N). The CFD analysis shows that the latest design improvements to the clam shell doors have increased flow through the ejector over that achieved with previous designs.

Rolls-Royce

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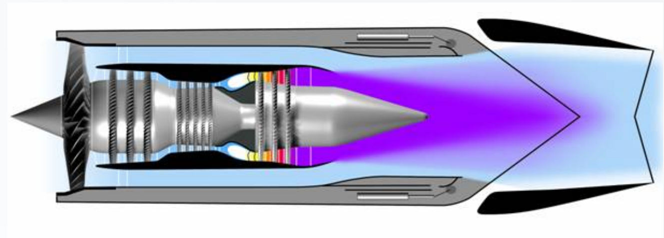
Supersonics Project – Airport Noise

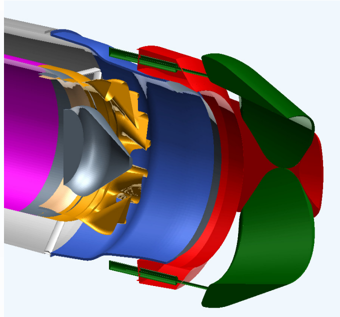
SUP.07.04 SUP Noise Engineering

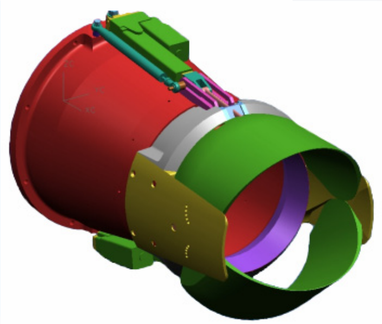
- Milestone SUP.07.04.012
  - HVC model system delivered – 4/2009
- Milestone SUP.07.04.013
  - HVC acoustic system performance assessed – 12/2007

Historical Background

- **Propulsion System for Supersonic Aircraft**
  - Medium BPR Turbofan
  - Variable Cycle Optimized for OPR at low speed
  - Jet Noise at Take-off
  - Based on earlier Design for SSBJ (NAS3-03123)
  - RB577-260-LM2 engine-NASA QSV-IIPS Study - Tests conducted in June 2003 at Nozzle Acoustic Test Rig (NATR), GRC.
- **Exhaust Nozzle Development**
  - Based on Concord Nozzle Design
  - Variable Geometry Nozzle
  - Early CFD Flow Simulations

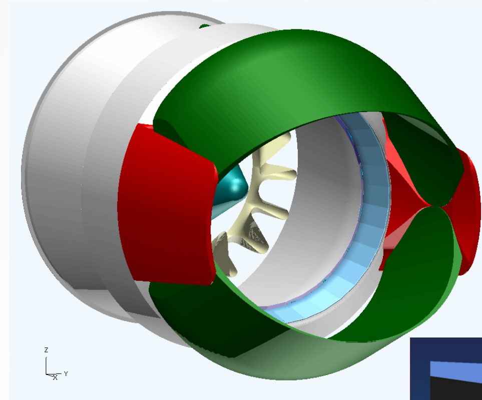
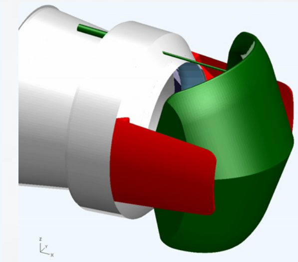
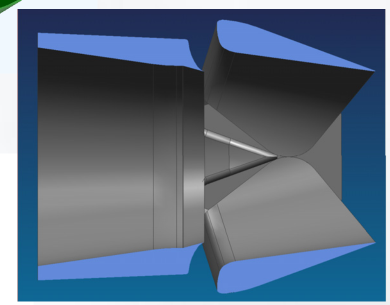
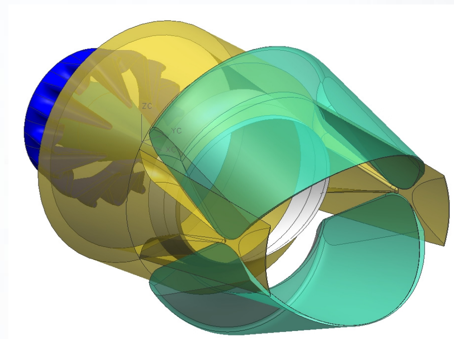
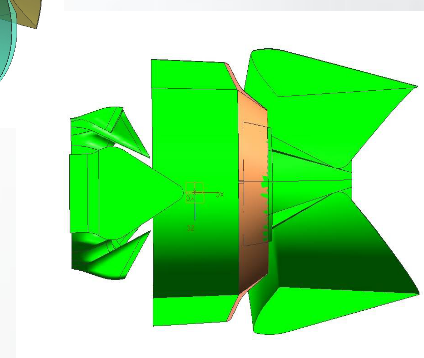






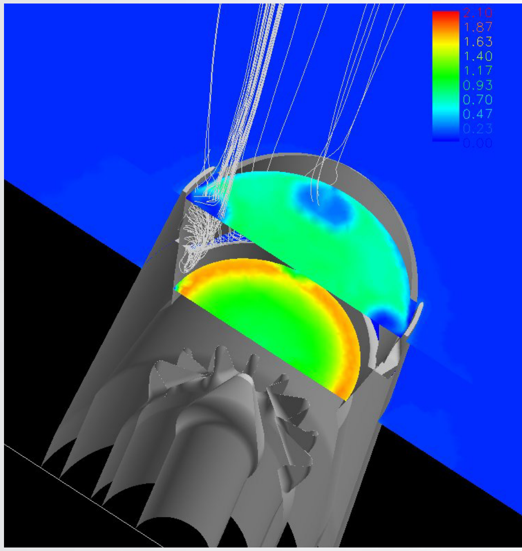
Variable Geometry Exhaust System

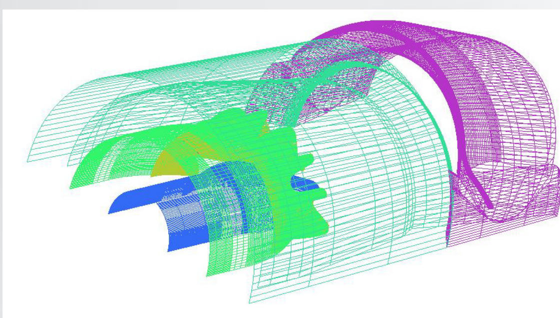
- **Baseline Exhaust Nozzle**
  - Mixed Flow Exhaust
  - Variable geometry CD nozzle – A8 and A9 (Exit)
  - Actuated Clam Shell Doors or buckets as ejectors
- **Re-design for Low Noise**
  - CFD design Validation
  - Optimum ejector door setting for thrust and jet noise
  - Performance Improvement
  - High Fidelity nozzle model design for acoustic prediction

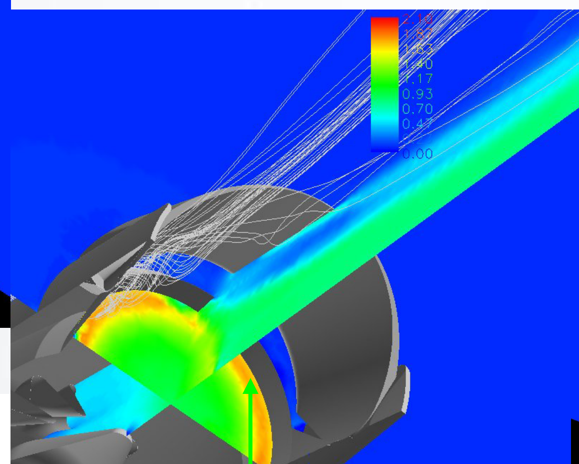






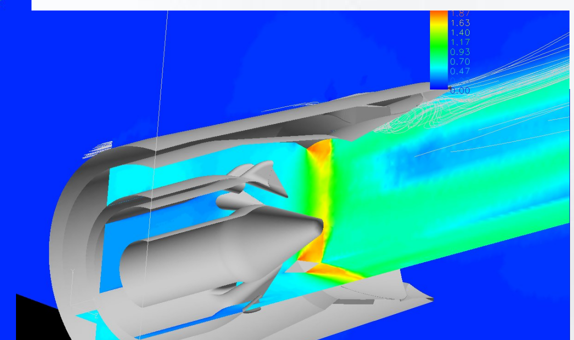
Baseline Analysis-Validation (April 2006)

- **Design and CFD Analysis -Fluent**
  - 2003 design tested in 2003 at NASA GRC
  - Navier-Stokes Viscous Compressible Solution - Standard ke turbulence model
  - Second order explicit / implicit solution

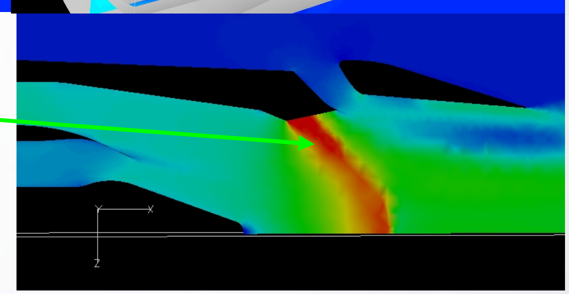








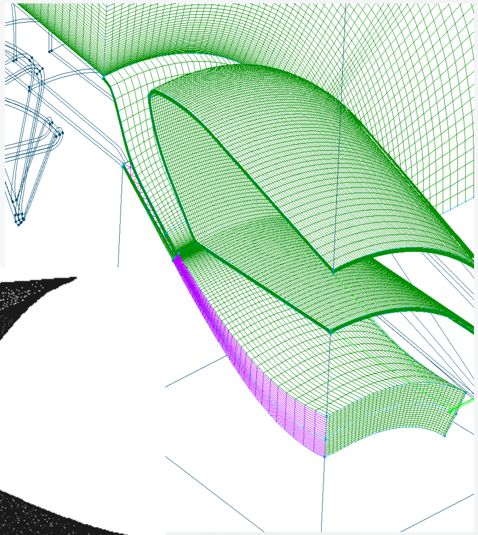
Mpeak ~1.6

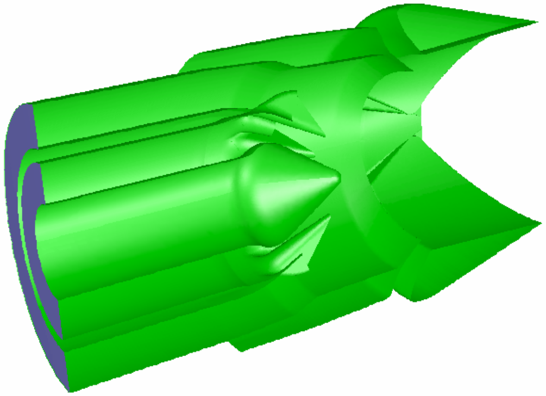


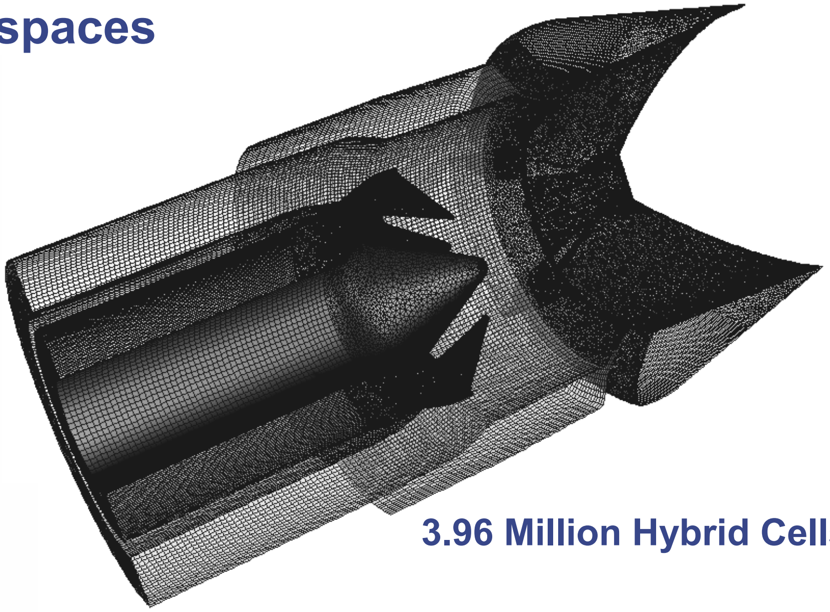
CFD Based Design and Analysis

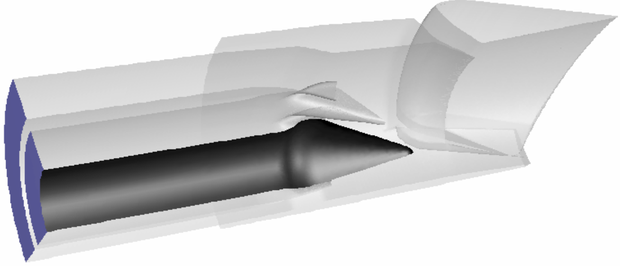
Computational Domain and GRID

- **Pointwise Code: Gridgen – Mesh**
- **Structured grid in far-field plume**
- **Prisms in boundary layer zone**
- **Unstructured in complex spaces**









3.96 Million Hybrid Cells

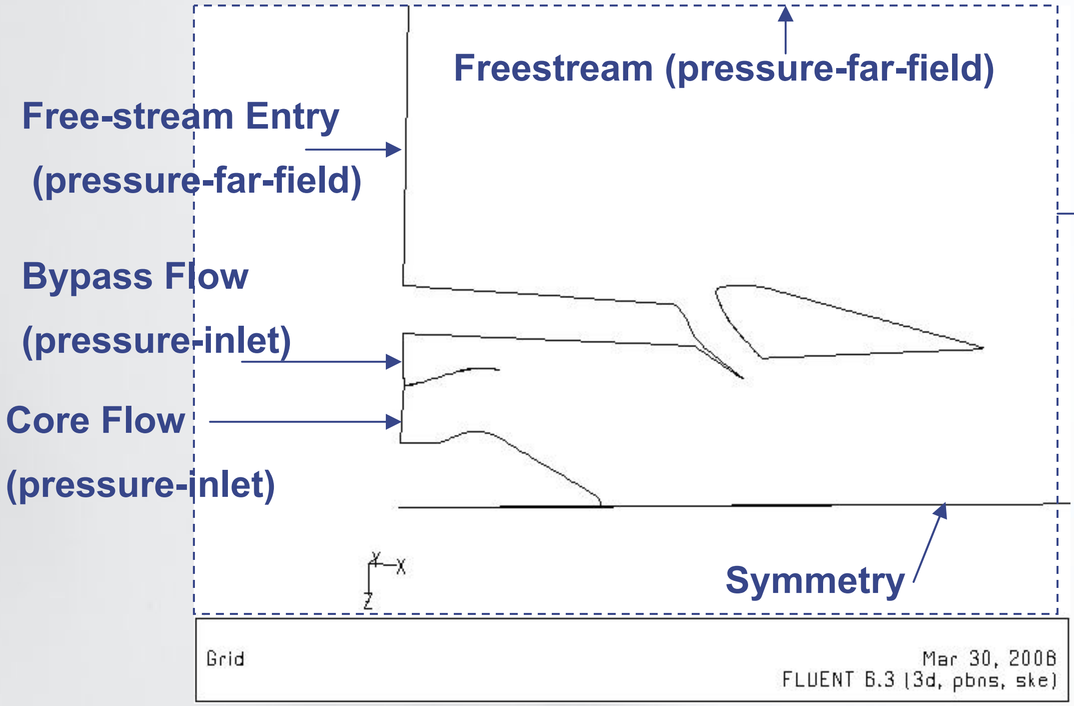
90 Degree Sector Meshed and Modeled

Operating Condition
Mach 0.3 SL Take-off

Half Cross Section

CFD Computational Problem Set Up & BC's

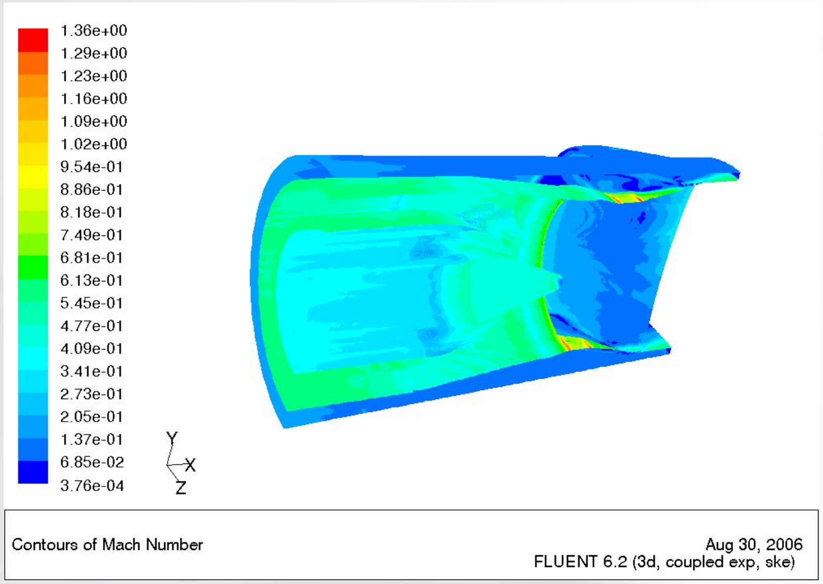
- Solver used: Fluent 6.2 - Density-based explicit
- Turbulence Model: standard k-ε turbulence model with wall functions
- Discretization: first-order upwind w/ under-relaxation, second-order upwind

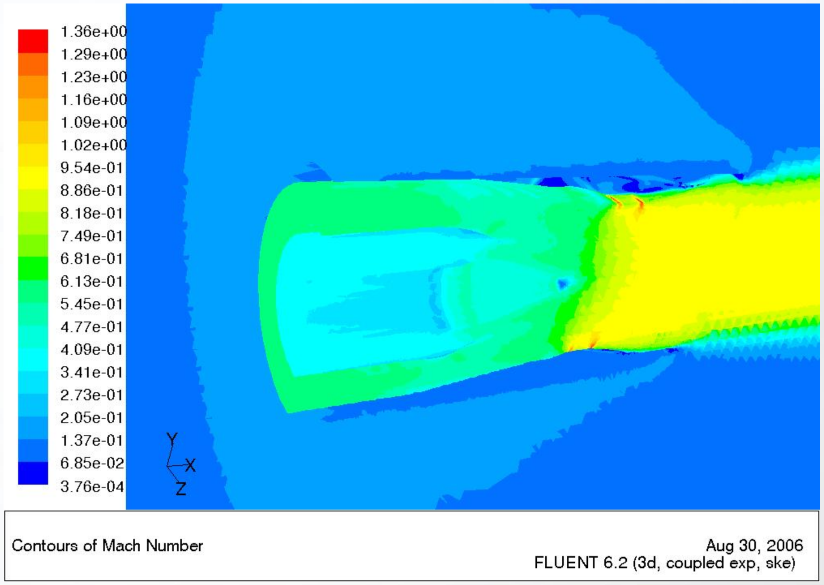


Note: The grid extends over 7.5 nozzle diameters radially from the centerline and about 10 diameters downstream.

Preliminary Nozzle Design Modifications

- Objective: Reduce High Mach Numbers
  - Mpeak < 1 upstream of throat
  - Mpeak ~ 1.05 on the side wall holding the buckets
  - Estimated increase in Wp at 0.3M TO Operation Case over Original Nozzle baseline ~ 8%
  - Clean flow through Ejector Passages

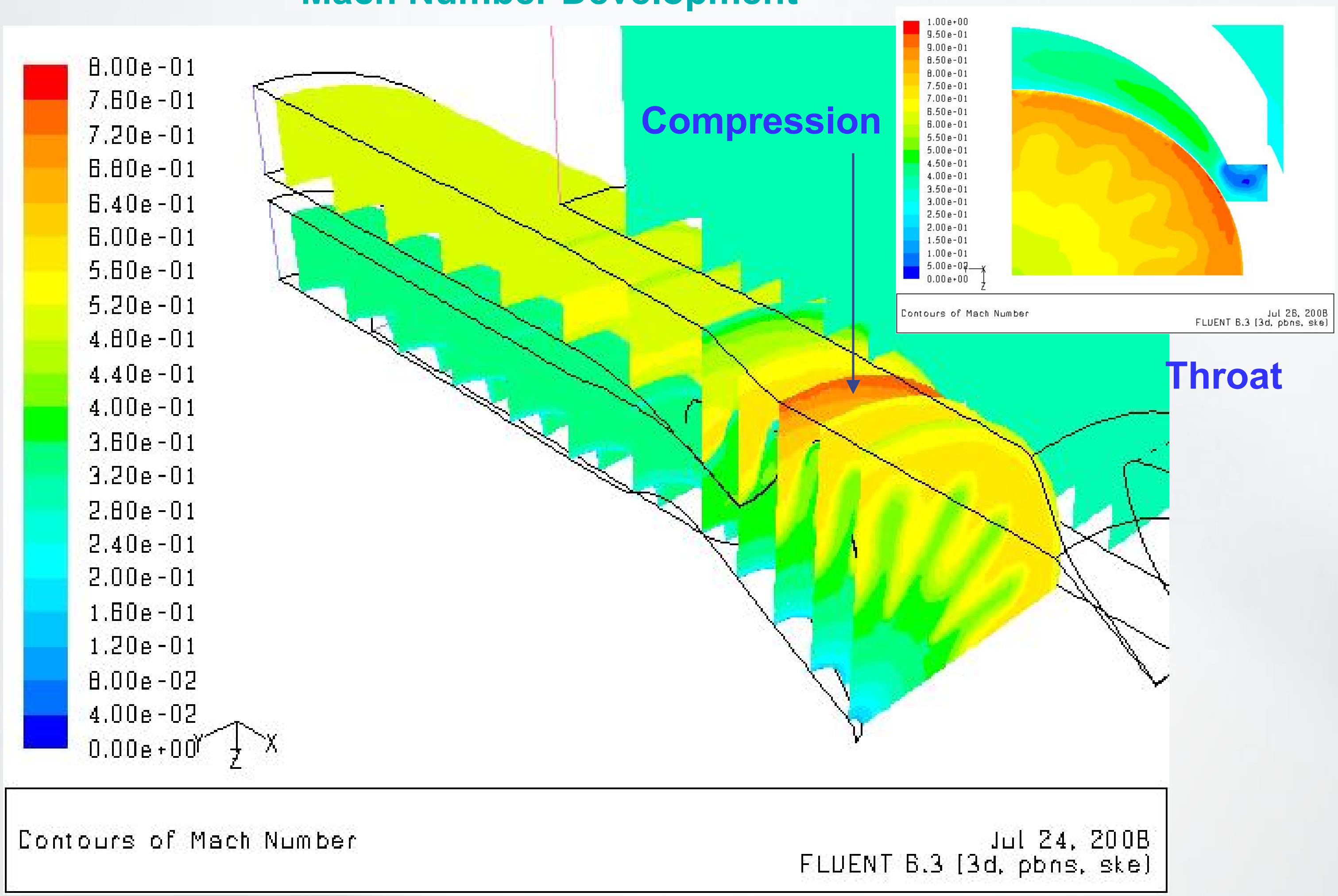




2008 Nozzle Design Configuration

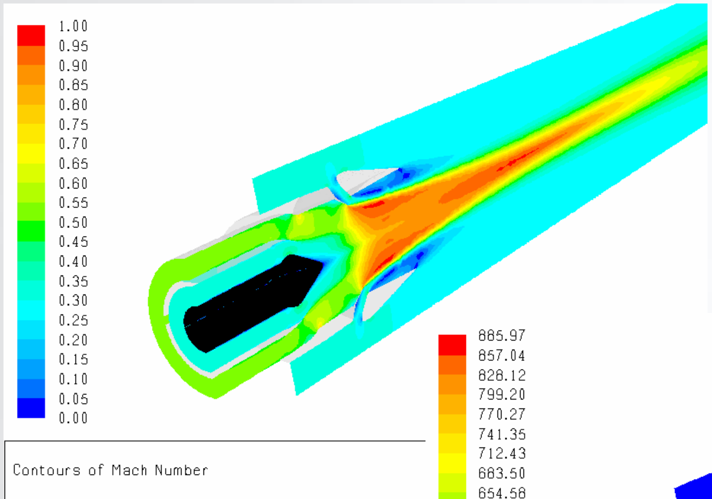
Internal Nozzle Flow-field

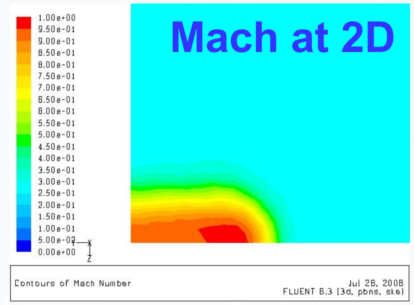
Mach Number Development

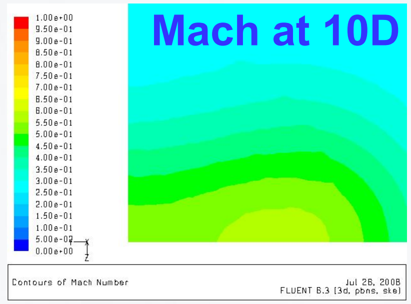


Nozzle Plume Characteristics

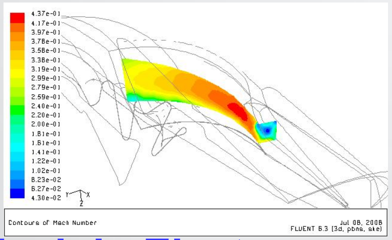
Take off Configuration



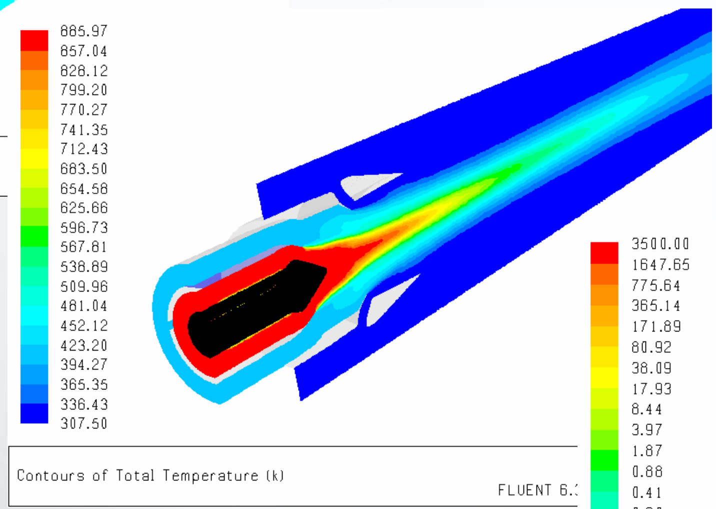




Mach Numbers

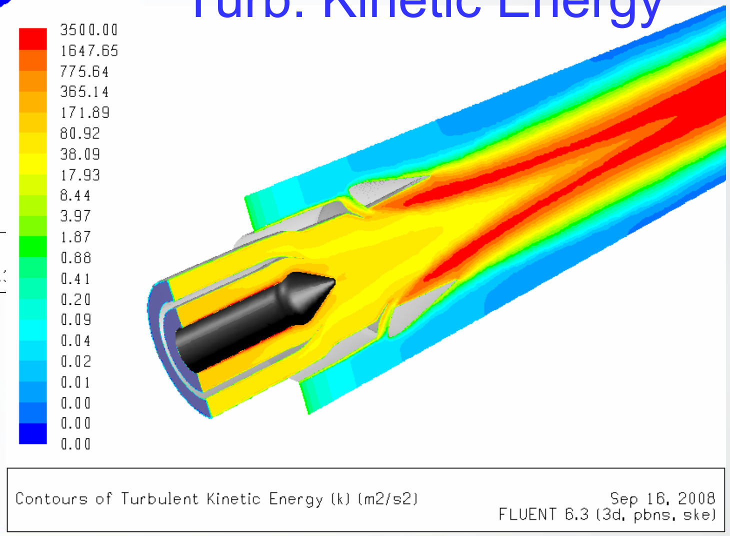


Mach in Ejector Slot region



Total Temperatures

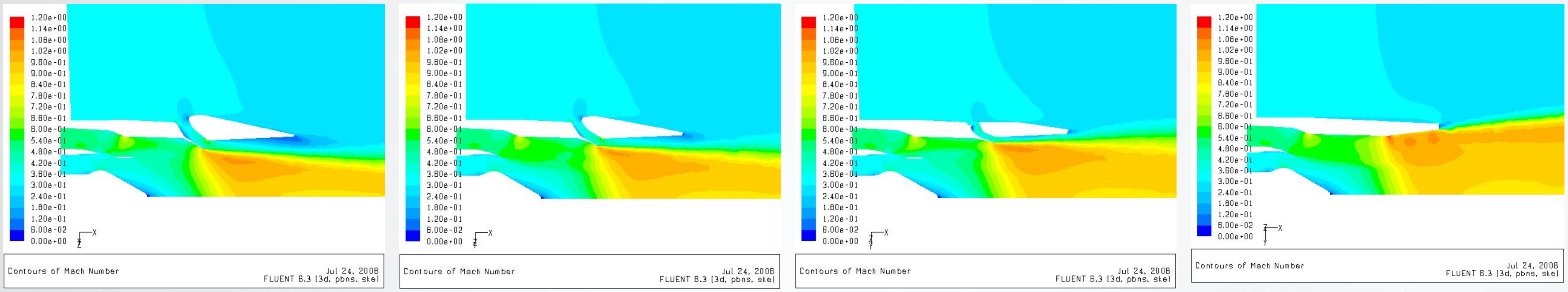
Turb. Kinetic Energy



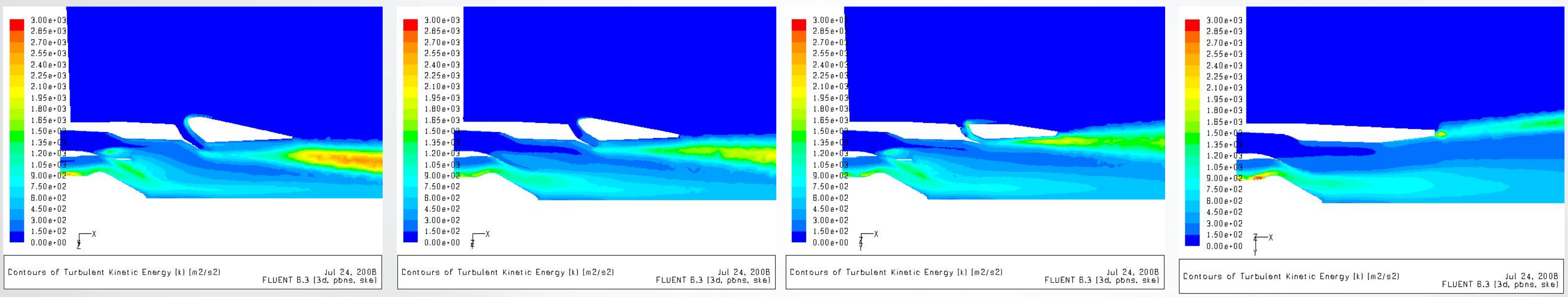
Good Plume Mixing at 10 diameters

Nozzle/Ejector Flow-Field Region

30° Slice | 45° Slice | 60° Slice | 90° Slice



Mach number Distribution

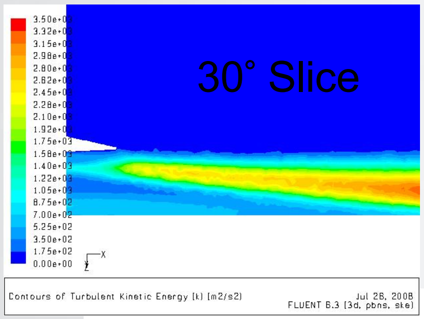


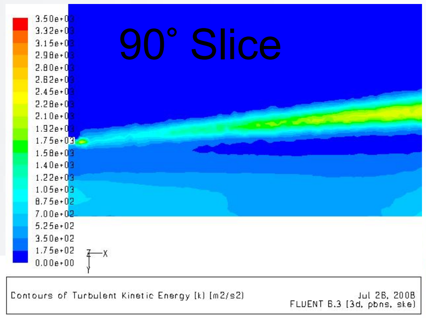
TKE Distribution

- Low Mach numbers – more noise suppression
- No reverse flow through ejector; some recirculation in slot corner
- Vorticity from sidewall and blunt TE increases the turbulent wakes

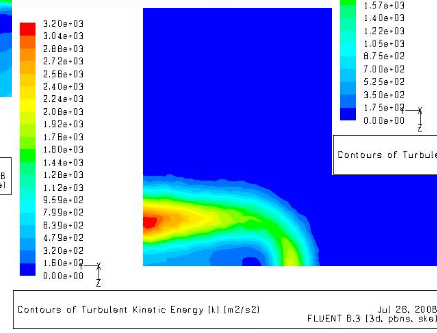
Downstream Plume Flow-Field

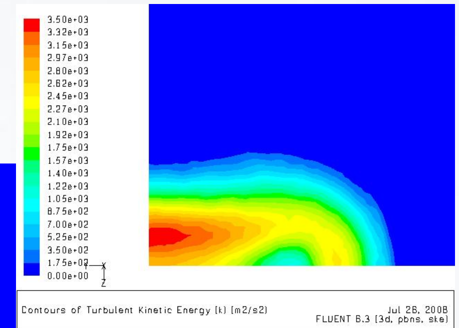
Turbulent Energy Decay





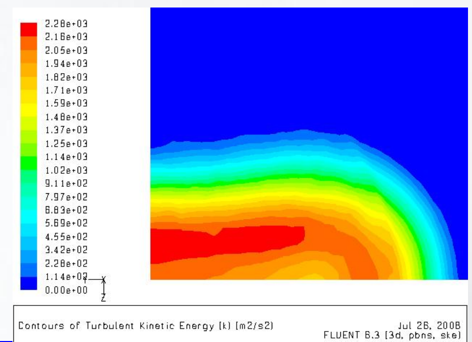
at 2D

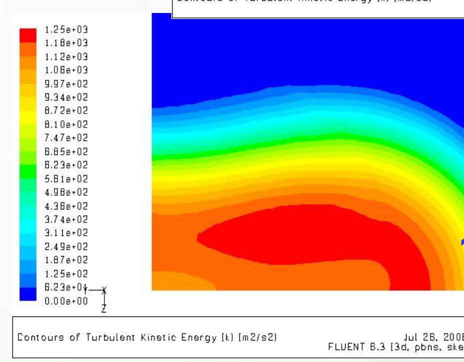




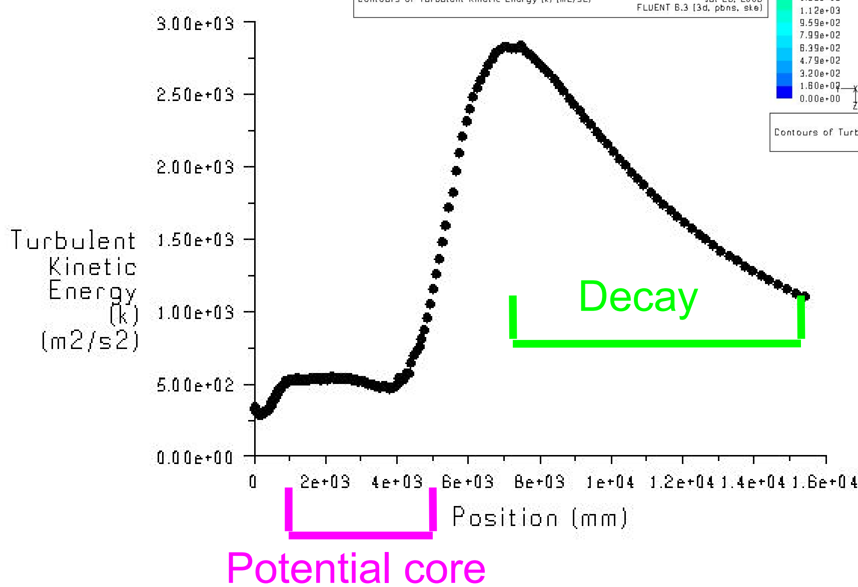
5D

7.5D



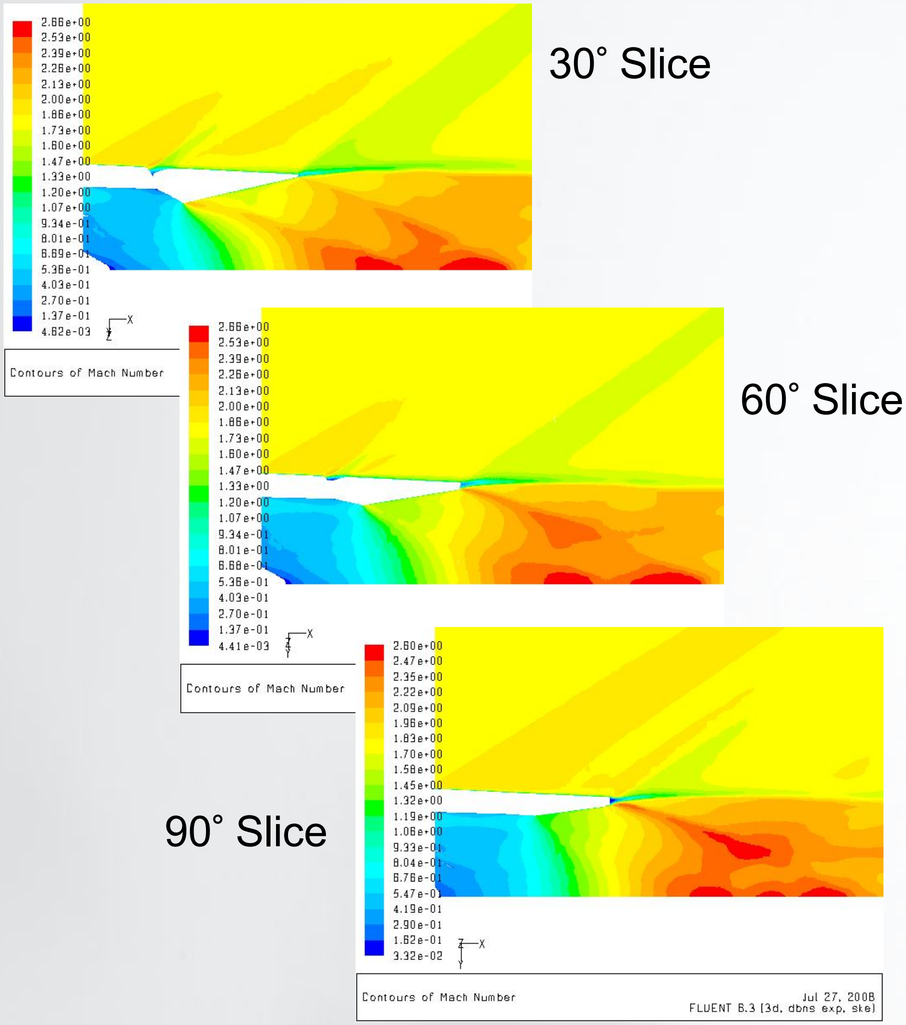


~10D

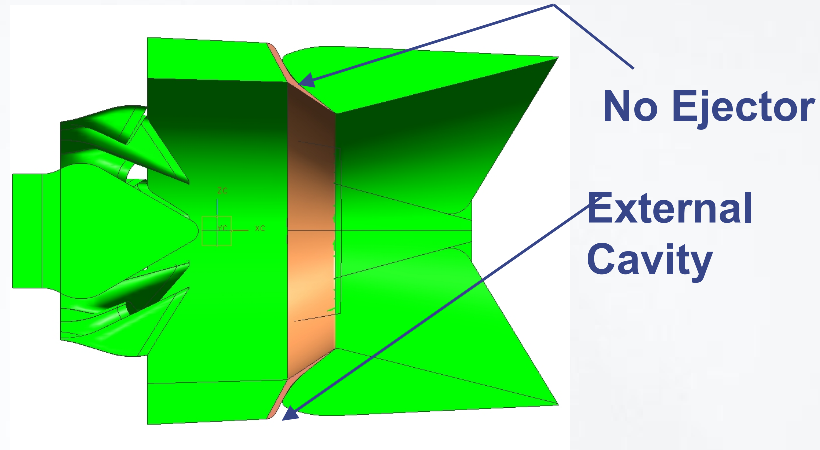


Turbulent kinetic Energy along jet centerline

CFD Analysis at M=1.8 Cruise Case (CR)



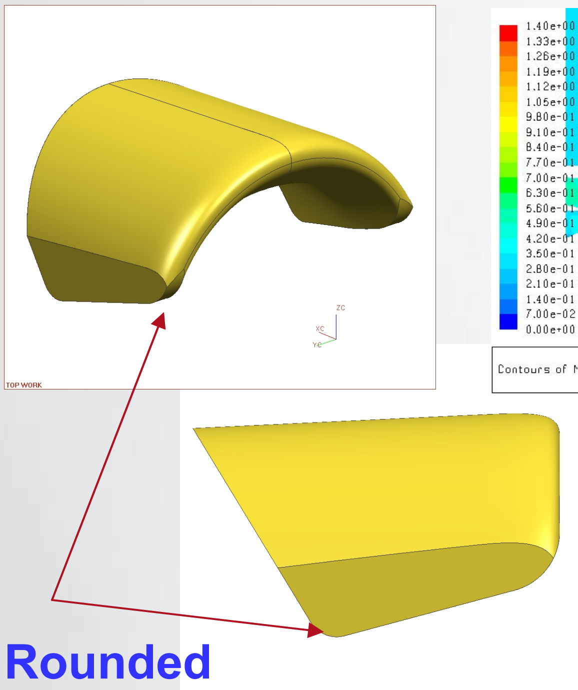
Shock predicted over ejector seam



- Grid: ~10.4 million cells
- Grid resolved for boundary layers, mixing layers, and discontinuities over ejector seam
- High-speed flow and shocks slowing convergence – second-order-accurate solution drifting/ oscillating, but stable

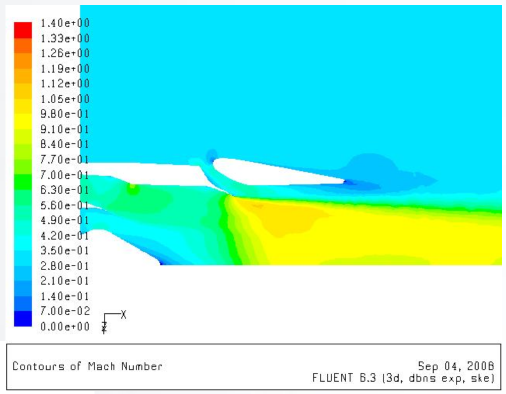
Modifications to Ejector Doors of the SS Nozzle

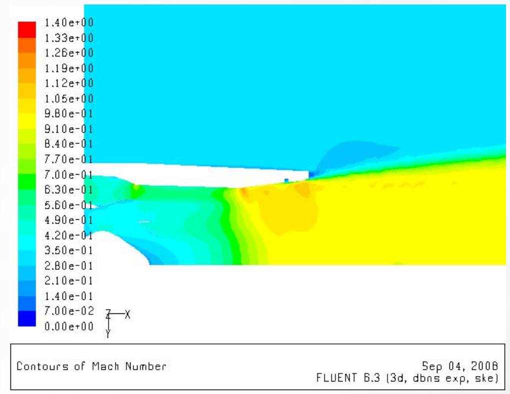
- **CFD analysis indicated 20% more ejector flow with no separation on the inner surface, lower turbulence and also increased thrust.**



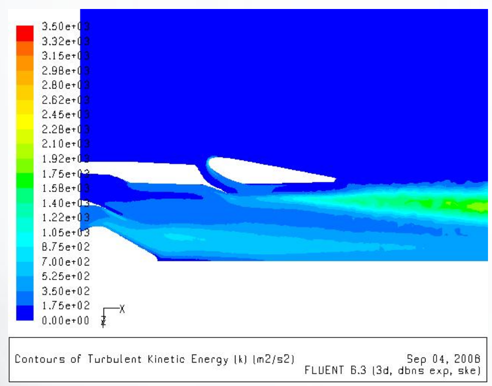
Rounded Edges

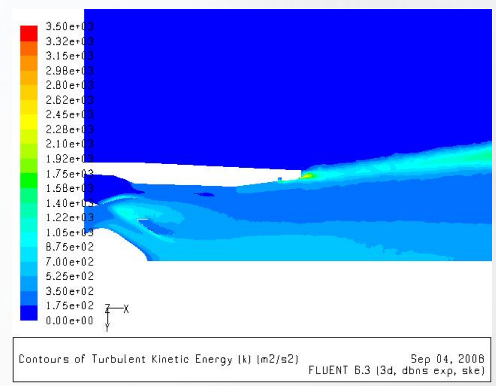
90° Plane Slice





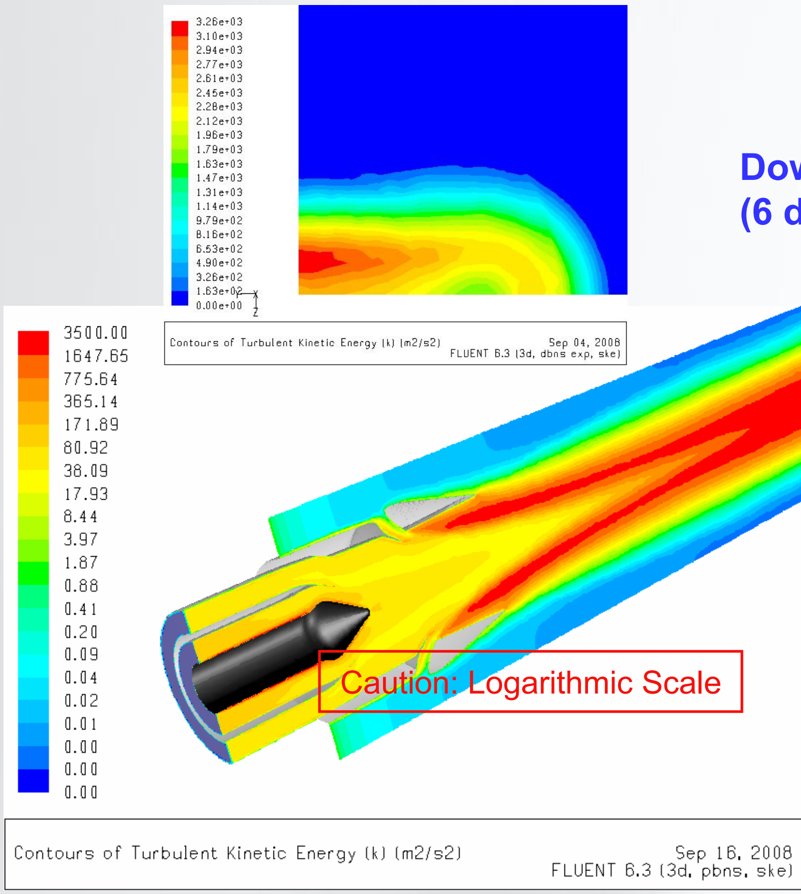
90° Plane Slice



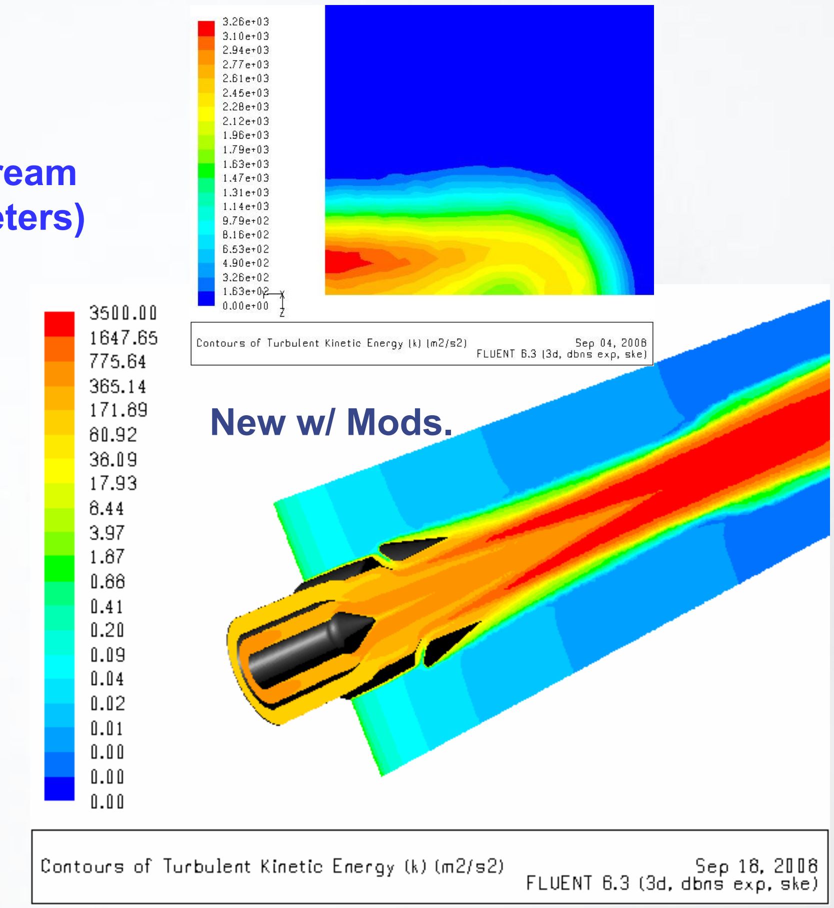


Distribution of Turbulent Kinetic Energy

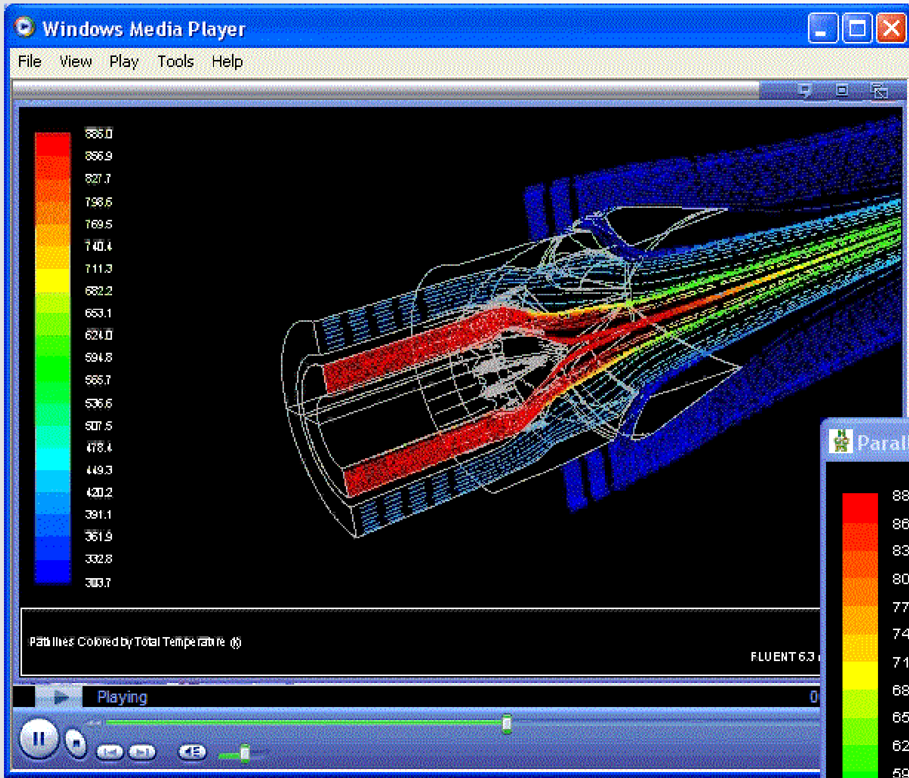
Mach 0.3, SL Take off Configuration



Downstream (6 diameters)

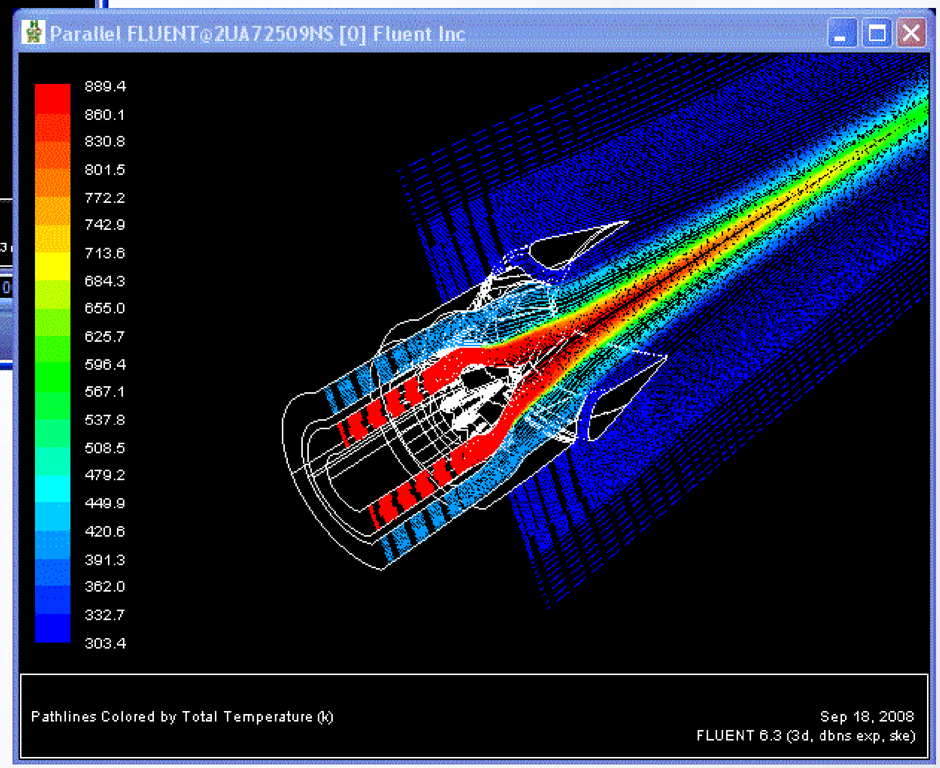


Ejector Flow Path



Current Nozzle Design

Current Nozzle Design
w/ Modified ejector Door



Conclusions

- Analysis of Rolls-Royce Variable Geometry SS Nozzle shows improved noise suppression features during Take-off
  - Low Mach numbers in throat region
  - Adequate ejector flow for plume suppression with minimum flow separation, turbulence decay and efficient mixing
  - Small improvement from ejector flow passage
- The scaled model nozzle design can proceed with the current configuration improvements.