# Combustion Devices CFD Team Analyses Review

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Abstract

A variety of CFD simulations performed by the Combustion Devices CFD Team at Marshall Space Flight Center will be presented. These analyses were performed to support Space Shuttle operations and Ares-1 Crew Launch Vehicle design. Results from the analyses will be shown along with pertinent information on the CFD codes and computational resources used to obtain the results.

Six analyses will be presented – two related to the Space Shuttle and four related to the Ares I-1 launch vehicle now under development at NASA. First, a CFD analysis of the flow fields around the Space Shuttle during the first six seconds of flight and potential debris trajectories within those flow fields will be discussed. Second, the combusting flows within the Space Shuttle Main Engine's main combustion chamber will be shown. For the Ares I-1, an analysis of the performance of the roll control thrusters during flight will be described. Several studies are discussed related to the J2-X engine to be used on the upper stage of the Ares I-1 vehicle. A parametric study of the propellant flow sequences and mixture ratios within the GOX/GH2 spark igniters on the J2-X is discussed. Transient simulations will be described that predict the asymmetric pressure loads that occur on the rocket nozzle during the engine start as the nozzle fills with combusting gases. Simulations of issues that affect temperature uniformity within the gas generator used to drive the J-2X turbines will described as well, both upstream of the chamber in the injector manifolds and within the combustion chamber itself.

MSFC-739

# COMBUSTION DEVICES CFD TEAM ANALYSIS REVIEW

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# COMBUSTION DEVICES CFD TEAM ANALYSIS REVIEW
## OUTLINE

- Team Charter,
- Computational Tools - CFD Codes and Grid Generators,
- Computational Resources - PC Clusters,
- Customers - Vehicle and Combustion Devices Project Offices,
- Vehicles and Associated Rocket Engines,
- Space Shuttle-Related Analyses:
  * Space Shuttle and Launch Pad Lift-Off Debris Transport Analysis,
  * Study of Propellant Mixing and Performance of a SSME Main Injector,
- Ares-I/Ares-V-Related Analyses:
  * Study of Fuel Flow in Manifold of the J-2X Gas Generator,
  * Study of Ares-I First-Stage Roll Control System Performance and Plume Effects,
  * Study of J-2X Augmented Spark Igniter Propellant Flow Sequencing and Mixture Ratio,
  * Study of Side Loads in a J-2X Engine Nozzle During Start-Up,
- Summary.

# COMBUSTION DEVICES CFD TEAM ANALYSIS REVIEW
## TEAM CHARTER

- *Combustion Devices CFD Team Charter:*

*"To provide state-of-the-art CFD support for MSFC propulsion project systems and components in a timely manner."*

*Kevin Tucker,*
*Team Leader, Combustion Devices CFD Team*

- *This support applies to the following areas:*

  * *Design analysis,*

  * *Test design and support analysis,*

  * *Anomaly resolution (flight or test),*

  * *Contractor insight and/or oversight.*

## COMBUSTION DEVICES CFD TEAM ANALYSIS REVIEW

### COMPUTATIONAL TOOLS - CFD CODES
### Loci-Chem

- ***Developer:** Mississippi State University, circa 2004, funded by NASA and NSF,*
- ***Significance:** "Loci-Chem" is the first product of the CFD code synthesizer, "Loci". Primary code used by most of Combustion Devices CFD Analysts,*
- ***Type of Code:** Density-based, Finite-Volume, for simulating low-to-high Mach number fluid flow and heat transfer on unstructured grids,*
- ***Time Integration Schemes:** Euler,Trapezoidal, 2nd-order Runge-Kutta,*
- ***Spatial Accuracy Schemes:** High-Resolution, Approximate Riemann solvers (1st-order & 2nd-order),*
- ***Turbulence Models:** k-ε, original k-ω(Wilcox), advanced k-ω(Wilcox), original k-ω/k-ε combination(Menter's Baseline), advanced k-ω/k-ε combination (Menter's Shear Stress Transport),*
- ***Fluid Properties Models:** Ideal Gas, Real Gas, Real Fluids Model,*
- ***Finite-Rate Chemistry Models:** Menu Options(Disassociated Air, $H_2/O_2$, $H_2$/Air) and Externally Specified(RP-1/$O_2$, $CH_4/O_2$, etc.),*
- ***Language:** C+ & C++.*

# COMPUTATIONAL TOOLS - CFD CODES
## Loci-Stream

- *Developer: Mississippi State University, circa 2005, funded by NASA and NSF,*
- *Significance: "Loci-Stream" is the second product of the CFD code synthesizer, "Loci". Secondary code used by a few Combustion Devices CFD Analysts,*
- *Type of Code: Pressure-based, Finite-Volume, for simulating zero-to-high Mach number fluid flow and heat transfer on unstructured grids,*
- *Time Integration Schemes: Euler, Trapezoidal, 2nd-order Runge-Kutta,*
- *Spatial Accuracy Schemes: High-Resolution, Approximate Riemann solvers (1st-order & 2nd-order),*
- *Turbulence Models: k-ε, original k-ω(Wilcox), advanced k-ω(Wilcox), original k-ω/k-ε combination(Menter's Baseline), advanced k-ω/k-ε combination (Menter's Shear Stress Transport),*
- *Fluid Properties Models: Ideal Gas, Real Gas, Real Fluids Model,*
- *Finite-Rate Chemistry Models: Menu Options(Disassociated Air, $H_2/O_2$, $H_2$/Air) and Externally Specified,*
- *Language: C+ & C++.*

# COMBUSTION DEVICES CFD TEAM ANALYSIS REVIEW

## COMPUTATIONAL TOOLS - CFD CODES

## UNIC

- *Developer: Engineering Sciences, Inc.(ESI), circa 2001, funded by NASA,*
- *Significance: UNIC(Unstructured-Grid Navier-Stokes Internal-External CFD) was a recipient of the 2007 Software of the Year Award at NASA/MSFC. Only used by one Combustion Devices CFD analyst with "Emeritus" status,*
- *Type of Code: Pressure-based, Finite-Volume, for simulating zero-to-high Mach number fluid flow and heat transfer(conjugate & radiative) on unstructured grids(fixed and adaptive),*
- *Time Integration Schemes: Euler,Trapezoidal, 2nd-order Runge-Kutta,*
- *Spatial Accuracy Schemes: High-Resolution 1st-order & 2nd-order,*
- *Turbulence Models: k-ε, extended k-ε, PANS(RANS with LES anisotropic turbulence features),*
- *Fluid Properties Models: Ideal Gas, Real Gas, Real Fluids Model, Plasma Model (5000°K - 200,000°K),*
- *Finite-Rate Chemistry Models: Externally Specified(Disassociated Air, $H_2/O_2$, $H_2$/Air, ionization, etc.),*
- *Language: Fortran & C+.*

# COMPUTATIONAL TOOLS - GRID GENERATORS

## Grid Generator: Gridgen,

- Developer: Pointwise, Inc.,
- Approach: Used a "bottoms-up" approach to grid generation(curves 1st, surfaces 2nd, & volumes 3rd),
- Significance: Principal grid generator, used by all Combustion Devices CFD Analysts for 2D & 3D grids(structured & unstructured). Now used for 2D grid generation(structure & unstructured) and 3D surface grid generation only,

## Grid Generator: SolidMesh/AFLR(Advancing Front/Local Reconnection),

- Developer: Mississippi State University/Engineering Research Center for Computational Field Simulation,
- Approach: Used an "Advancing Front" of calculated points from the 3D surface grid, then performed a "Local Reconnection" to form a new layer of tetrahedral cells and a new layer of triangular cells. The process is repeated to filled the 3D volume with tetrahedral cells,
- Significance: Newer grid generator, used by some Combustion Devices CFD Analysts for 2D & 3D grids(structured & unstructured). Mostly used for 3D volume grid generation from externally generated 3D surface grids. SolidMesh is a GUI for AFLR(3D volume grid generator),

## COMPUTATIONAL TOOLS - GRID GENERATORS

**Grid Generator: ANSA(Automatic Net-Generation for Structural Analysis),**

- Developer: Beta CAE Systems,
- Approach: Used a "tops-down" approach to grid generation(CAD model 1st, surface grid 2nd, & volume grid 3rd),
- Significance: Newer grid generator, adopted from Stress Analysis community, used by some Combustion Devices CFD Analysts for 3D grids(structured & unstructured). Mostly used for 3D volume grid generation from externally generated 3D CAD models.

# COMBUSTION DEVICES CFD TEAM ANALYSIS REVIEW

## COMPUTATIONAL RESOURCES - PC CLUSTERS


"Chimaera"


"Cerberus"


"Geryon"


"Bethe"

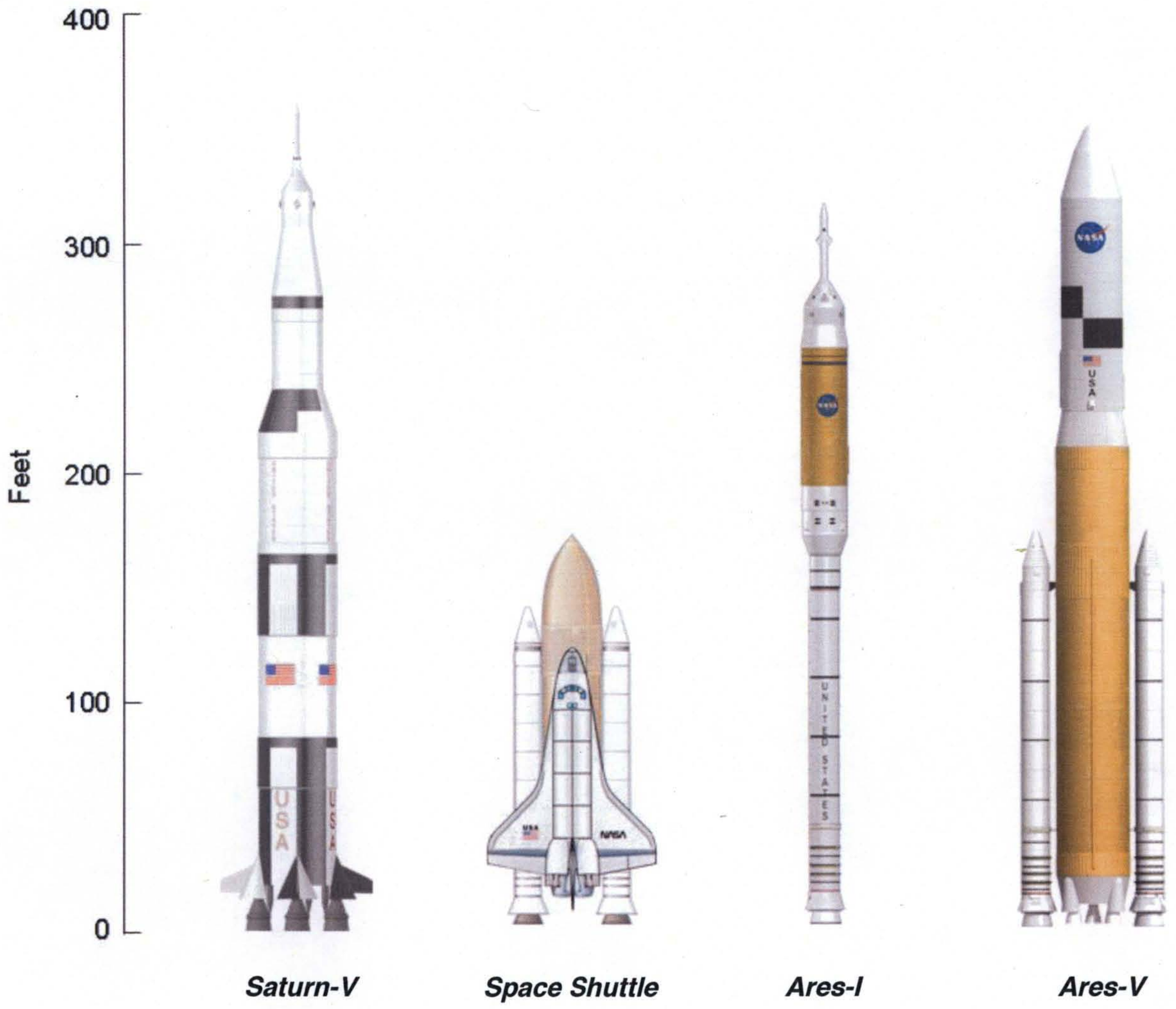

"Hydra"


"Orthrus"

| | Chimaera | Cerberus | Geryon | Bethe (now under Orthrus) | Hydra | Orthrus (twop) | Orthrus (twopdc) | Orthrus (fourp) |
|---|---|---|---|---|---|---|---|---|
| Circa | 2001 | 2003 | 2004 | 2004 | 2005 | 2006 | 2006 | 2006 |
| Number of PCs | 96 | 162 | 93 | 40 | 74 | 127 | 173 | 23 |
| CPUs/PC | 2 | 2 | 2 | 2 | 2 | 2 | 4 | 4 |
| Total Cluster CPUs | 192 | 324 | 186 | 80 | 148 | 254 | 692 | 92 |
| Accumilative CPUs | 192 | 516 | 702 | 782 | 930 | 1184 | 1876 | 1968 |
| CPU Type | Athlon MP 1800 | Athlon MP 2600 | Athlon MP 2800 | Opteron 242 | Opteron 246 | Opteron 250 | Opteron 270 | Opteron 850 |
| CPU Memory (Gbytes) | 1.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 8.0 |
| CPU Speed (GHz) | 1.5 | 2.1 | 2.1 | 1.6 | 2.0 | 2.4 | 2.0 | 2.4 |
| Monthly Usage (jobs/CPU-hrs) | 330/110,000 | 24/217,000 | 300/120,000 | TBD | 200/78,000 | TBD | TBD | TBD |

## COMBUSTION DEVICES CFD TEAM ANALYSIS REVIEW

## CUSTOMERS - VEHICLE AND COMBUSTION DEVICES PROJECTS OFFICES

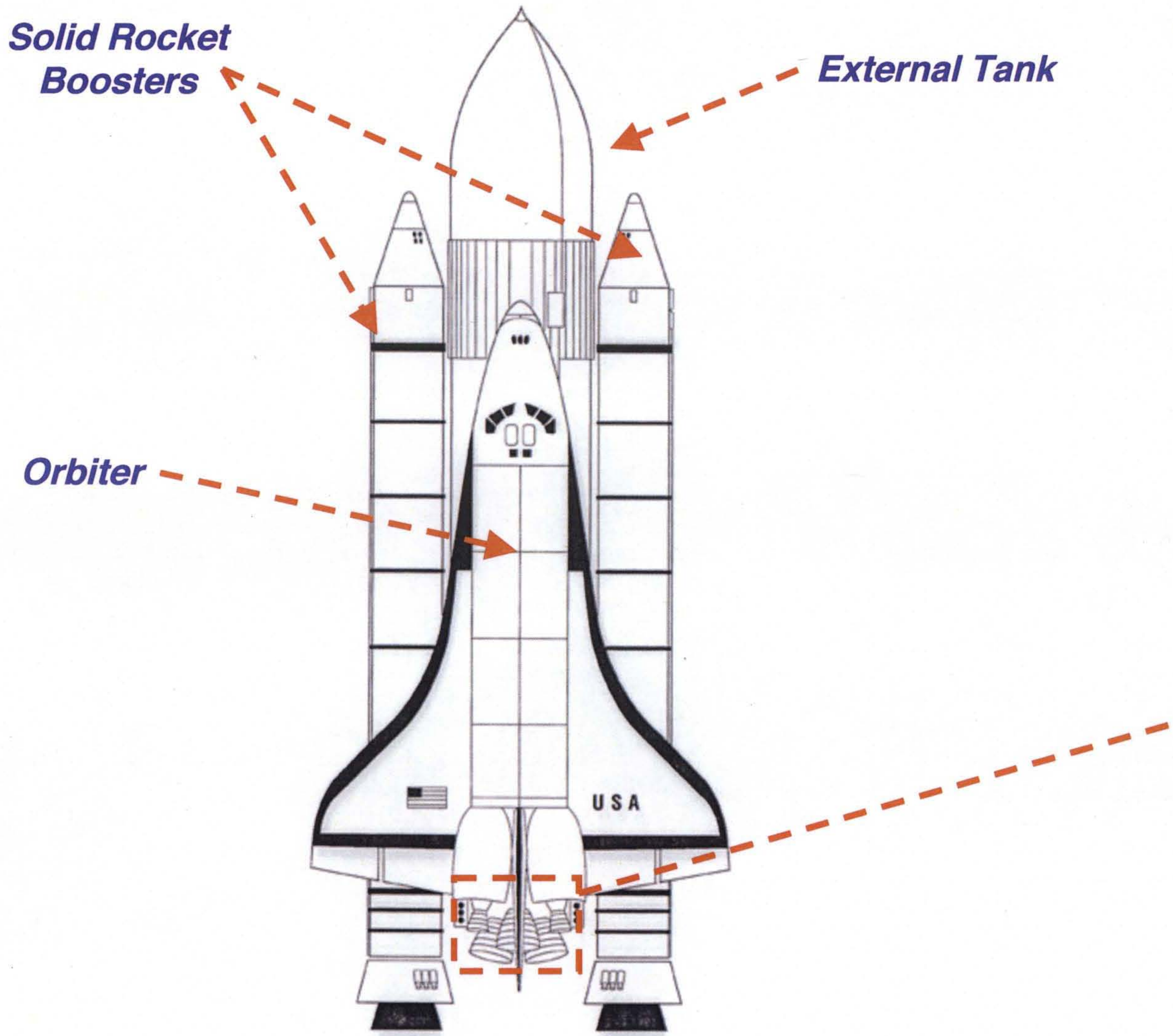



- ***Space Shuttle-Related Customers:***
  - * ***Vehicle: Propulsion Systems Engineering and Integration,***
  - * ***Combustion Devices: SSME Project Office /Design Engineering Team***
- ***Ares-I & Ares-V-Related Customers:***
  - * ***Vehicle: Ares-I Roll Control System(RCS) Integrated Product Team,***
  - * ***Combustion Devices: J-2X Program Office.***

# COMBUSTION DEVICES CFD TEAM ANALYSIS REVIEW

## VEHICLES AND ASSOCIATED ROCKET ENGINES

### Space Shuttle



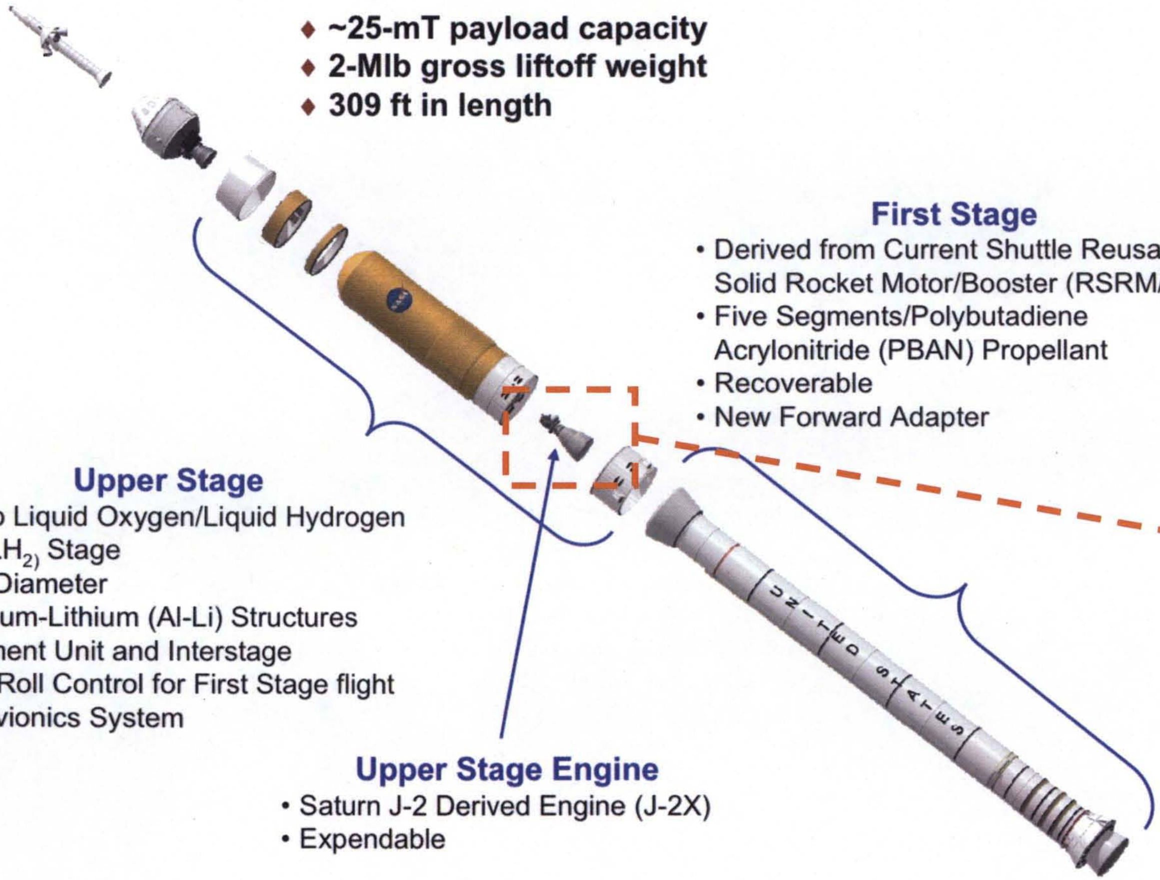

### SSME(RS-24) Rocket Engine:

- Developer: Pratt&Whitney /Rocketdyne,
- Propellants: LOX/LH2,
- Thrust: 400,000 lbs,
- Thrust Duration: 510 sec,
- Weight: 7000 lbs,
- Height: 168 in,
- Diameter: 90 in,

# VEHICLES AND ASSOCIATED ROCKET ENGINES

## Ares-I Crew Launch Vehicle

- ~25-mT payload capacity
- 2-Mlb gross liftoff weight
- 309 ft in length



**First Stage**
- Derived from Current Shuttle Reusable Solid Rocket Motor/Booster (RSRM/B)
- Five Segments/Polybutadiene Acrylonitride (PBAN) Propellant
- Recoverable
- New Forward Adapter

**Upper Stage**
- 280-klb Liquid Oxygen/Liquid Hydrogen ($LOX/LH_2$) Stage
- 5.5-m Diameter
- Aluminum-Lithium (Al-Li) Structures
- Instrument Unit and Interstage
- RCS / Roll Control for First Stage flight
- CLV Avionics System

**Upper Stage Engine**
- Saturn J-2 Derived Engine (J-2X)
- Expendable

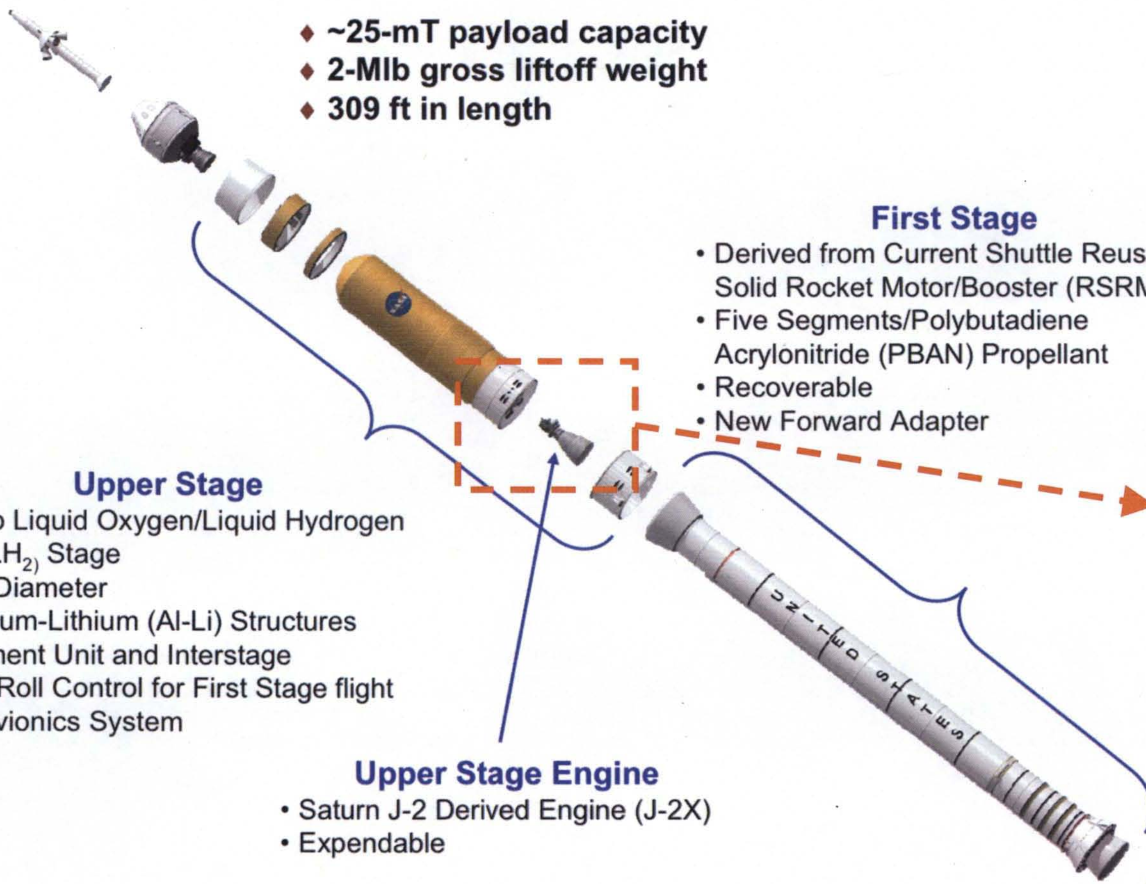
## J-2X Rocket Engine:

- ***Developer: Pratt&Whitney /Rocketdyne,***
- ***Propellants: LOX/LH2,***
- ***Thrust: 294,000 lbs,***
- ***Thrust Duration: 465 sec,***
- ***Weight: 5300 lbs,***
- ***Height: 185 in,***
- ***Diameter: 120 in,***

# VEHICLES AND ASSOCIATED ROCKET ENGINES

## Ares-I Crew Launch Vehicle

- ~25-mT payload capacity
- 2-Mlb gross liftoff weight
- 309 ft in length




**First Stage**

- Derived from Current Shuttle Reusable Solid Rocket Motor/Booster (RSRM/B)
- Five Segments/Polybutadiene Acrylonitride (PBAN) Propellant
- Recoverable
- New Forward Adapter

**Upper Stage**

- 280-klb Liquid Oxygen/Liquid Hydrogen ($LOX/LH_2$) Stage
- 5.5-m Diameter
- Aluminum-Lithium (Al-Li) Structures
- Instrument Unit and Interstage
- RCS / Roll Control for First Stage flight
- CLV Avionics System

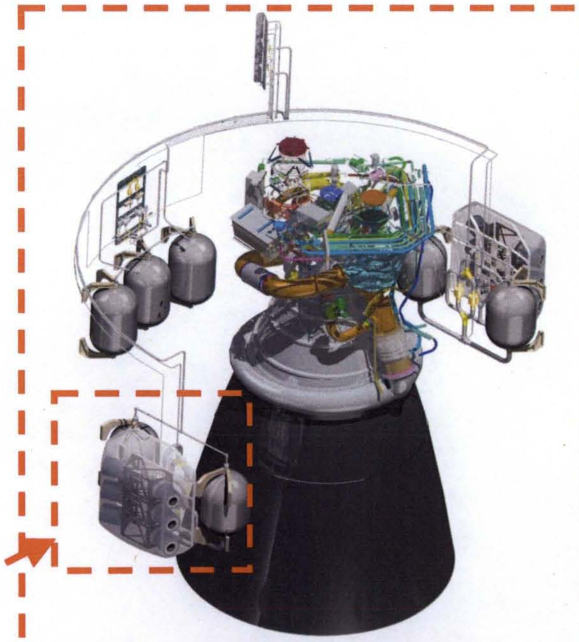
**Upper Stage Engine**

- Saturn J-2 Derived Engine (J-2X)
- Expendable

***RCS Thruster Pod: 6 Thrusters/Pod***

## Roll Control System (RCS) Thruster:

- *Developer: Aerojet,*
- *Propellant: hydrazine,*
- *Thrust: 600 lbs,*
- *Thrust Duration: 264 sec,*
- *Weight: 19 lbs,*
- *Height: 16 in,*
- *Diameter: 8.5 in,*

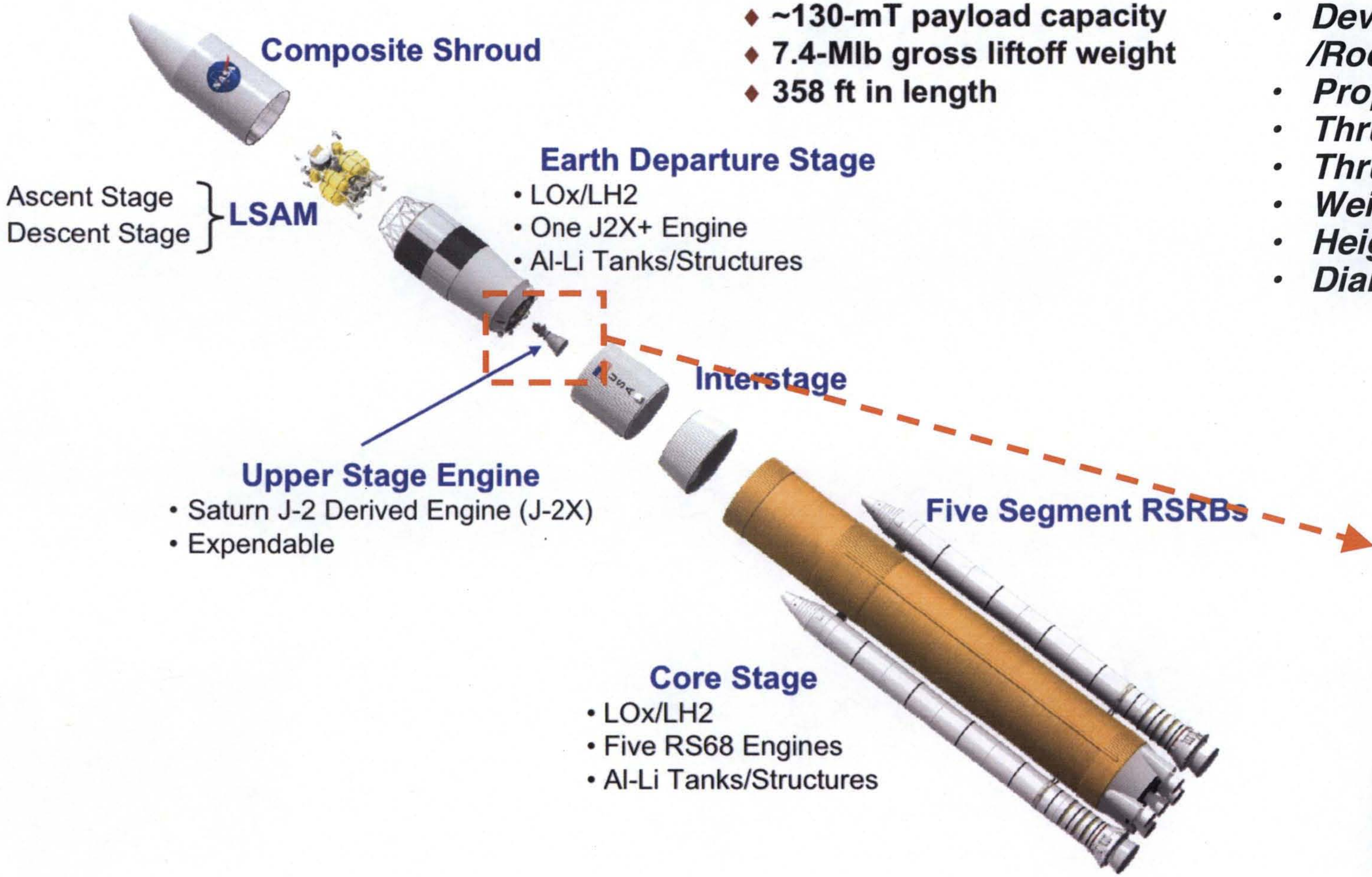


***J-2X Engine with RCS Thruster Pods***

# VEHICLES AND ASSOCIATED ROCKET ENGINES

## Ares-V Cargo Launch Vehicle

- ~130-mT payload capacity
- 7.4-Mlb gross liftoff weight
- 358 ft in length



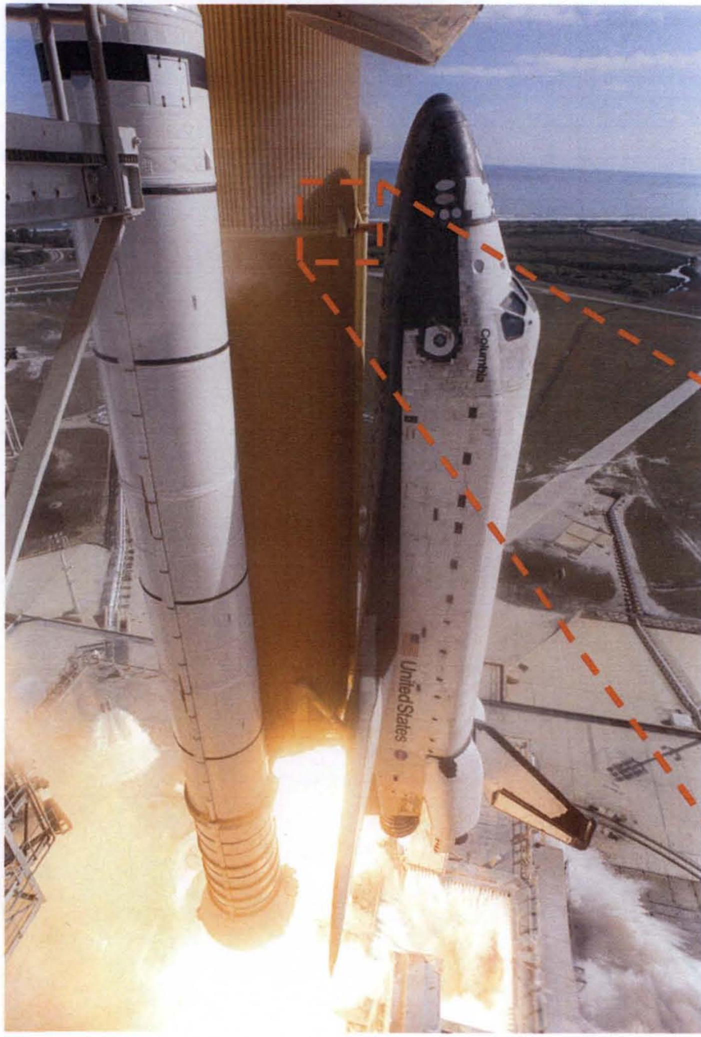

## J-2X Rocket Engine:

- *Developer: Pratt&Whitney /Rocketdyne,*
- *Propellants: LOX/LH2,*
- *Thrust: 294,000 lbs,*
- *Thrust Duration: 465 sec,*
- *Weight: 5300 lbs,*
- *Height: 185 in,*
- *Diameter: 120 in,*

## COMBUSTION DEVICES CFD TEAM ANALYSIS REVIEW

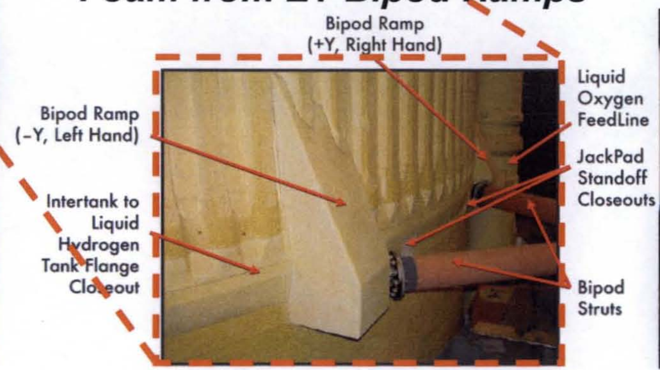
### SPACE SHUTTLE AND LAUNCH PAD LIFF-OFF DEBRIS TRANSPORT ANALYSIS

*Lift-Off of Columbia for Mission STS-107*

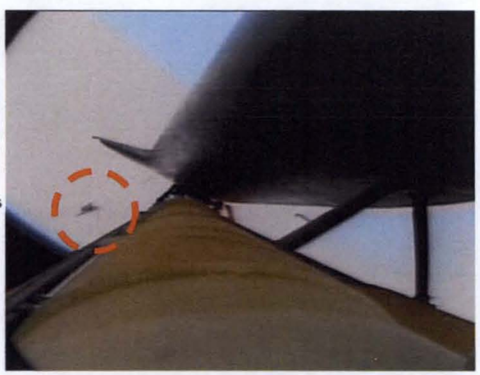



- ***Analysts: Jeff West, Sam Dougherty, Peter Liever, & Jerry Radke,***
- ***Customer: NASA/MSFC Propulsion Systems Engineering and Integration,***
- ***Customer Concern: Identify and control every possible source of debris liberation for return-to-flight, after the Columbia tragedy,***
- ***Items to be Modeled: Orbiter, SRBs, SSMEs, Launch Pad, SRB & SSME Plumes.***

*A Debris Source: Foam from ET Bipod Ramps*




*Falling Debris During Ascent*



# SPACE SHUTTLE AND LAUNCH PAD LIFF-OFF DEBRIS TRANSPORT ANALYSIS

- **Objectives:**

  * Perform quasi-steady flow field simulations of the interaction of exhaust plumes from the integrated Space Shuttle Vehicle with the Launch Facility and ground winds during various stages of the first few seconds of Lift-Off,

  * Perform trajectory simulations of debris particles falling into the plume-driven, Lift-Off flow field,

  * Determine if debris particles will impact the Vehicle and with what impact energy,

- **Tools Used: Loci-Chem(CFD code), ANSA & SolidMesh/AFLR(grid generators),**

- **Process(& Status):**

  * Generate flow fields around a highly detailed, 3D, symmetric-half model of a SRB with the Launch Facility with ground winds, with an exhaust plume(completed),

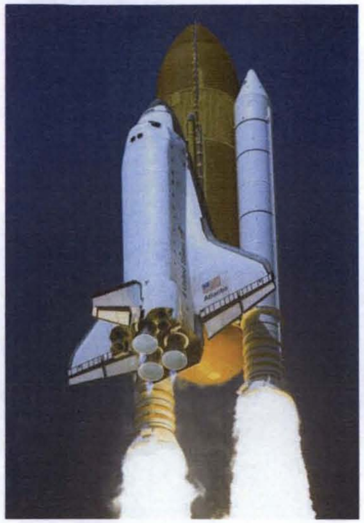
  * Generate flow fields around a less detailed, full-3D model of a single SRB with the Launch Facility with ground winds, with an exhaust plume(in progress),

  * Generate flow fields around a full-3D model of the Space Shuttle Vehicle with the Launch Facility with ground winds, without and with exhaust plumes from SSMEs and SRBs(in set-up).

# COMBUSTION DEVICES CFD TEAM ANALYSIS REVIEW

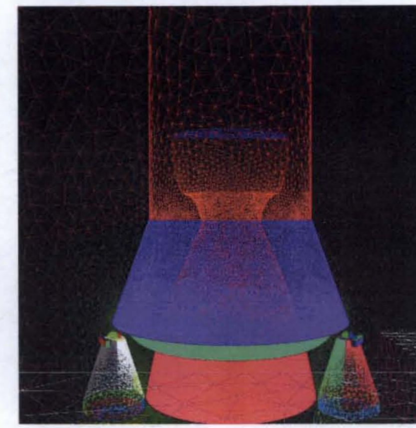
## SPACE SHUTTLE AND LAUNCH PAD LIFF-OFF DEBRIS TRANSPORT ANALYSIS

### Space Shuttle Vehicle Grid Generation:



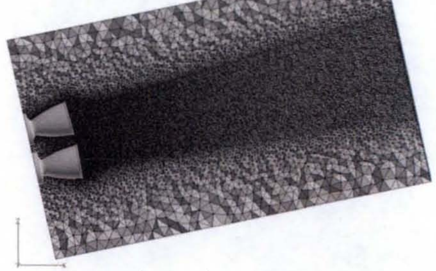
### Space Shuttle Orbiter Grid Generation: Surface & Volume Meshes

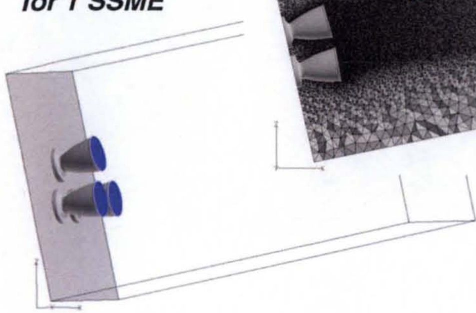
### SRB Surface Mesh:



### SSME Cluster Grid Generation For Preliminary Plume Study:

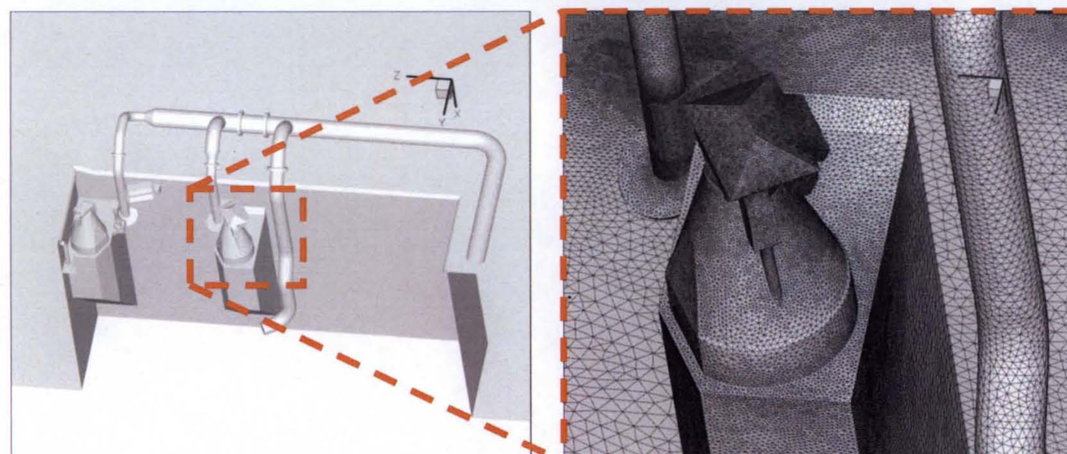
***grid size: 5 million cells (on 15 CPUs) for 1 SSME***





***grid size: 17 million cells (on 28 CPUs) for 3 SSMEs***

### Launch Pad SRB Exhaust Hole Grid Generation: Surface Mesh



***grid size: 80 million cells(on 156 CPUs) for the Space Shuttle Vehicle, Launch Pad, Service Structure, SSME Plumes, & SRB Plumes***

# COMBUSTION DEVICES CFD TEAM ANALYSIS REVIEW

# SPACE SHUTTLE AND LAUNCH PAD LIFF-OFF DEBRIS TRANSPORT ANALYSIS

## Typical Results: Preliminary Studies of SSME Exhaust Plumes

### Validation of Single SSME Plume Flow Structure Simulations Against Test Stand Imagery

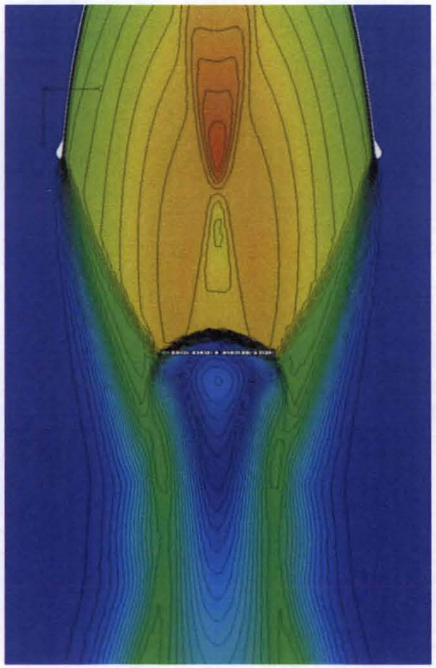
- *Mach disk size and location measured from optical footage,*
- *Full 3-D SSME Solution, Reacting Flow,*
- *Captures Mach Disk And Downstream Plume Flow Structure Correctly,*
- *Good Agreement For Mach Disk Location And Size.*

### Three-Cluster SSME Plume Mixing Simulations

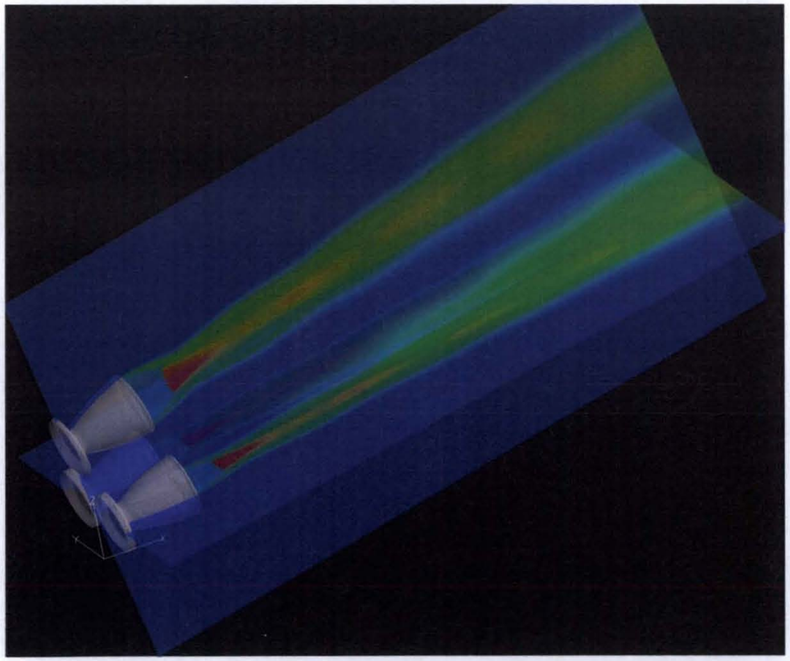
- *Nozzle Exit Plane BC Utility Program maps a precalculated 2D/axisymmetric nozzle exit profile onto the SSME exit planes in the SSME cluster coordinates,*
- *Nozzle Exit Plane BC Utility Program accounts for the location and gimbal angle of each SSME.*

**Test Stand Imagery**


**Mach Number Contours**



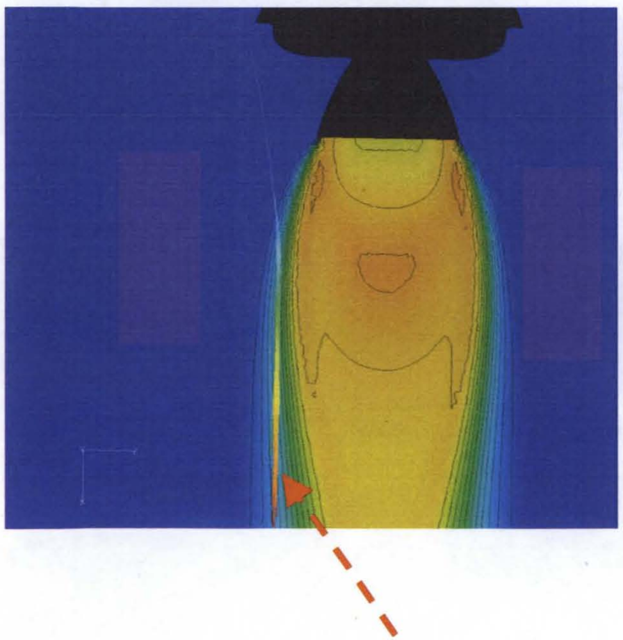
**Temperature(100% Power Level)**



# SPACE SHUTTLE AND LAUNCH PAD LIFF-OFF DEBRIS TRANSPORT ANALYSIS

## Typical Results: Preliminary Studies of SRB Exhaust Plumes

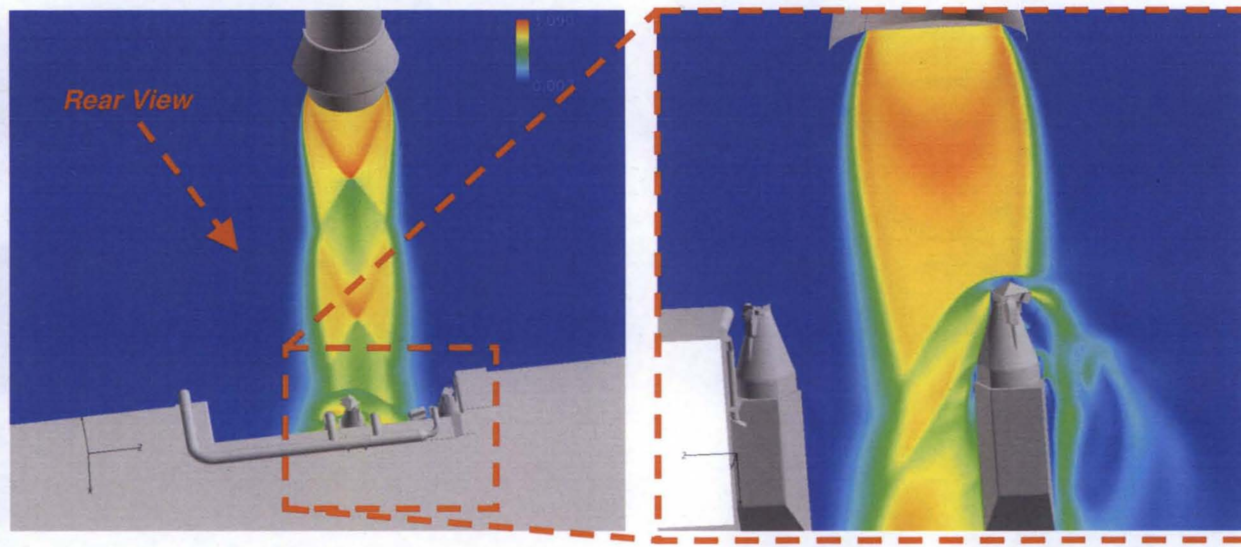
**Mach Number Contours of a Single SRB Plume, Featuring Velocity of Entrained Debris**



**Entrained Debris Trajectory (colored by Entrainent Velocity)**

**Mach Number Contours of a Single SRB Plume, At Lift-Off from Launch Pad, Featuring Impingement**

**Mach Number Contours of a Single SRB Plume, At Lift-Off from Launch Pad, Featuring Impingement**

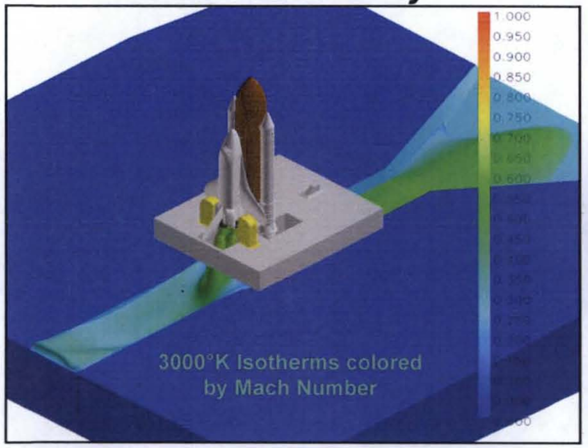



**Rear View and Zoom**

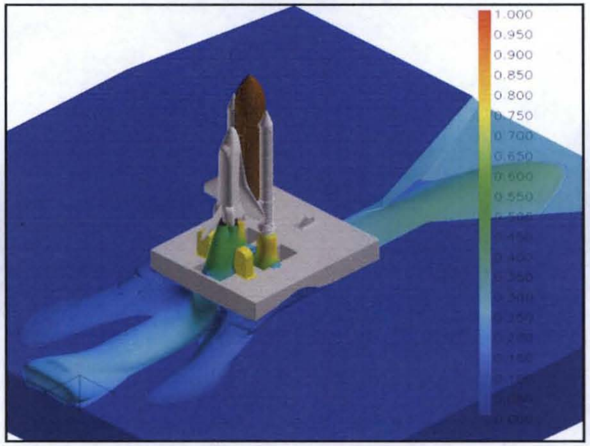
# SPACE SHUTTLE AND LAUNCH PAD LIFF-OFF DEBRIS TRANSPORT ANALYSIS

## Typical Results: Preliminary Results of CFD Simulation of Plumes from Integrated Space Shuttle Vehicle during Lift-Off

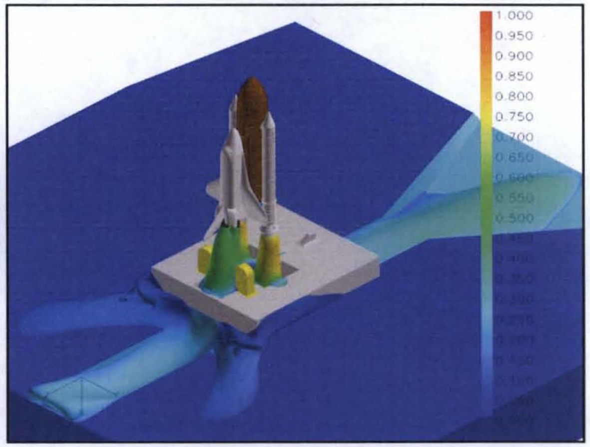
**t = 0 seconds: SSME Plumes Only**



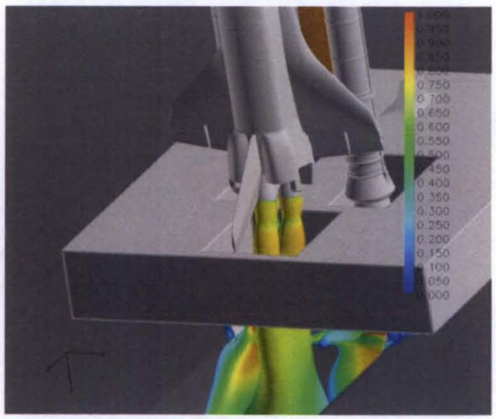

**t = 2 seconds: SSME Plumes with SRB Plumes**



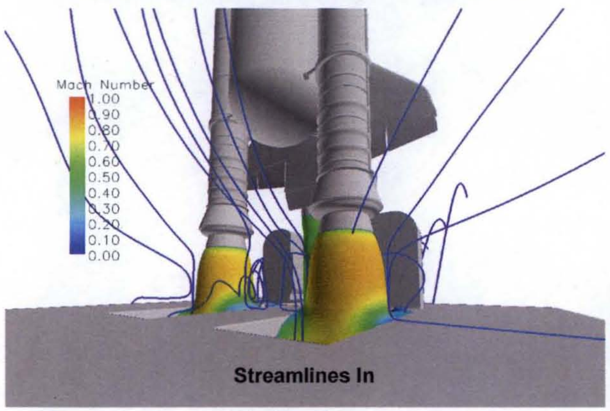

**t = 3 seconds: SSME Plumes with SRB Plumes**



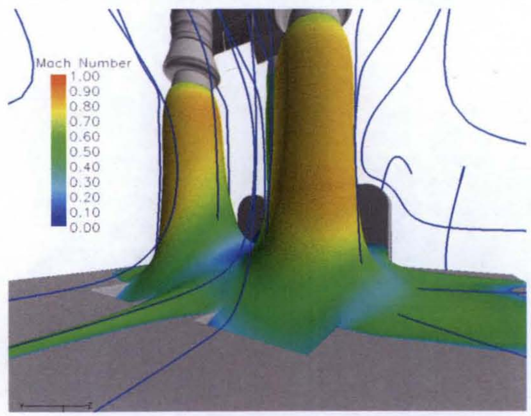

**t = 0 seconds:**



**t = 2 seconds: Plume Entrainment of Streamlines**




**t = 3 seconds: Plume Entrainment of Streamlines**

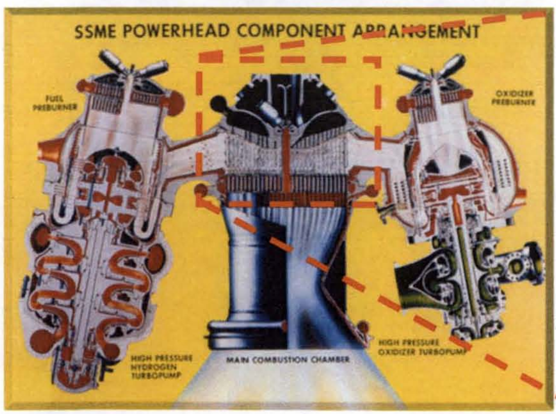


# COMBUSTION DEVICES CFD TEAM ANALYSIS REVIEW

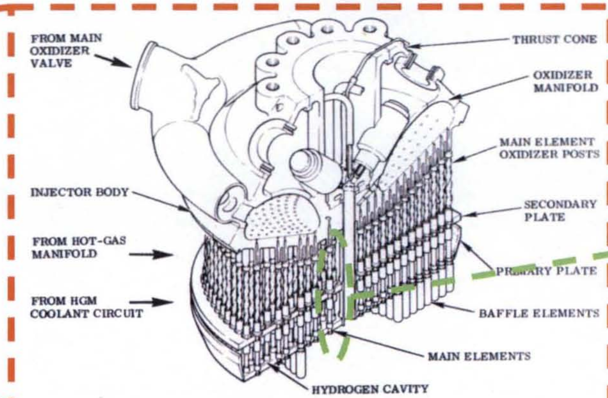
## STUDY OF PROPELLANT MIXING AND PERFORMANCE OF A SSME MAIN INJECTOR

- ***Analysts: Marvin Rocker & Jeff West***
- ***Customer: SSME Project Office/Design Engineering Team,***
- ***Customer Concern: The effect of injector element design and operating conditions on combustion performance, which effects the maximum payload capacity,***
- ***Item to be Modeled: SSME Main Combustion Chamber and Main Injector:***

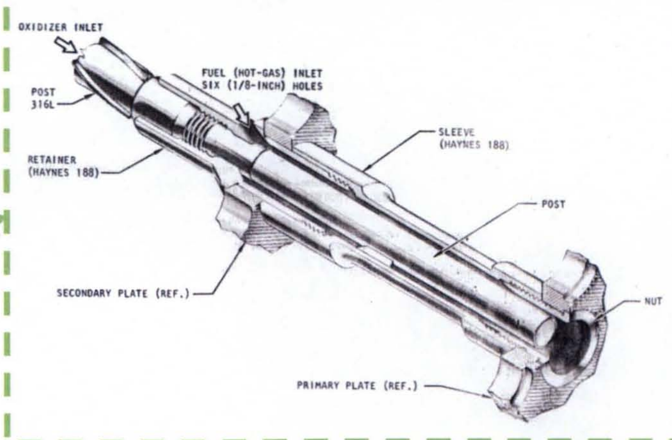
***Space Shuttle Main Engine Powerhead***




***Space Shuttle Main Engine Main Injector***




***Space Shuttle Main Engine Main Injector Element***



# STUDY OF PROPELLANT MIXING AND PERFORMANCE OF A SSME MAIN INJECTOR

- ***Objectives:** Perform simulations of a core element(s) at 100% and 104.5% power levels. Verify solution convergence, solution quality, and calculate performance,*

- ***Tools Used:** Loci-Chem(CFD code), Gridgen/SolidMesh(grid generators),*

- ***Process(& Status):***

  * *Simulate a 2D/axisymmetric, single-element injector model of the main combustion chamber to verify grid independence, and to obtain optimal-size grid for extension to 3D(completed for structured grids).*

  * *Simulate a full-3D, single-element injector model of the main combustion chamber to verify 2D/axisymmetric, single-element model results(completed for structured grid, in progress for unstructured grid).*

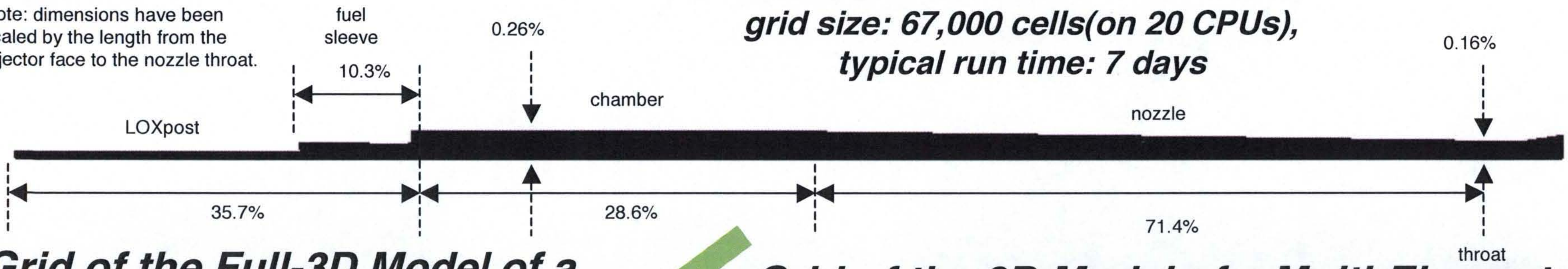
  * *Simulate a slice-3D, multi-element injector model of the main combustion chamber(TBD for unstructured grids).*

# STUDY OF PROPELLANT MIXING AND PERFORMANCE OF A SSME MAIN INJECTOR

## Grid of the 2D/Axisymmetric Model of a Single-element Injector

Note: dimensions have been scaled by the length from the Injector face to the nozzle throat.

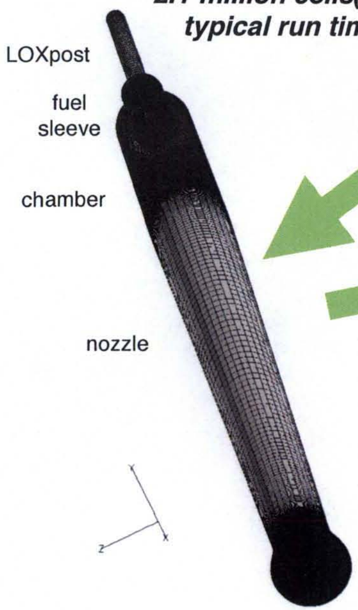
***grid size: 67,000 cells(on 20 CPUs), typical run time: 7 days***




## Grid of the Full-3D Model of a Single-Element Injector

***structured grid size: 2.1 million cells(on 40 CPUs), typical run time: 21 days***

***360° rotation about x-axis***

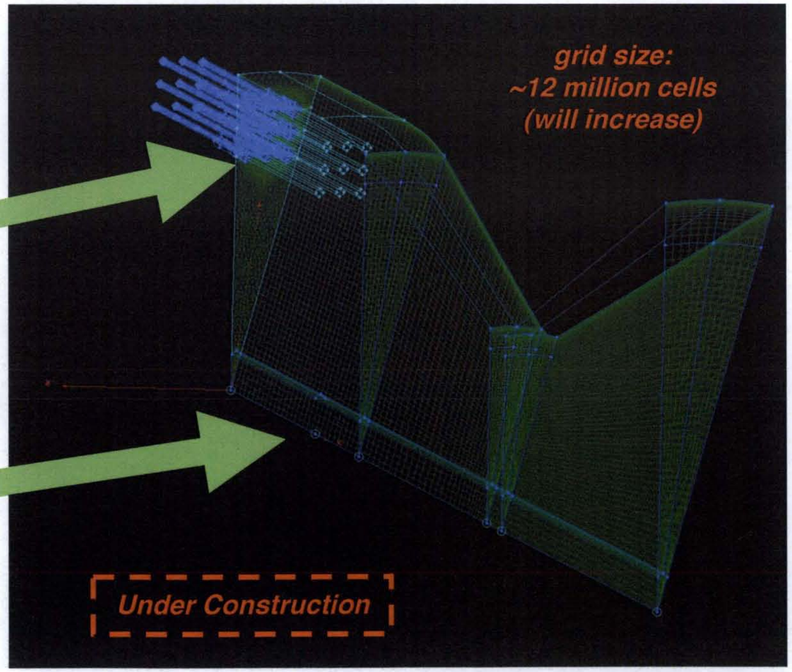



***unstructured grid size: 7.5 million cells(on 48 CPUs), Typical run time: TBD***

***Duplicated grid for injector and flame streamtube to 9 locations on the injector face for rows 10, 11, and 12.***

***Constructed grid of Main Combustion Chamber, 3 row-10 elements wide.***

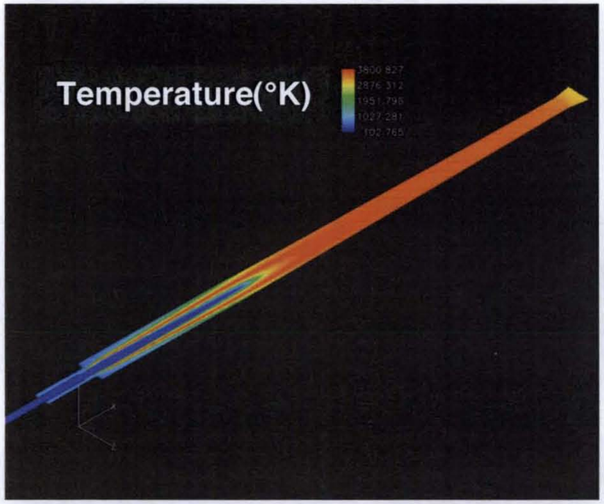
## Grid of the 3D Model of a Multi-Element Injector with the Main Combustion Chamber

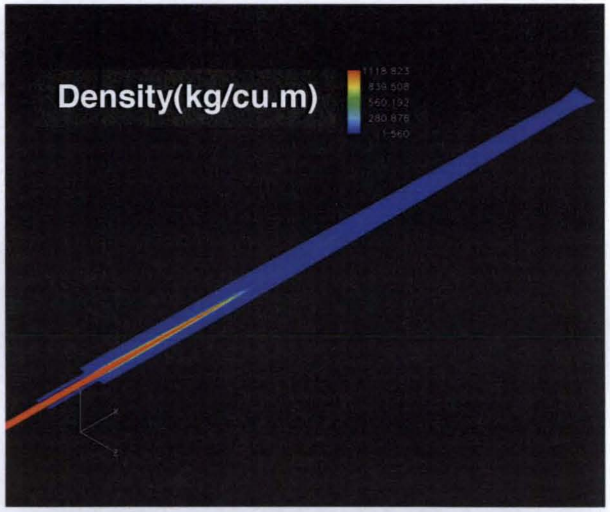


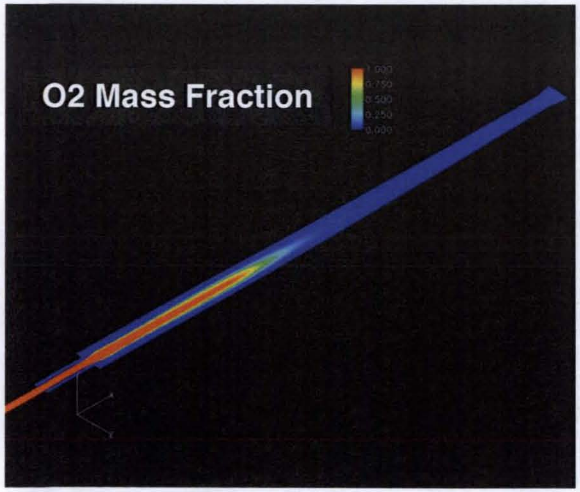
# STUDY OF PROPELLANT MIXING AND PERFORMANCE OF A SSME MAIN INJECTOR

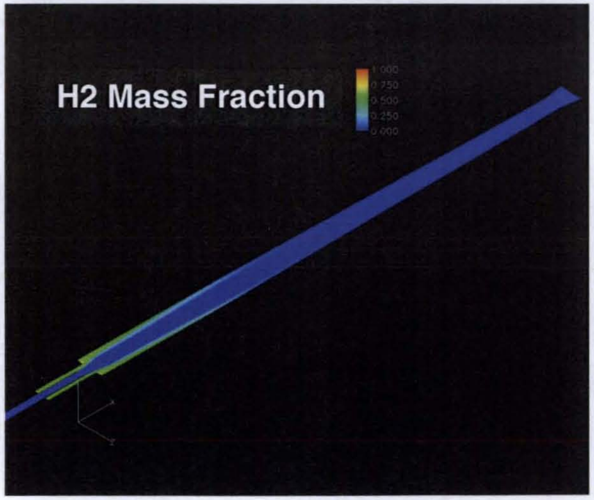
## *Typical Results: Solution Fields for a Full-3D Model of a Single-element Injector*

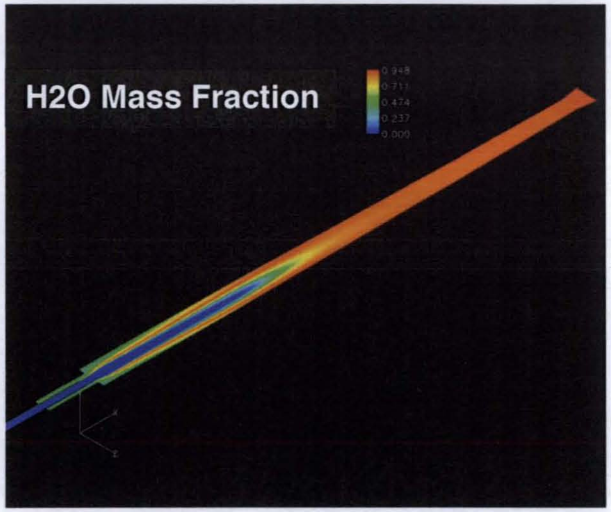
- ***Grid overall view:***



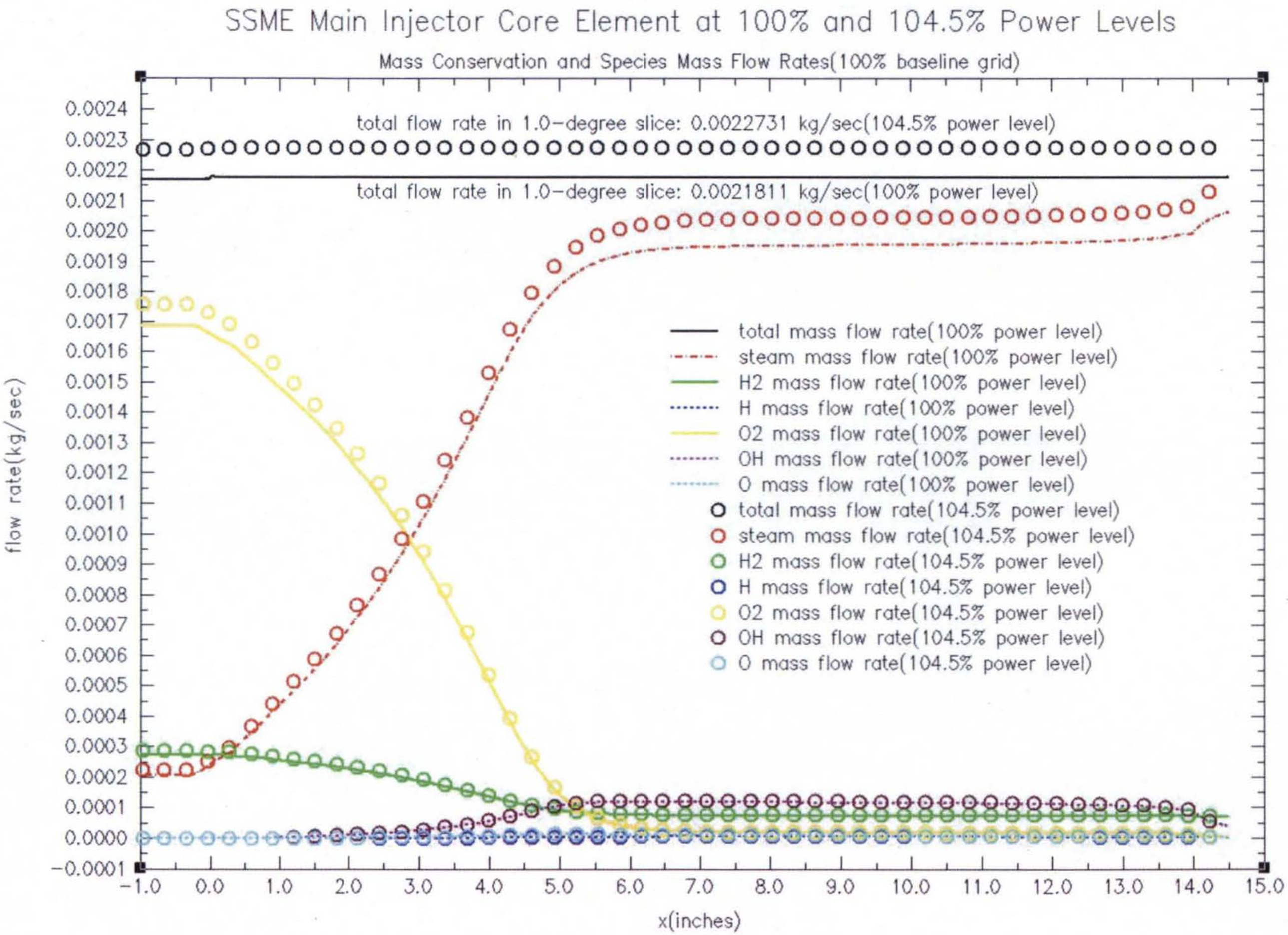



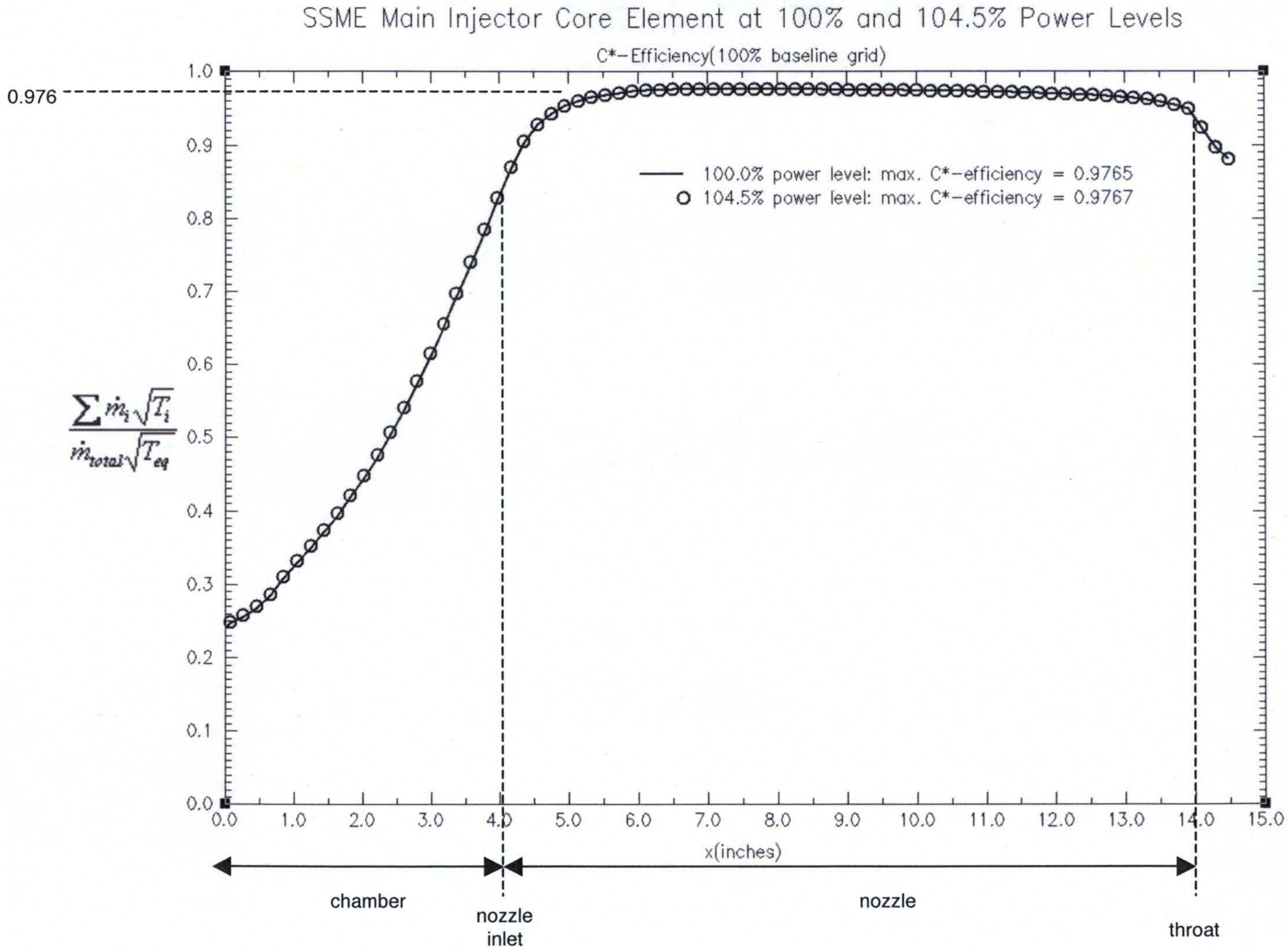



## Typical Results: Species Flow Rates vs x for a 2D/Axesymmetric Model of a Single-element Injector



# STUDY OF PROPELLANT MIXING AND PERFORMANCE OF A SSME MAIN INJECTOR

## Typical Results: C*-Efficiency vs x for a 2D/Axesymmetric Model of a Single-element Injector

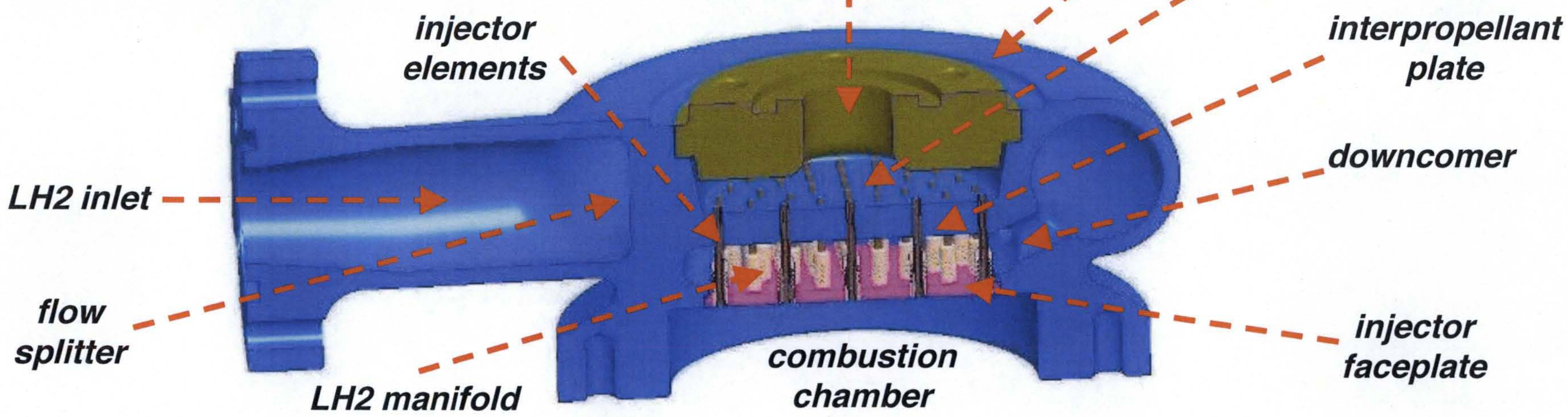


# COMBUSTION DEVICES CFD TEAM ANALYSIS REVIEW

## STUDY OF FUEL FLOW IN THE MANIFOLD OF THE J-2X GAS GENERATOR

- ***Analysts: Doug Westra & Jeff West***
- ***Customers: Combustion Devices Design and Development Branch & J-2X Program Office,***
- ***Customer Concern: The effect of fuel flow non-uniformities across the injector face will cause a non-uniform mixture ratio, which will cause a non-uniform hot-gas temperature, which will violate ±50°R criterion,***
- ***Item to be Modeled: J-2X Gas Generator Fuel Manifold with Injector Elements:***

***GAS GENERATOR MANIFOLD***



# COMBUSTION DEVICES CFD TEAM ANALYSIS REVIEW

## STUDY OF FUEL FLOW IN THE MANIFOLD OF THE J-2X GAS GENERATOR

- ***Objective: Simulate fuel flow through the Gas Generator manifold and through the 61 shear-coaxial injector elements, determine flow uniformity through:***

  * ***torus & downcomers,***

  * ***LH2 manifold & injector elements,***

  * ***injector elements internally & element-to-element comparison,***

- ***Objective: Investigate fuel flow patterns and pressure drops,***
- ***Tools Used: Loci-Chem & Loci-Stream(CFD codes), ANSA & SolidMesh/AFLR(grid generators),***
- ***Process(& Status):***

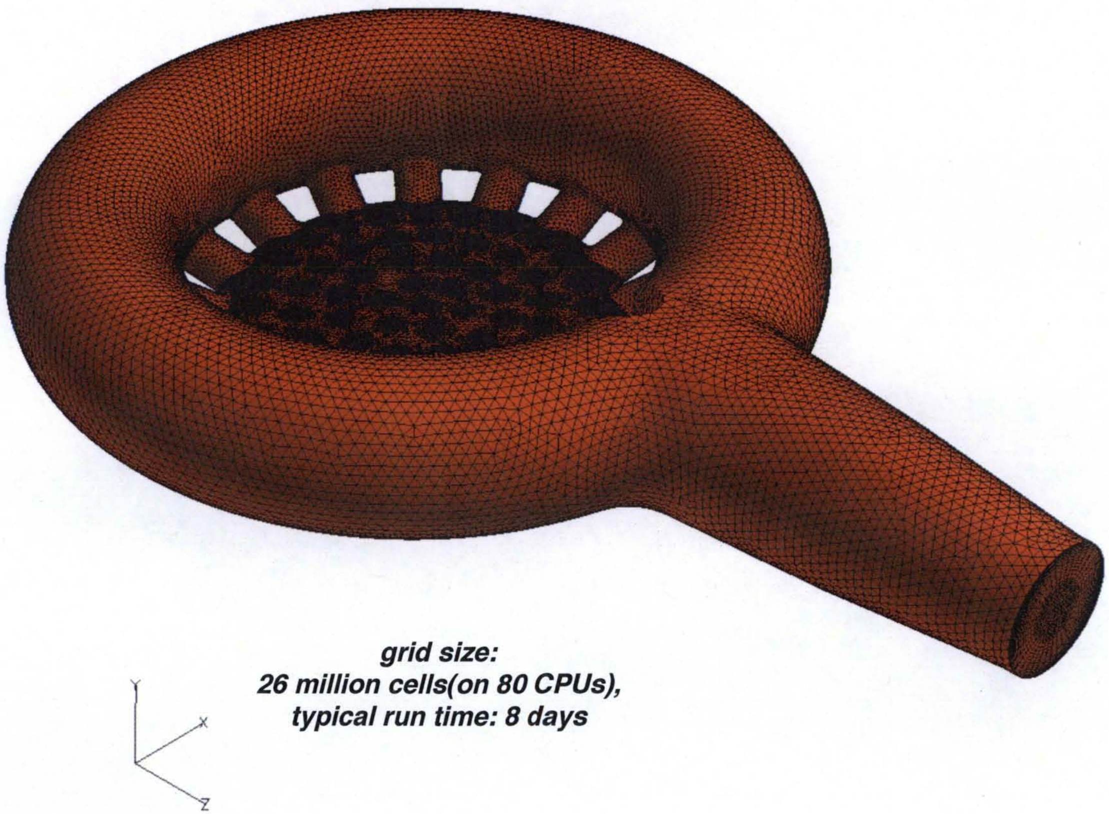
  * ***Convert existing CAD model of Gas Generator manifold to a 3D surface grid with ANSA & generate 3D volume grid of Gas Generator manifold with SolidMesh/AFRL(completed),***

  * ***Simulate compressible, cold real fluid flow of H2 with Loci-Chem(completed),***

  * ***Simulate incompressible liquid flow of H2 with Loci-Stream(in progress).***

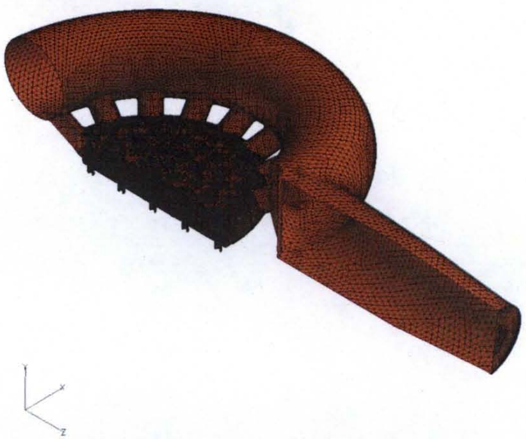
# STUDY OF FUEL FLOW IN THE MANIFOLD OF THE J-2X GAS GENERATOR

## Grid of the Fuel Manifold

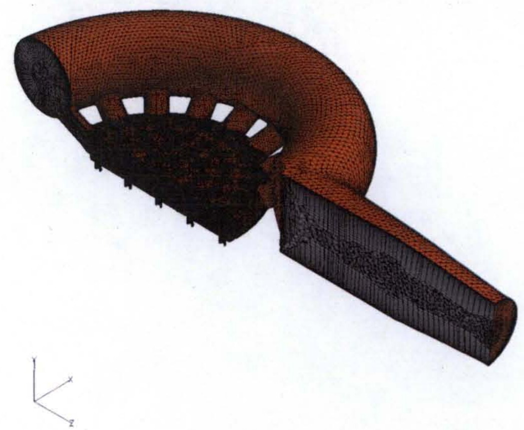



*grid size:*
*26 million cells(on 80 CPUs),*
*typical run time: 8 days*

## Surface Grid Details



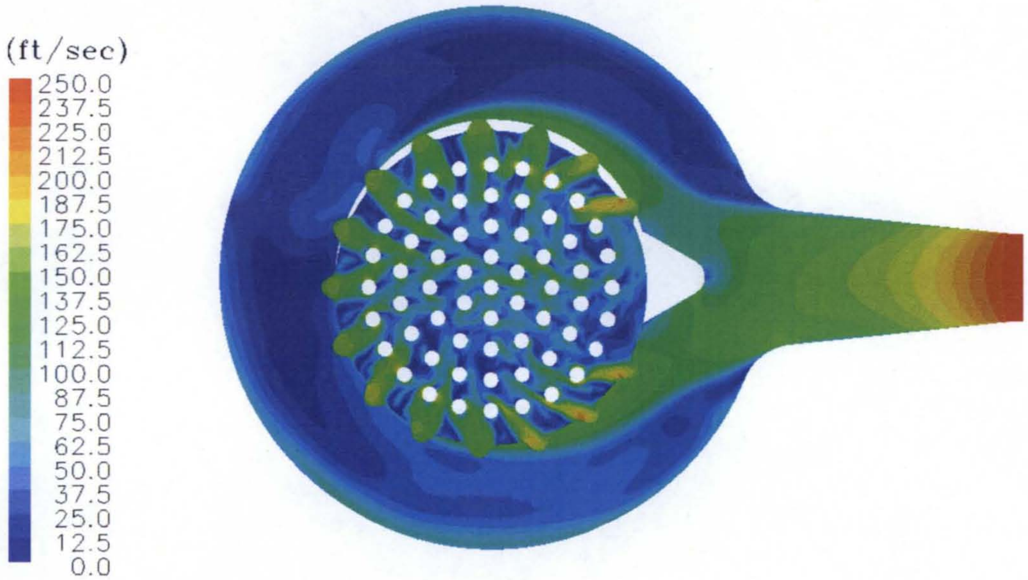
## Volume Grid Details



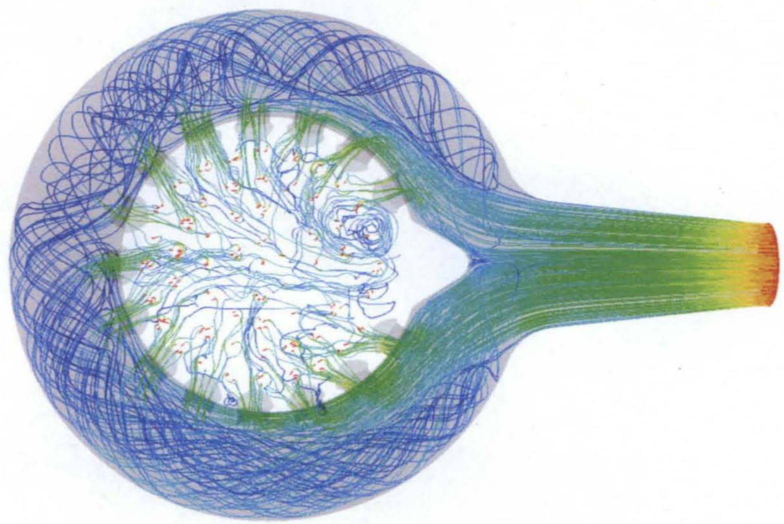
# STUDY OF FUEL FLOW IN THE MANIFOLD OF THE J-2X GAS GENERATOR

## Typical Results: Fuel Flow Patterns

### Velocity Magnitude

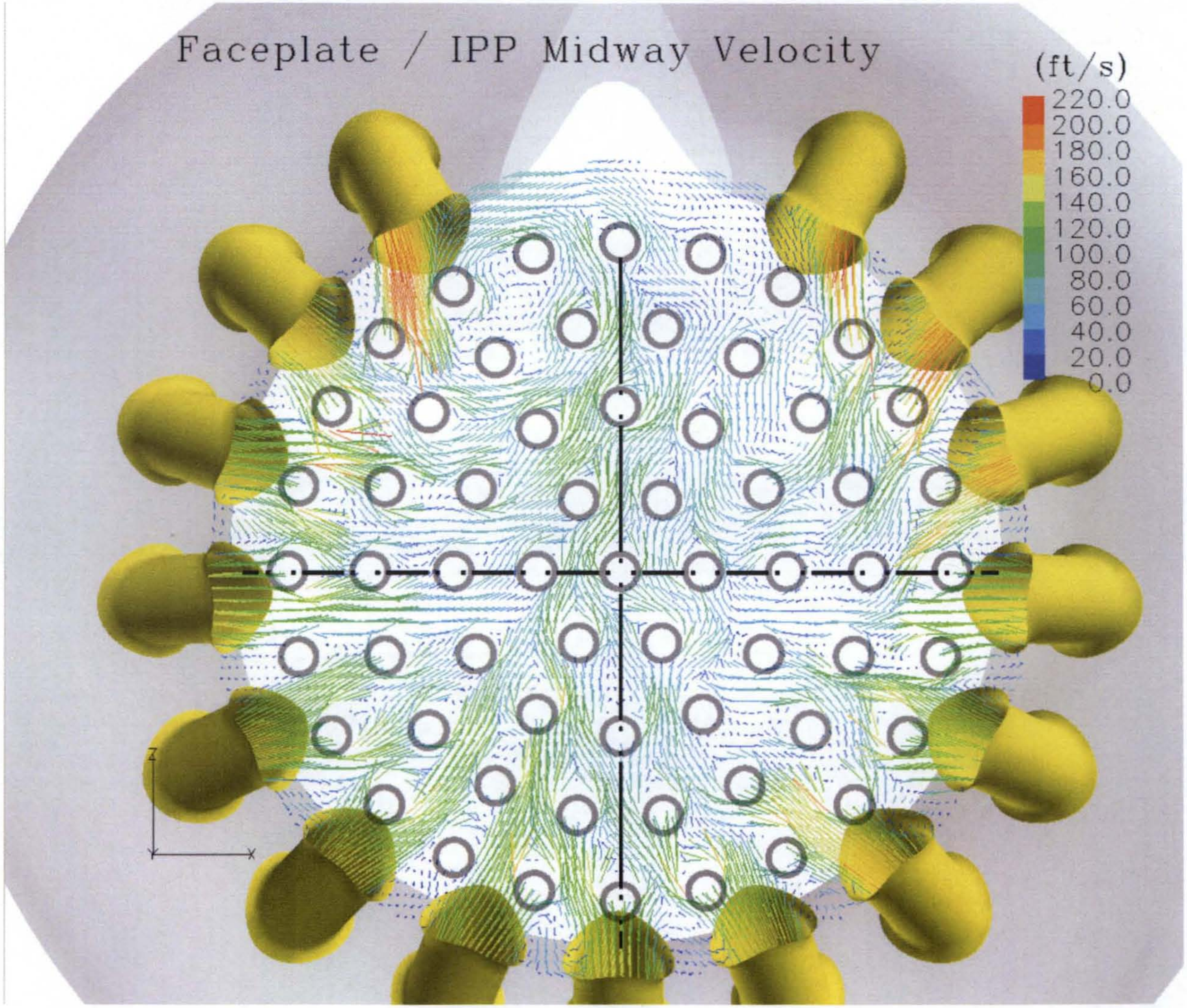



### Streamlines



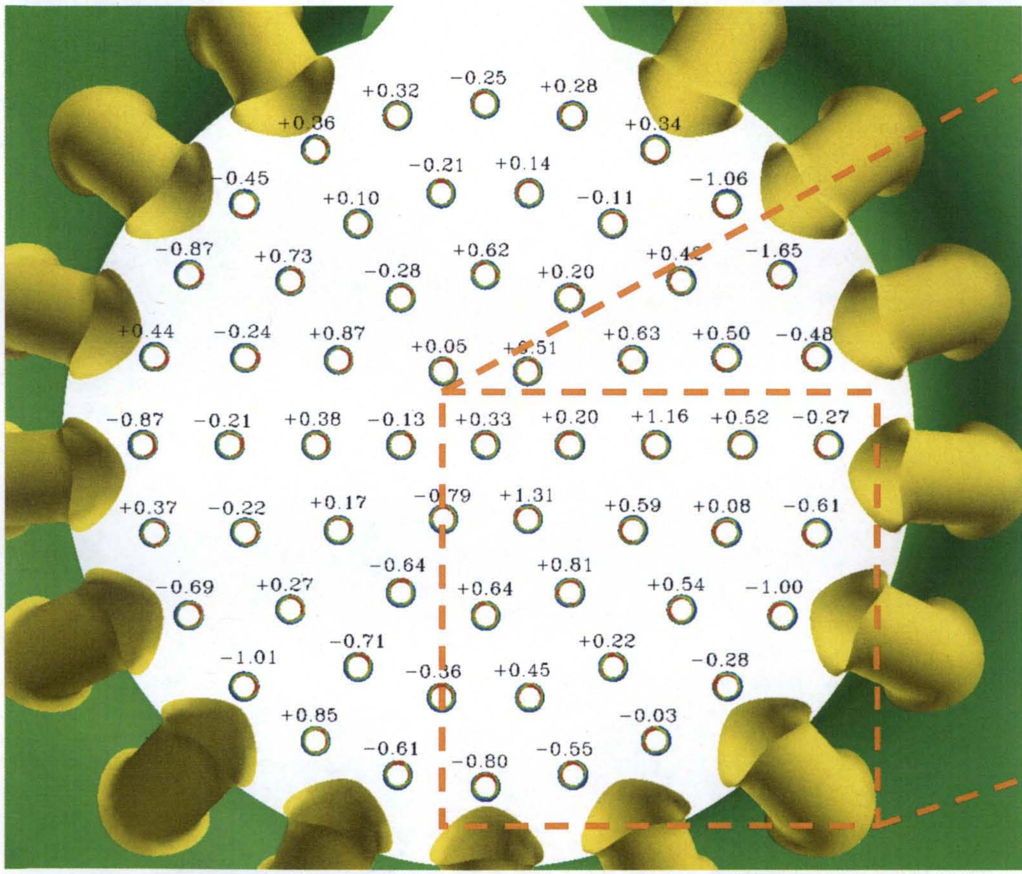
## STUDY OF FUEL FLOW IN THE MANIFOLD OF THE J-2X GAS GENERATOR

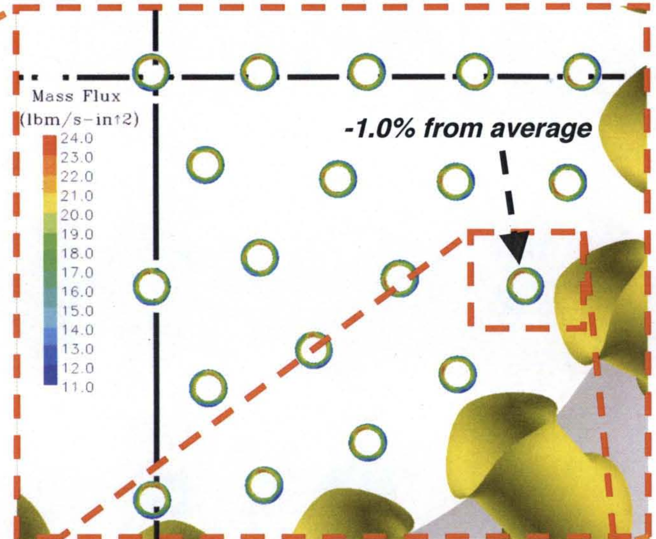
### Typical Results: Fuel Manifold Velocity Vectors Featuring Flow Non-Uniformity

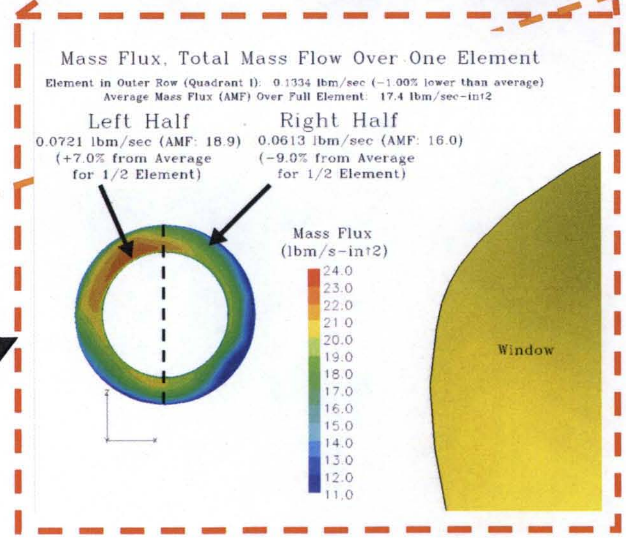


# STUDY OF FUEL FLOW IN THE MANIFOLD OF THE J-2X GAS GENERATOR

## Typical Results: Injector Element Mass Flux Across Injector Faceplate



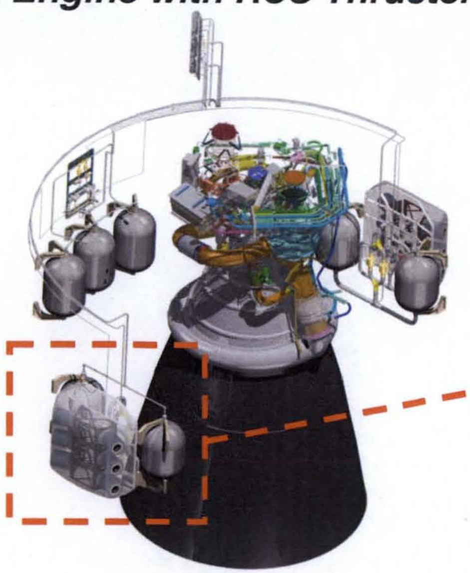

- ***Element-to-Element Percent Deviation from Average Injector Element Fuel Flow Rate,***
- ***Internal Element Percent Deviation from Average Injector Element Fuel Flow Rate.***

# COMBUSTION DEVICES CFD TEAM ANALYSIS REVIEW

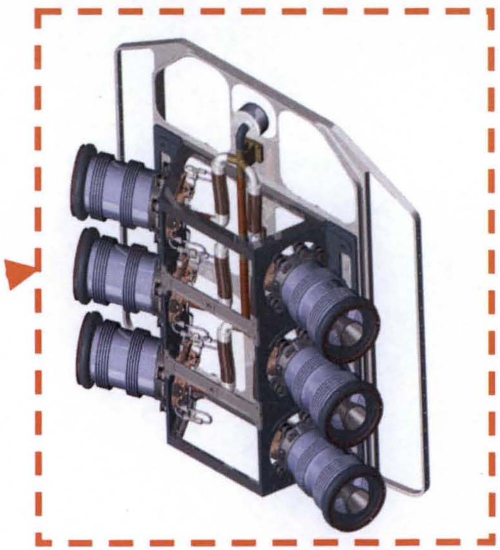
## STUDY OF ARES-I FIRST-STAGE ROLL CONTROL SYSTEM PERFORMANCE AND PLUME EFFECTS

- ***Analysts: Chris Morris & Joe Ruf***
- ***Customers: Spacecraft and Vehicle Systems Aerosciences Branch & Ares-I RCS Integrated Product Team,***
- ***Customer Concern: The roll moment performance of the installed roll control system(RCS) thrusters and the effects of thruster plume impingement on the vehicle,***
- ***Items to be Modeled: The Ares-I vehicle with the installed RCS thrusters.***

***J-2X Engine with RCS Thruster Pods***



***RCS Thruster Pod w/o Casing***



# STUDY OF ARES-I FIRST-STAGE ROLL CONTROL SYSTEM PERFORMANCE AND PLUME EFFECTS

- ***Objectives:***

  *** Simulate installed RCS thruster plume flows injected into air cross flow moving along upper portion of the Ares-I vehicle during subsonic through hypersonic flight conditions,***

  *** Determine roll moments as a function of angle-of-attack($\alpha$) and side-slip angle($\beta$).***

  *** Determine heat flux due to thruster plume impingement.***

- ***Tools Used: Loci-Chem(CFD code), Gridgen & SolidMesh/AFLR(grid generators),***

- ***Process(& Status):***

  *** Simulate the upper portion of the Ares-I vehicle over all flight conditions, subsonic-thru-hypersonic, for all ranges of $-5° < \alpha < 5°$ and $-5° < \beta < 5°$, with and w/o RCS thrusters activated(done for 360° grid, in-progress for 180° grid),***

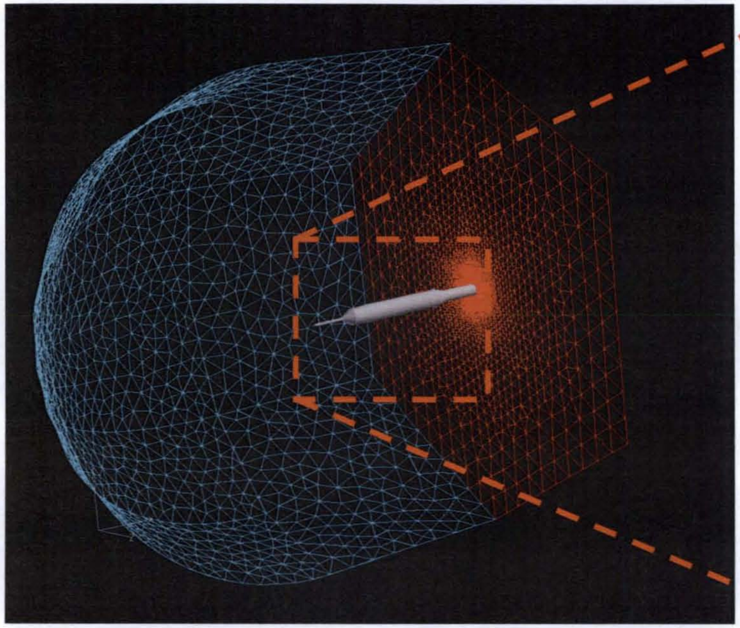
  *** Calculate difference in roll moment with and w/o RCS thrusters activated for all flight conditions(done for 360° grid, in-progress for 180° grid),***

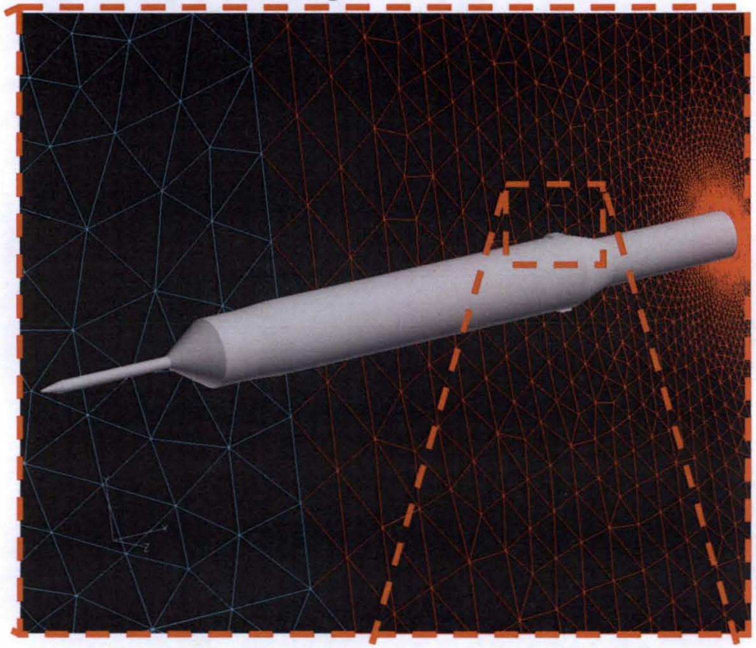
  *** Calculate local vehicle wall temperature, wall pressure, and wall heat flux due to plume impingement(done for 360° grid, in-progress for 180° grid).***

# COMBUSTION DEVICES CFD TEAM ANALYSIS REVIEW

## STUDY OF ARES-I FIRST-STAGE ROLL CONTROL SYSTEM PERFORMANCE AND PLUME EFFECTS

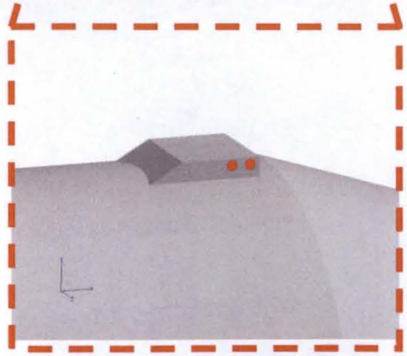
### *Surface Grid of the Ares-I Upper Stage, Upper Portion of the SRB, and the Far Field Boundary*





- ***360° Grid:***
  **** grid size: 20 million cells(on 30 CPUs), typical run time: 4 days,***

- ***180° Grid:***
  **** grid size: 40 million cells(on 60 CPUs), typical run time: 7 days,***



***2-Thruster RCS Pod***

# STUDY OF ARES-I FIRST-STAGE ROLL CONTROL SYSTEM PERFORMANCE AND PLUME EFFECTS

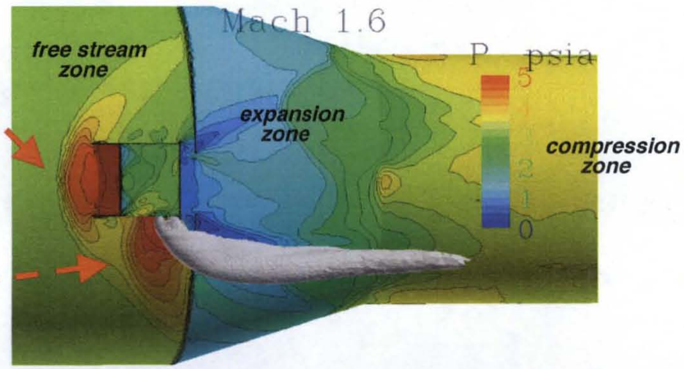
## Typical Results: Plume Impingement and Plume-Induced Separation

- RCS thruster plumes visualized by gray iso-surfaces of 15% thruster exhaust mass fraction,
- Vehicle surface pressure visualized by colors.

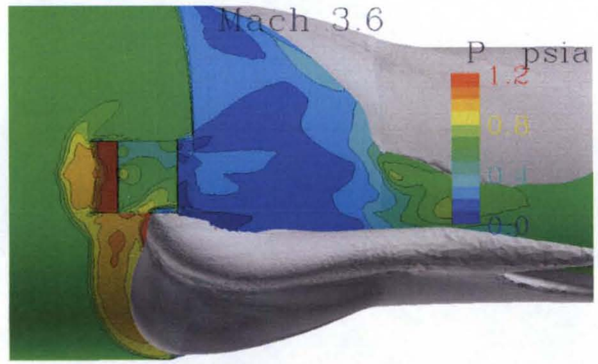
Thruster Pod Bow Shock

Bow Shock due to Plumes

Mach 1.6(58.5 sec @ 38,600 ft)

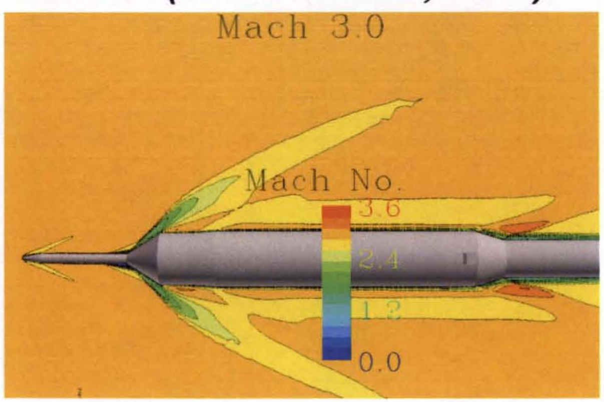



Mach 3.6(90.33 sec @ 95,800 ft)

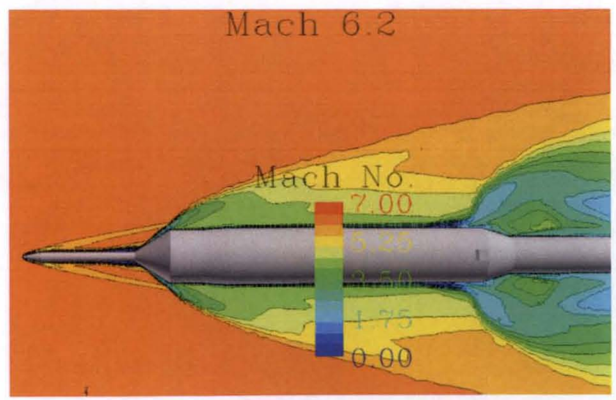



- No plume-induced flow separation for flight Mach numbers ≤ 3.0,
- Plume-induced separation at flight Mach number 6.2.

Mach 3.0(81.0 sec @ 72,800 ft)




Mach 6.2(130.26 sec @ 194,000 ft)

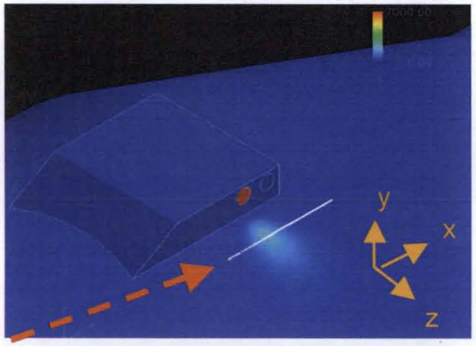


# STUDY OF ARES-I FIRST-STAGE ROLL CONTROL SYSTEM PERFORMANCE AND PLUME EFFECTS

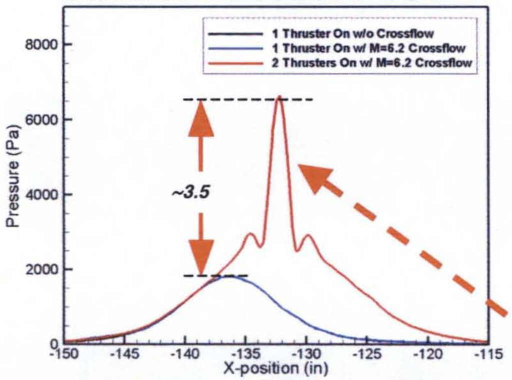
## Typical Results: Surface Pressure/Surface Heat Flux at Flight Mach Number 6.2

- *Vehicle experts calculated surface heat flux by modeling a thruster w/ plume and w/o a free stream,*
- *Current CFD Analysis has insufficient grid resolution for a surface heat flux calculation,*

### 1 Thruster without Crossflow

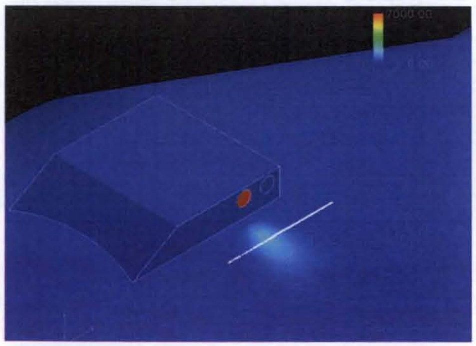



### Surface Pressure vs x

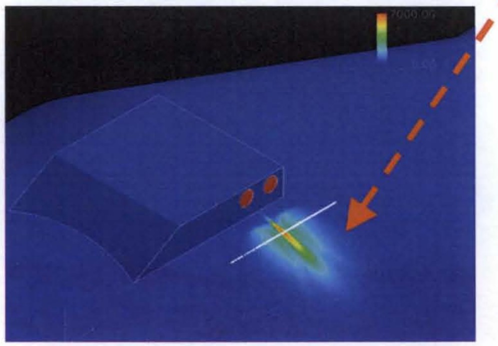



*White line indicates where the pressure and temperature were extracted from the CFD solutions.*

### 1 Thruster with Crossflow



### 2 Thrusters with Crossflow



*Plume-Plume Interaction*

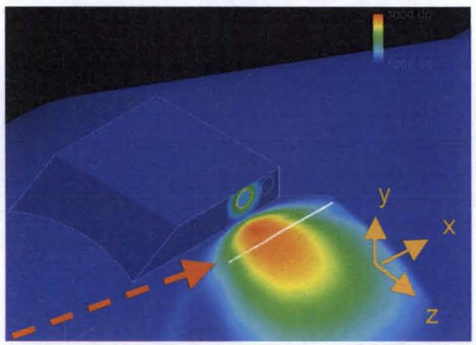
- **Estimate peak surface heat flux:** $q_{2\text{-plume}} = q_{1\text{-plume}} (p_{2\text{-plume}}/p_{1\text{-plume}})^{0.8} = 2.72\, q_{1\text{-plume}}$ .

# STUDY OF ARES-I FIRST-STAGE ROLL CONTROL SYSTEM PERFORMANCE AND PLUME EFFECTS

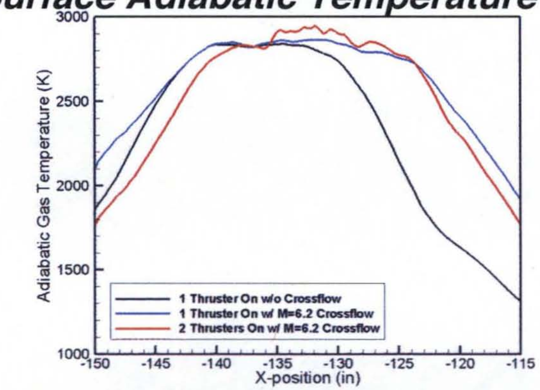
## Typical Results: Surface Adiabatic Temperature at Flight Mach Number 6.2

- *Single plume temperature shows that the effect of the free stream is to push the plume downstream,*
- *Double plume temperature show the plume-plume interaction that gives a rise of ~150°K,*

**1 Thruster without Crossflow**

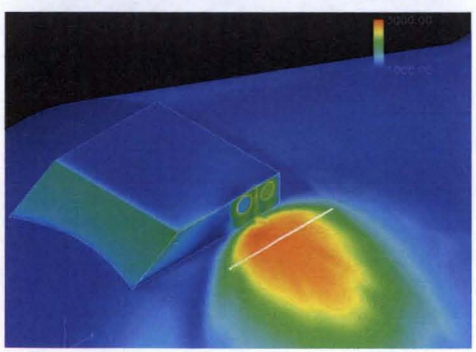



**Surface Adiabatic Temperature vs x**

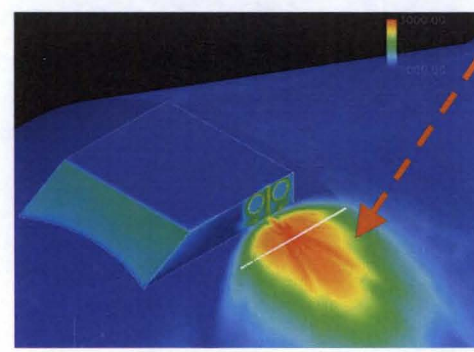



*White line indicates where the pressure and temperature were extracted from the CFD solutions.*

**1 Thruster with Crossflow**



**2 Thrusters with Crossflow**



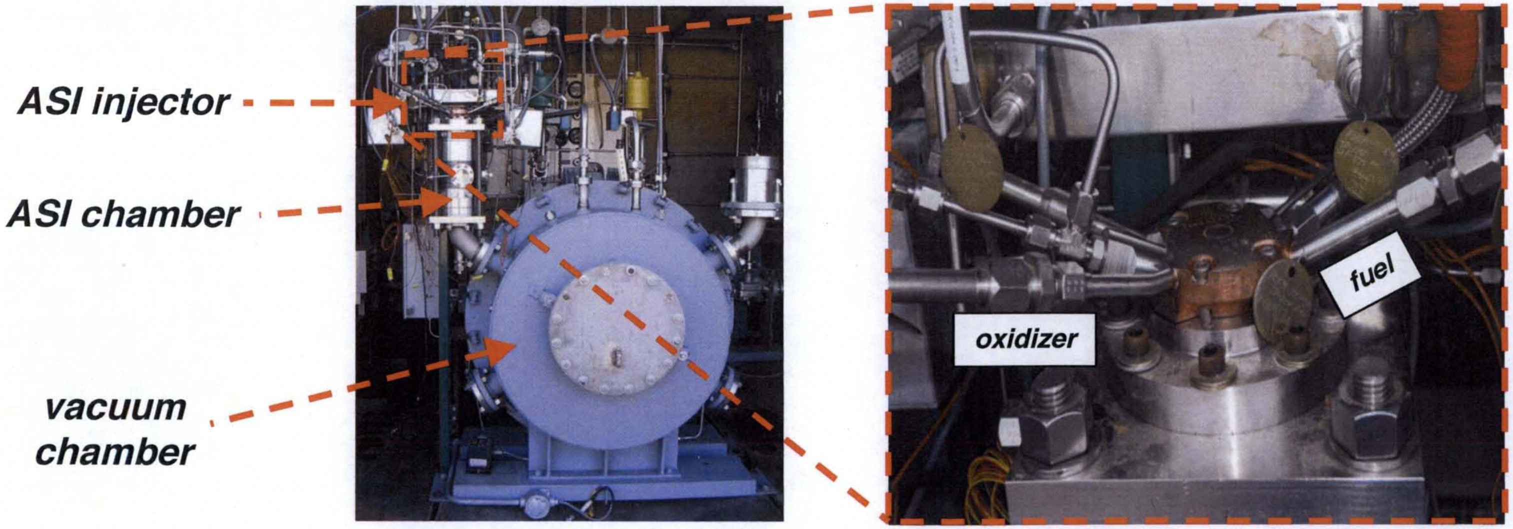
*Plume-Plume Interaction*

- *Surface temperature fields are more widespread that surface pressure fields.*

# STUDY OF J-2X AUGMENTED SPARK IGNITER PROPELLANT SEQUENCING AND MIXTURE RATIO

- ***Analysts: Jeff Lin & Jeff West***
- ***Customers: Combustion Devices Design and Development Branch & J-2X Program Office,***
- ***Customer Concern: Successful Augmented Spark Igniter(ASI) firing depends on the timing of individual propellant injection and mixture ratio,***
- ***Item to be Modeled: The J-2X ASI Injector and Chamber.***

**ASI Test Set-Up** **ASI Injector**



# STUDY OF J-2X AUGMENTED SPARK IGNITER PROPELLANT SEQUENCING AND MIXTURE RATIO

- ***Objective:***

  * *Simulate, for 4 conditions/cases with 2 mixture ratios, the transient injection of O2 into the ASI, flowing with a steady-state injection H2, and determine if the mixture ratio near the spark plug is sufficient to produce ignition.*

- ***Tools Used:*** *Loci-Chem(CFD code), ANSA & SolidMesh/AFLR(grid generators),*

- ***Process(& Status):***

  * *Convert existing CAD model of ASI injector and chamber to a 3D surface grid with ANSA & generate 3D volume grid of ASI injector and chamber with SolidMesh/AFRL(completed),*

  * *Simulate steady-state injection of warm GH2 only(completed for case-1),*

  * *Simulate transient injection of warm GO2 with the steady-state injection of warm GH2 to produce ignition. Converge to steady-state(TBD for case-1),*

  * *Simulate steady-state combustion of warm GO2/GH2 injection(TBD for case-1 only),*

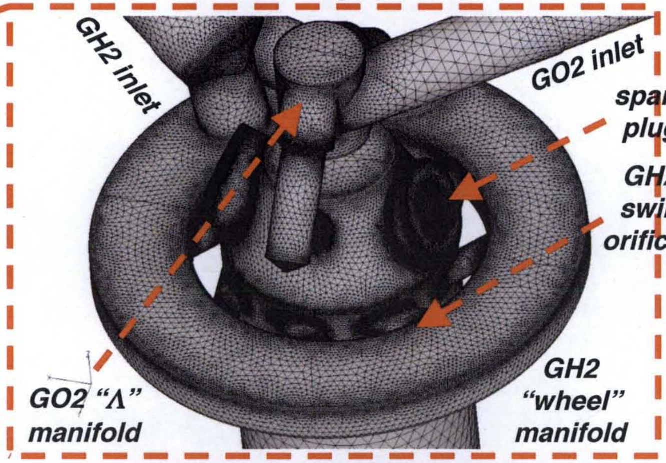
  * *Repeat steps 2 and 3 for cases 2-4(TBD).*

# STUDY OF J-2X AUGMENTED SPARK IGNITER PROPELLANT SEQUENCING AND MIXTURE RATIO

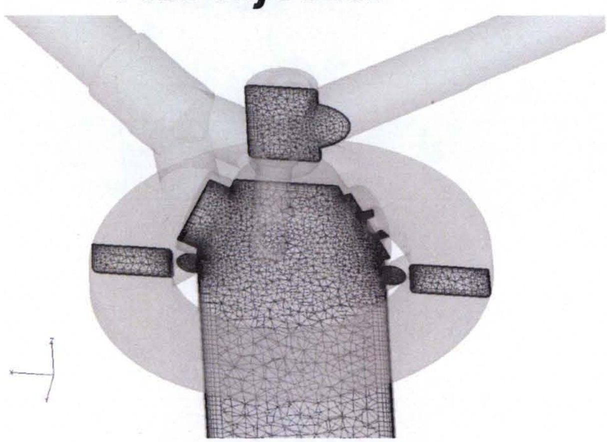
## Surface Grid of the ASI Injector & Chamber

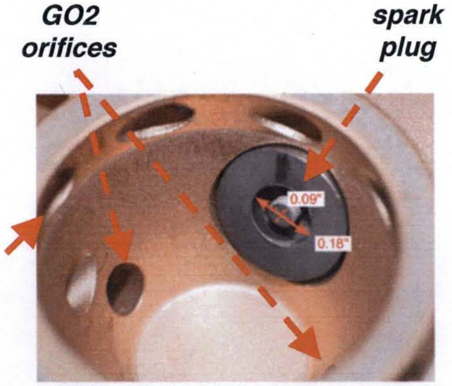

grid size:
6 million cells(on 12 CPUs),
typical run time: 21 days

## Surface Grid of the ASI Injector

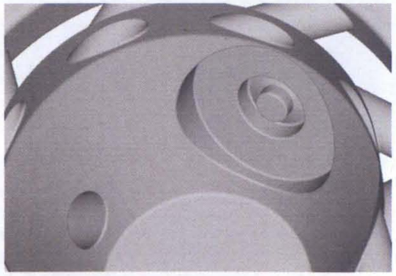



## Volume Grid of the ASI Injector






## Upstream View of the Actual ASI Injector

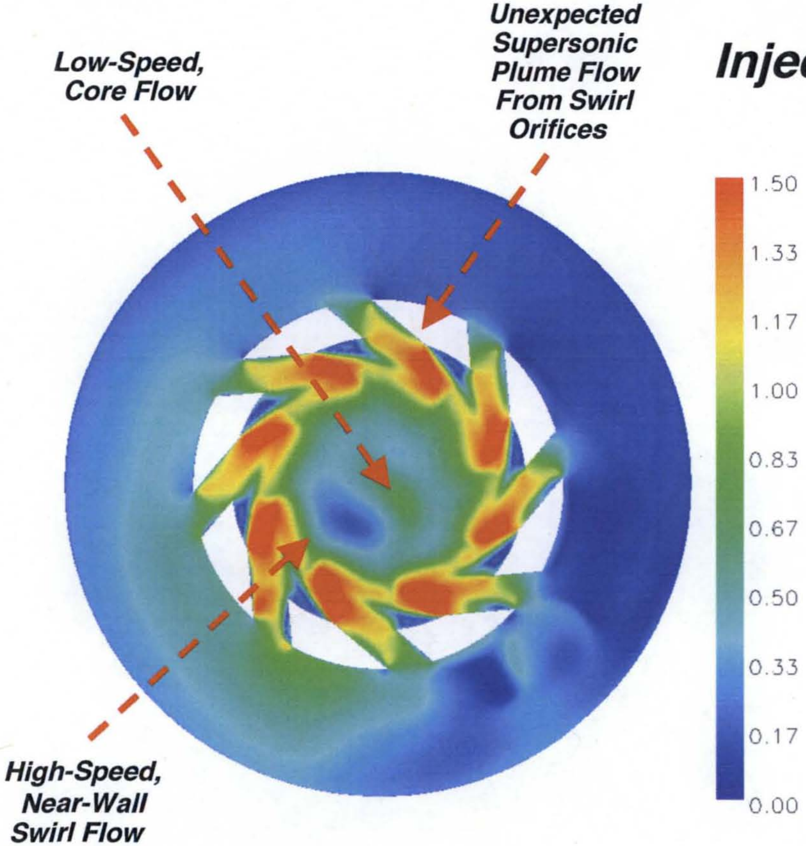


## Upstream View of the Modeled ASI Injector

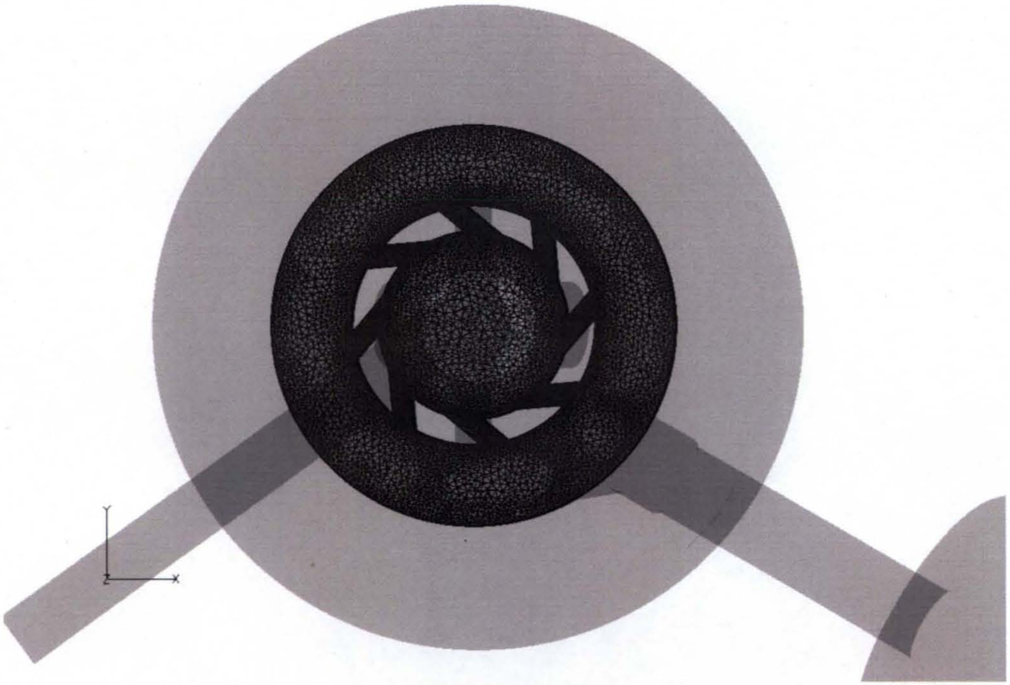
# STUDY OF J-2X AUGMENTED SPARK IGNITER PROPELLANT SEQUENCING AND MIXTURE RATIO

## Typical Results: Steady-State Injection of Warm GH2 for Case-1

### Injector Top View




**Mach Number**



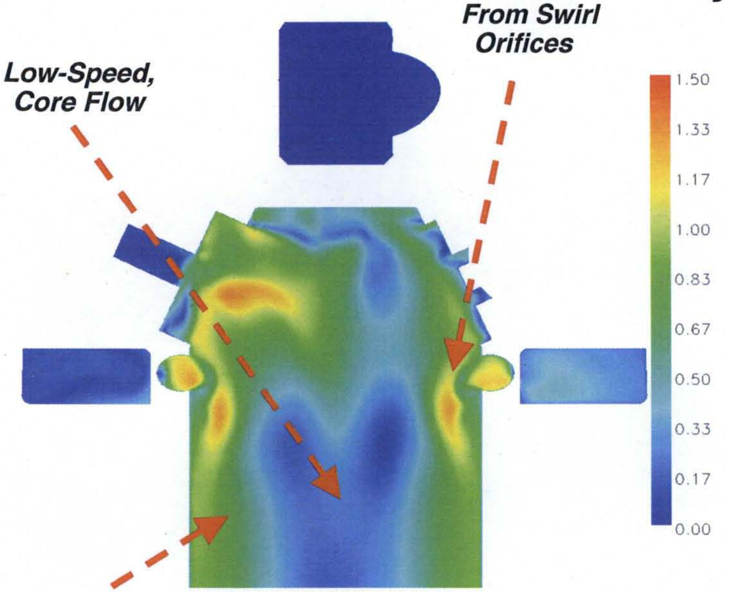
**Top View Cross-Section of the ASI Injector**

# COMBUSTION DEVICES CFD TEAM ANALYSIS REVIEW

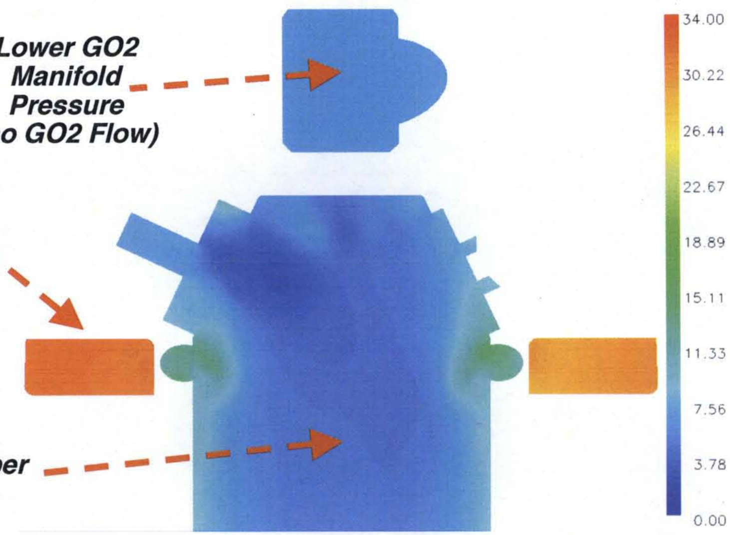
## STUDY OF J-2X AUGMENTED SPARK IGNITER PROPELLANT SEQUENCING AND MIXTURE RATIO

### Typical Results: Steady-State Injection of Warm GH2 for Case-1

**Injector Side View**

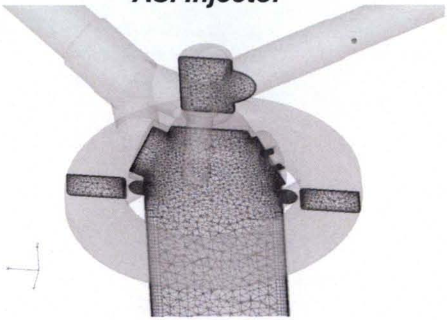



**Mach Number**




**Pressure(psi)**

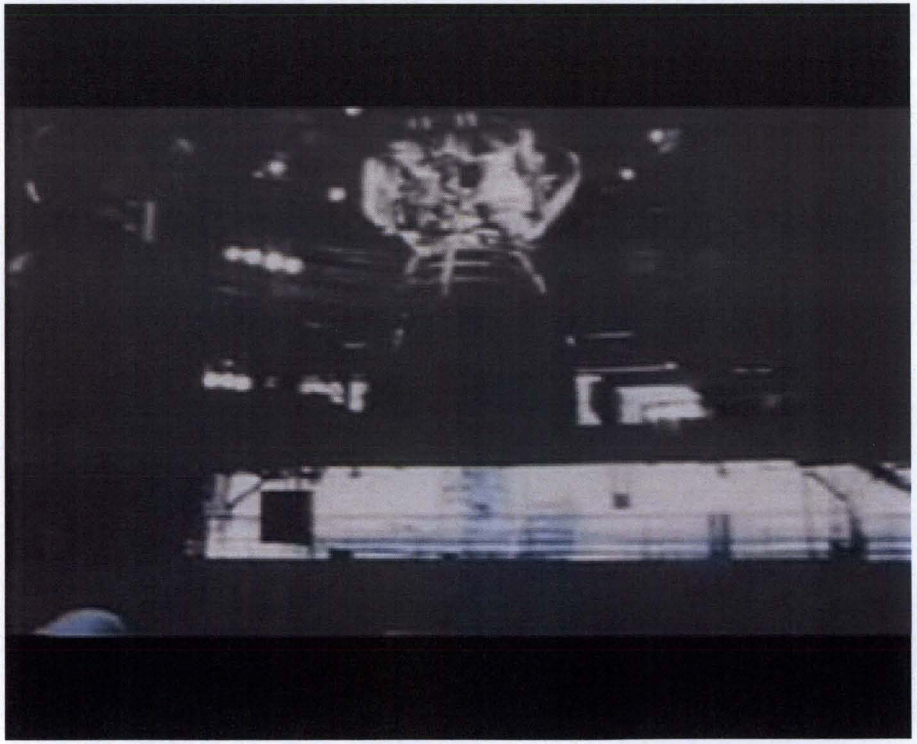
Side View Cross-Section of the ASI Injector



# STUDY OF SIDE LOADS IN A J-2X ENGINE NOZZLE DURING START-UP

- *Analyst: Ten-See Wang*
- *Customers: Liquid Engine and Main Propulsion Systems Branch & J-2X Program Office,*
- *Customer Concern: Nozzle side loads experienced during engine start-up and shut-down may result in reduced structural integrity,*
- *Item to be Modeled: The Chamber and Nozzle for the SSME and J-2X engines.*

*SSME Test Featuring Nozzle Deformations during Start-Up*



*J-2X Engine (expendable)*

## STUDY OF SIDE LOADS IN A J-2X ENGINE NOZZLE DURING START-UP

- ***Objective:*** ***To calculate J-2X engine nozzle side loads during start-up transient,***
- ***Tools Used: UNIC(CFD code), Gridgen(grid generator),***
- ***Process(& Status):***

**** Simulate the SSME during start-up to establish CFD code credibility in the calculation of wall heat transfer, thrust, and side loads(completed),***

**** Simulate the J-2X engine chamber and nozzle during steady-state with 2D/axisymmetric and 3D grids to address the following issues:***

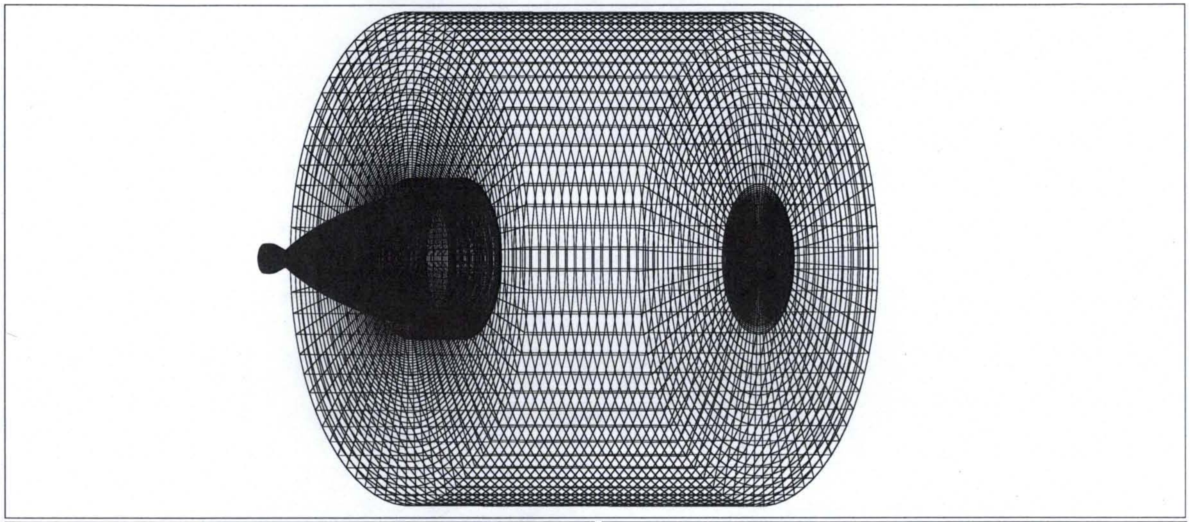
***- Grid sizes required for solution grid independence(completed),***

***- Effect of conjugate heat transfer and radiation heat transfer on thrust (completed),***

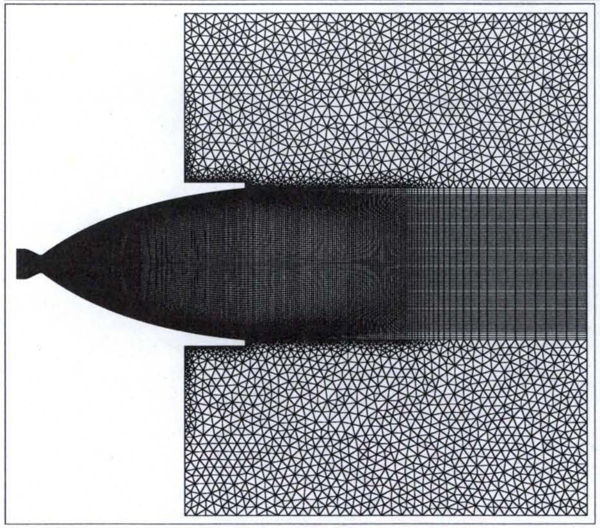
**** Simulate the J-2X engine chamber and nozzle during start-up and shut-down to calculate side loads(in progress).***

# STUDY OF SIDE LOADS IN A J-2X ENGINE NOZZLE DURING START-UP

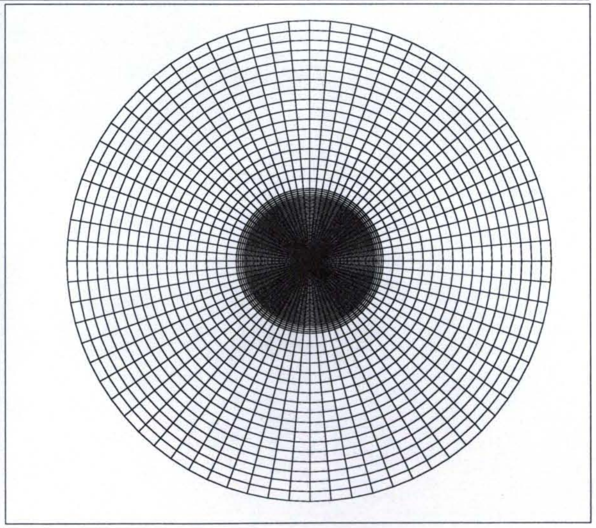
***Surface Grid of the SSME Chamber and Nozzle***



***Side View Cross-Section of the Volume Grid of Chamber and Nozzle***



*grid size:*
*1.3 million cells(on 13 CPUs),*
*typical run time: 28 days*

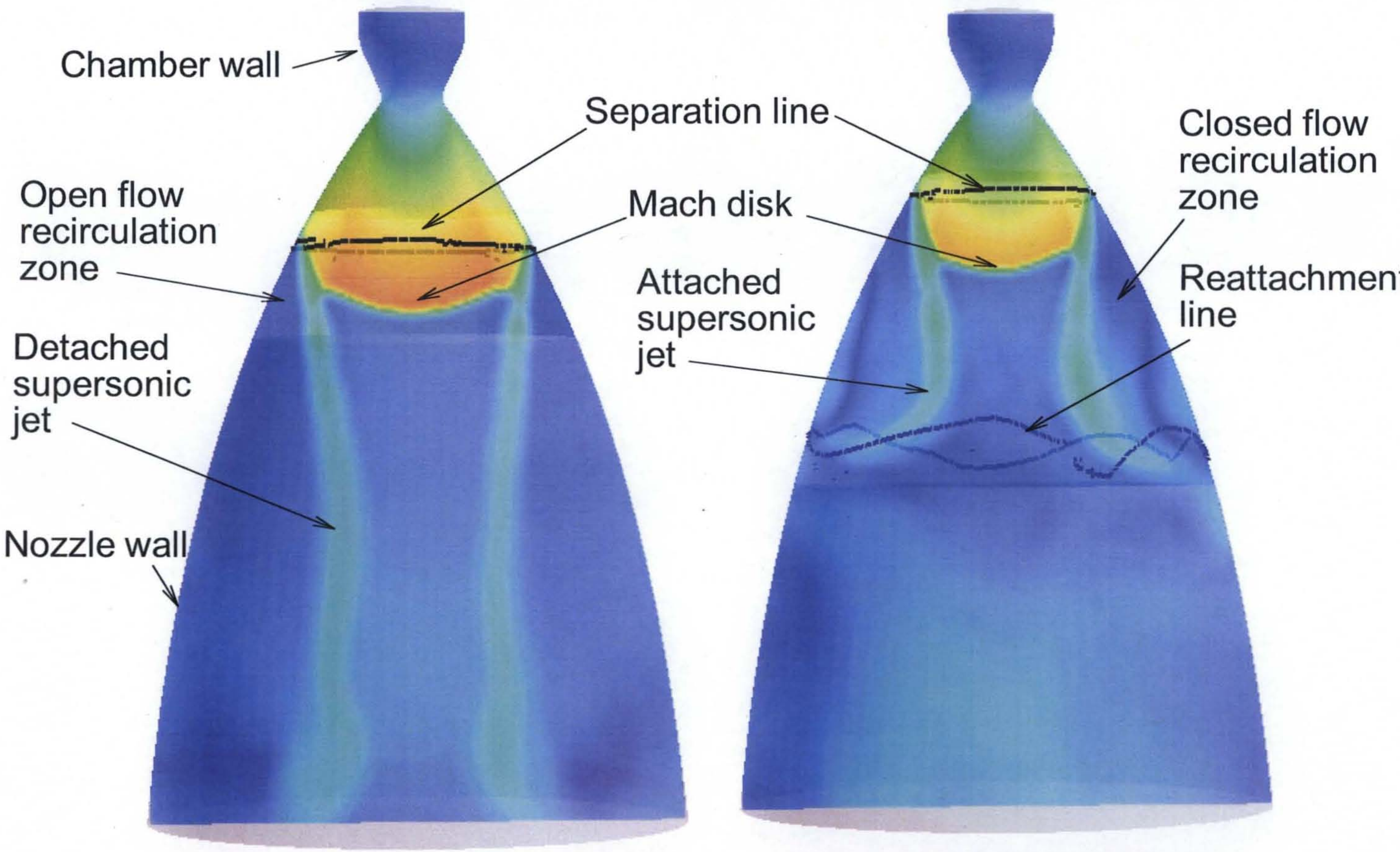


***End View of the Surface Grid***

# COMBUSTION DEVICES CFD TEAM ANALYSIS REVIEW

## STUDY OF SIDE LOADS IN A J-2X ENGINE NOZZLE DURING START-UP

### Typical Results: 3D CFD Simulation of SSME Start-Up Featuring Transition from Free-Shock Separation(FSS) to Restricted-Shock Separation(RSS)

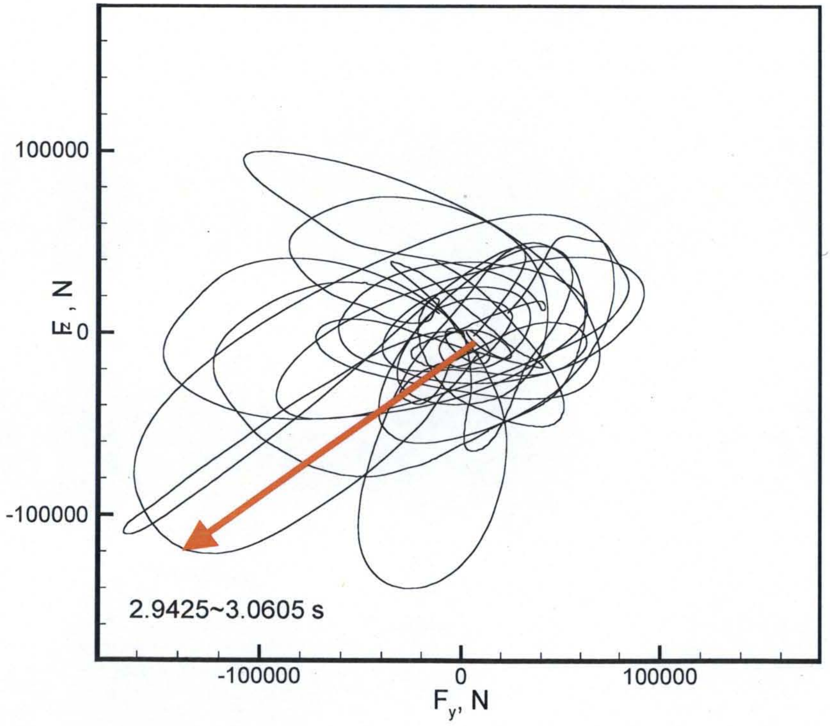



Free-shock separation
Mach disk flow at 1.513s

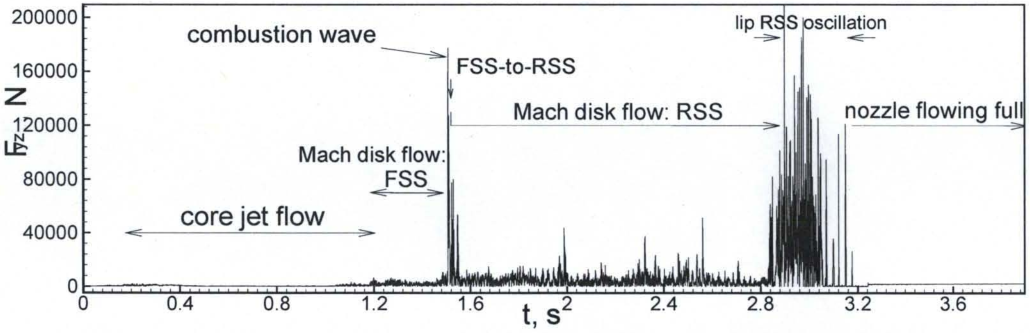
Restricted-shock separation
Mach disk flow at 1.523s

# Typical Results: SSME Start-Up Transient Side Loads

## Loci of Calculated Side Force Vector




## Time History of Calculated Side Force Magnitude




| Effect Contributing to Side Load | Experimentally Measured Side Force Magnitude(KN) | CFD Calculated Side Force Magnitude(KN) |
|---|---|---|
| Combustion Wave | n/a | 176 |
| FSS-to-RSS Transition | 90 | 80 |
| RSS Oscillation at Nozzle Lip | 200 | 212 |

| Effect Contributing to Side Load | Experimentally Measured Side Force Frequency(Hz) | CFD Calculated Side Force Frequency(Hz) |
|---|---|---|
| Combustion Wave | n/a | n/a |
| FSS-to-RSS Transition | n/a | n/a |
| RSS Oscillation at Nozzle Lip | > 100 | 122(pressure)/125(heat flux) |

# COMBUSTION DEVICES CFD TEAM ANALYSIS REVIEW

## STUDY OF SIDE LOADS IN A J-2X ENGINE NOZZLE DURING START-UP

### Typical Results: Start-Up/Shut-Down Simulation of a J-2X Engine Chamber with a Truncated Nozzle at Sea Level From 1.2 to 7.2 Seconds

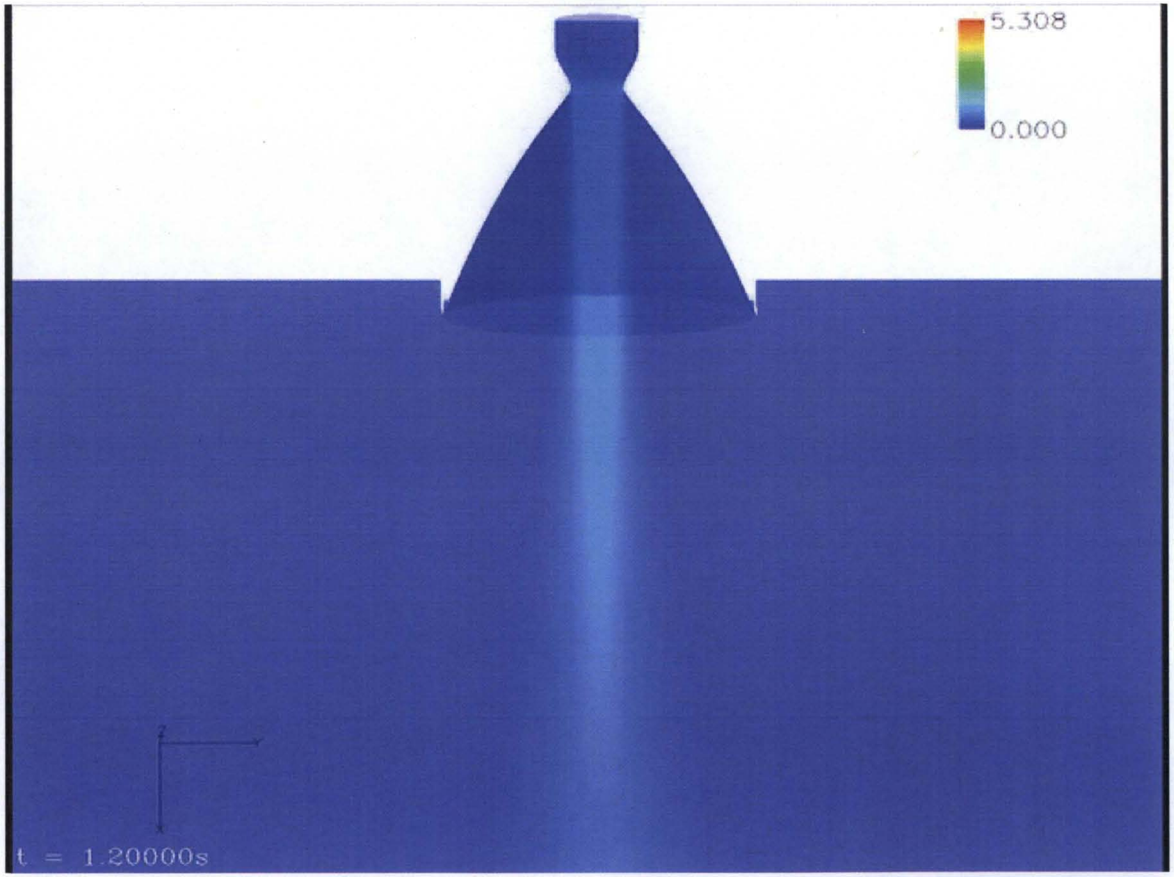
- *Mach number contours in the xy-plane highlights back-n-forth development of following features:*

  ** Core jet flow to full-nozzle flow,*

  ** Mach disk from the nozzle interior to the external plume,*

  ** Pulsating, asymmetric Mach disk flows,*

- *Wall OH contours highlight flow separation.*



# *COMBUSTION DEVICES CFD TEAM ANALYSIS REVIEW SUMMARY*

- ***To implement the team charter, "To provide state-of-the-art CFD support for MSFC propulsion project systems and components in a timely manner," the following have been acquired:***
    - * *Computational Tools:*
        - *Loci-Chem, Loci-Stream, UNIC(CFD Codes),*
        - *Gridgen, SolidMesh/AFRL, ANSA(Grid Generators),*
    - * *Computational Resources: PC Clusters totaling 192 CPUs in 2001 to 1968 CPUs currently,*
- ***These computational tools and resources are being used to address the concerns of Space Shuttle-Related Customers:***
    - * *Vehicle: Propulsion Systems Engineering and Integration,*
    - * *Combustion Devices: SSME Project Office/Design Engineering Team,*
- ***and the concerns of Ares-I & Ares-V-Related Customers:***
    - * *Vehicle: Ares-I Roll Control System(RCS) Integrated Product Team,*
    - * *Combustion Devices: J-2X Program Office.*