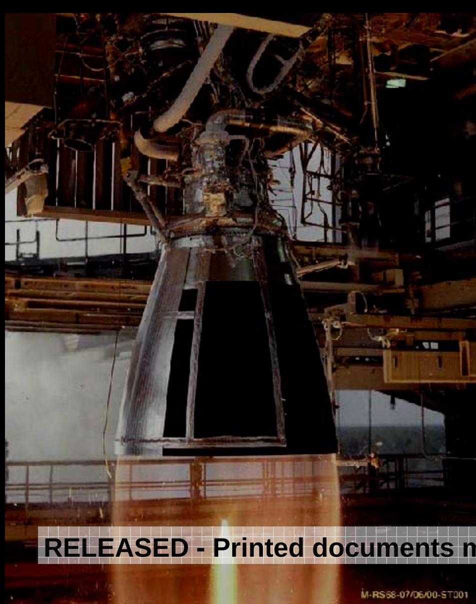
CFD Modeling Activities at the NASA Stennis Space Center

Presentation to the LSU Mechanical Engineering Department



Daniel Allgood, PhD

NASA Stennis Space Center

Technology Development and Transfer

NTOG - Jacobs Technology

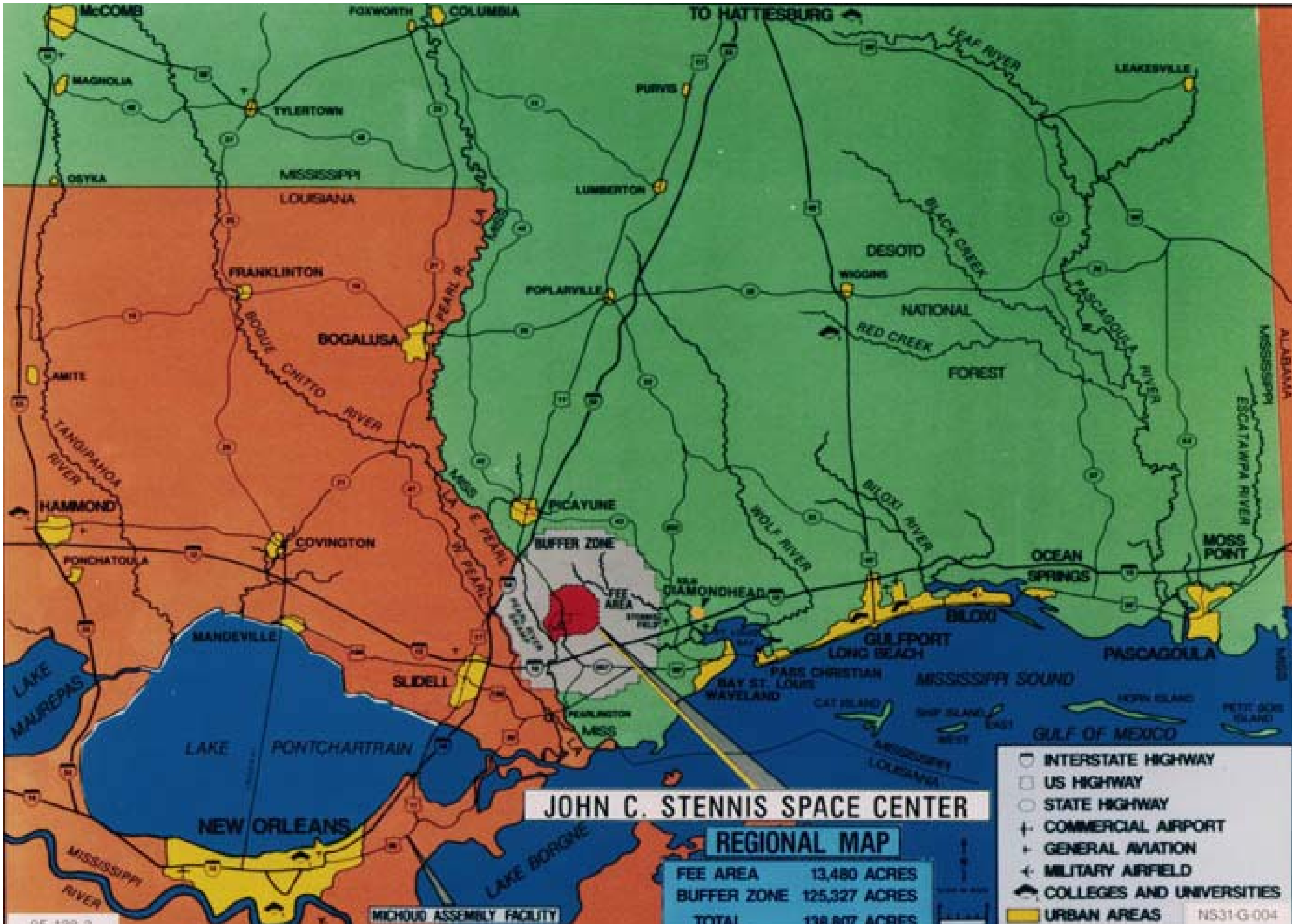
March 16, 2007

NASA Test Operations Group

OUTLINE

- Overview of NASA Stennis Space Center
- Role of Computational Modeling at NASA-SSC
- Computational Modeling Tools and Resources
- CFD Modeling Applications
  - Cryogenic Propellant Delivery Systems (Tanks, Runlines)
  - Propellant Control Elements (Valves)
  - Flow Measurement Devices (Cavitating Venturies, RTDs)
  - Plume Modeling:
    - Hydrocarbon Plumes and Diagnostic Support
    - Conceptual Stage Testing

Regional Map of NASA-SSC



NASA-SSC Test Facilities

E-1 Stand

High Press., Full Scale Engine Components

E-2

High Press.

Mid-Scale

& Subscale

E-3

High Press.

Small-Scale

Subscale

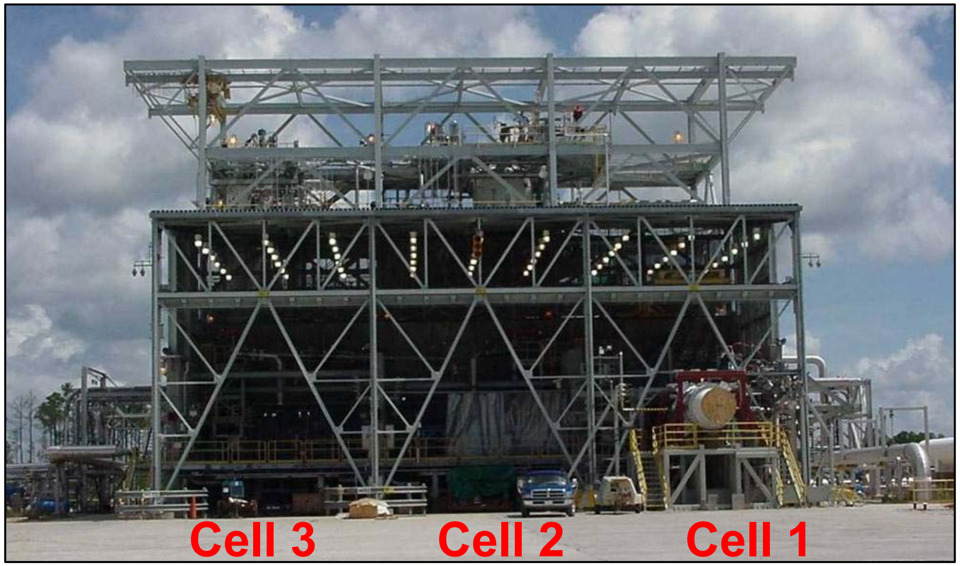
A-1 … Full Scale Engine Devt. & Cert … A-2

B-1/B-2 … Full Scale Engine/Stage Devt. & Cert

Components …Engines … Stages

NASA-SSC Test Facilities – E Complex

Component and Engine Testing (E-1)

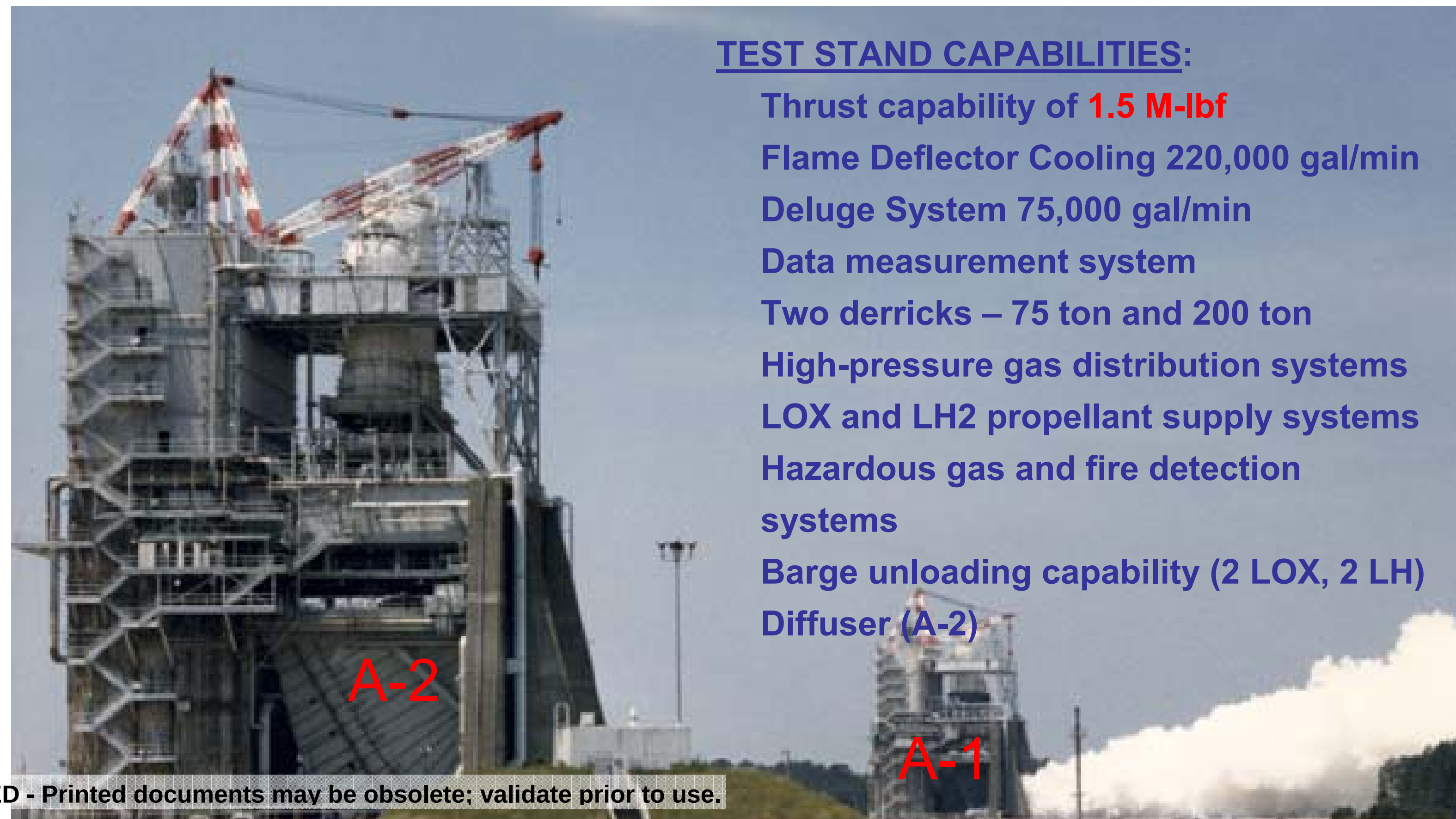


- High Pressure (Long Run) Capabilities
  - LOX/LH/RP ~ 8,500 psi
  - GN/GH ~ 15,000 psi
  - GHe ~ 10,000 psi
- State-of-the-Art DAC Systems
- E-1 Cell 1
  - Primarily Designed for Pressure-Fed LOX/LH/RP & Hybrid Test Articles
  - Thrust Loads up to 750K lb_f (horiz.)
- E-1 Cell 2
  - Designed for LH Turbopump & Preburner Assembly Testing
  - Thrust Loads up to 60K lb_f
- E-1 Cell 3
  - Designed for LOX Turbopump, Preburner Assembly & Engine Testing
  - Thrust Loads up to 750K lb_f

NASA-SSC Test Facilities – A Complex

❑ Full-scale Engine Development & Certification

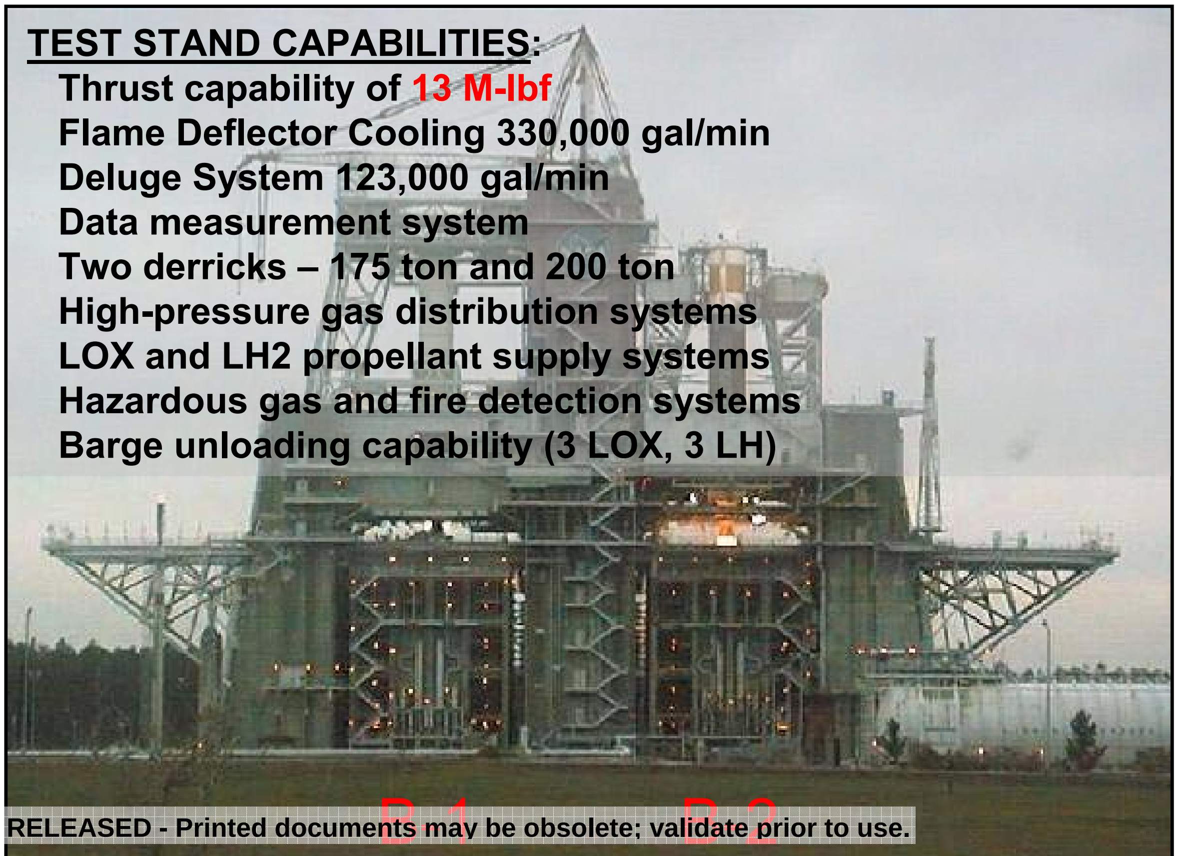
- Saturn V 2nd Stage J-2 engine (1.15 M-lbf cluster of 5 LH_2/LOX J-2 engines)
- SSME (375 K-lb LH_2/LOX) development, flight acceptance, & 65kft altitude (A-2)
- X-33 Aerospike



NASA-SSC Test Facilities – B Complex

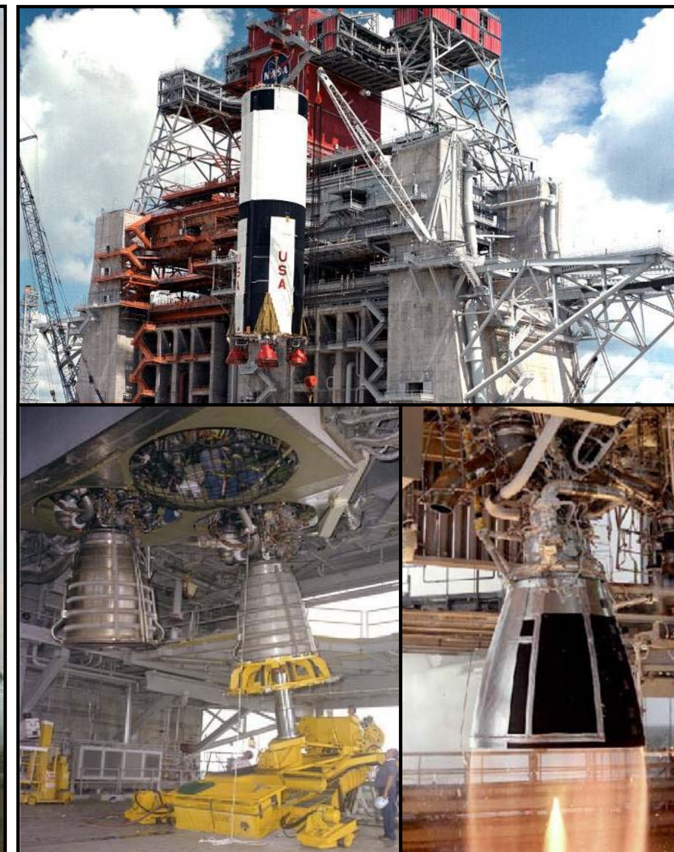
❑ Vehicle Stage & Full-scale Engine Testing

- SATURN V (7.7 M-lbf cluster of 5 RP-1/LOX F-1 engines)
- SSME MPTA (1.1 M-lbf cluster of 3 LH_2/LOX SSME)
- Delta IV Common Booster Core (650 K-lbf LH_2/LOX RS-68 engine)



TEST STAND CAPABILITIES:

Thrust capability of 13 M-lbf
Flame Deflector Cooling 330,000 gal/min
Deluge System 123,000 gal/min
Data measurement system
Two derricks – 175 ton and 200 ton
High-pressure gas distribution systems
LOX and LH2 propellant supply systems
Hazardous gas and fire detection systems
Barge unloading capability (3 LOX, 3 LH)



Role of Computational Modeling at NASA Stennis

- NASA Stennis is not a research and development center but rather the nations largest liquid rocket engine test facility.
- CFD codes are not developed at Stennis but rather applied to help support the current and future test operations.
- The avenue for code development is through the SBIR/STTR program were we can collaborate with small businesses and universities to develop the TOOLS we need.

NASA-SSC Computation Resources

- CRUNCH CFD code is currently the primary CFD code used at Stennis.
- Development of real-fluids (cryogenics), acoustically accurate cavitation, and fluid-structure interaction modeling capabilities have been sponsored by NASA Stennis under the NASA SBIR program.
- Additional codes such as Optimal Solutions, Loci-Stream/Chem, CFX and ANSYS are being applied as well.

NUMERICS	• Finite-Volume Roe/TVD Flux Construction, Vertex Storage
INTEGRATION	• Explicit Four-Step Runge-Kutta, Implicit GMRES, Implicit Gauss-Seidel
GRID ELEMENTS	• Tetrahedral, Hexahedral, Prismatic, Pyramid
PARALLEL PROCESSING CAPABILITIES	• Domain Decomposition MPI, Independent Grids with Noncontiguous Interfacing, Automated Load Balancing
DYNAMIC GRID CAPABILITIES	• Node Movement Solver (Implicit Elasticity Approach), Automated Embedding, Sliding Interfaces
GRID ADAPTION	• Variable Element Grid Refinement using Delaunay Procedure, Automated Load Balancing of Adapted Grid
THERMOCHEMISTRY	• Multi-component Real Gas Mixtures, Finite-Rate Kinetics
TURBULENCE RANS/LES	• k-epsilon /EASM Formulations with Compressibility/Vortical Upgrades • LES Subgrid Scale Models – Algebraic and One-equation • Algebraic (Smagorinsky) and Single Equation (k) SGS Models
MULTIPHASE FLOW	• Nonequilibrium Particle/Droplet Solvers (Eulerian and Lagrangian Formulations)

NASA-SSC Computation Resources

- Linux Beowulf Diskless Cluster
  - 48 Dual CPU AMD Opteron246 64-bit 2.0GHz w/ 2GB RAM each
  - Gigabit Ethernet with 3 Trunked HP ProCurve 2848 Switches
  - RedHat CentOS4.3, 2.6.9-22.0.1smp kernel
  - PVM (parallel virtual machine) & MPI (message passing interface) message passing
- Two High-End (64-bit) Workstations
  - AMD Athlon 64-bit 2.0 GHz *(servers as cluster head node)*
  - Dual CPU AMD Opteron244 64-bit 1.8GHz *(serves as primary CFD workstation)*
- Two 2-Terabyte Network Attached Servers with Backup Cap.
- NASA Ames Supercomputing Facility

Cryogenic Propellant Delivery Systems (Tanks & Runlines)

Propellant Tank Simulations

E-1 Test Facility High-Pressure LOX Tank Discharge

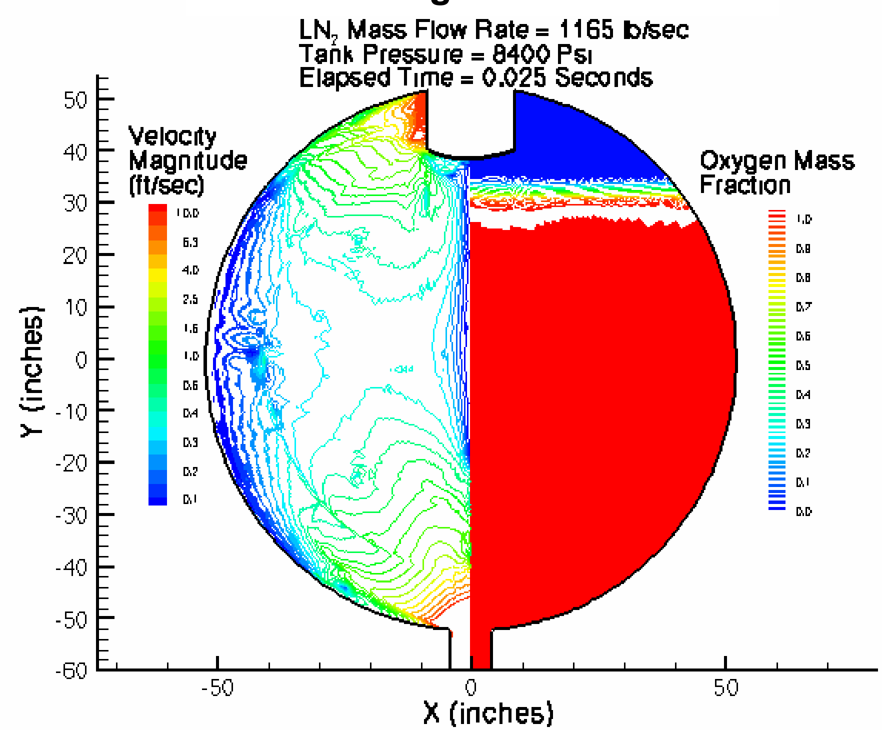
- CFD Investigations Indicate Pressurizing Gas Diffuser Flow Significantly Limits Flow Duration for High Flow Rate Cases

- Flow Conditions Assessed
  - 2500 lb/sec LOX Discharge Rate
  - 8400 psi Tank Pressure Maintained During Propellant Discharge

- GN Convective Mixing with LOX Propellant is Substantial
  - Only 50% Loaded LOX is Useable (<~2% N_2 Concentration)

- LOX Propellant Supply Limited to Approximately 4 seconds (vs an Estimated 10 seconds Determined Using Nominal Facility Pressurizing Gas & Propellant Supply Limits)

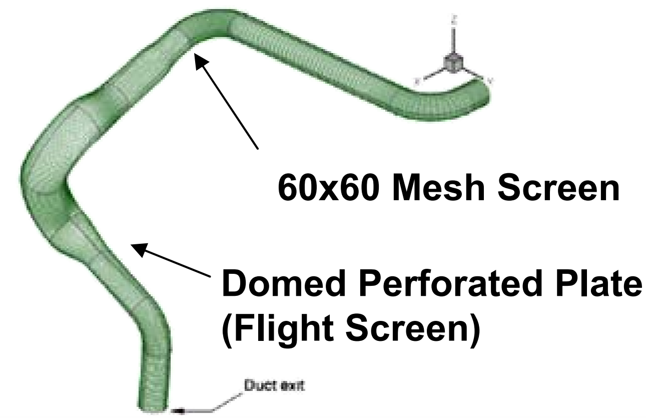
HP LOX Tank Propellant Discharge Simulation

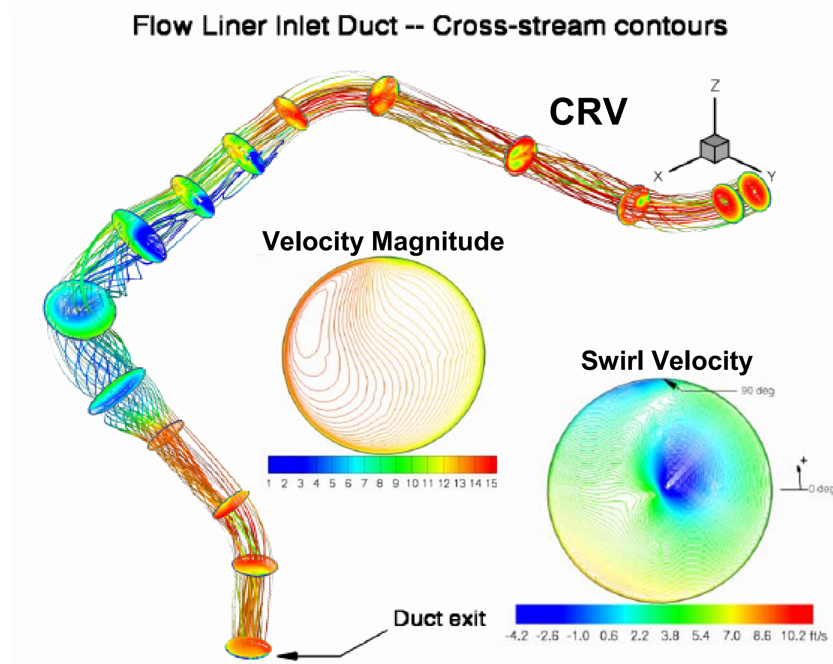


Propellant Flowline Simulations

Flow-Liner Inlet Duct at E-1

- Used k-epsilon turbulent CFD analysis to determine flow quality entering tests article (conceptual SSME LH_2 turbopump).
- Screens and porous plates were modeled using a parametric "stacked-spherical bed" model
  - provided a source term in momentum equation for pressure drop (matched to experimental data)
- Complex duct geometry was found to cause *significant swirl and non-uniformity*.
- Upstream screen was observed to adversely alter the exit flow profile in that the swirling flow angle deviation was higher (~2 deg.)

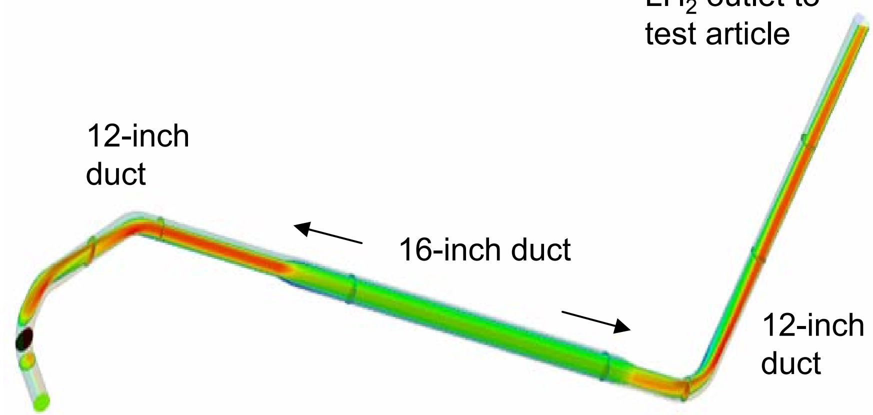




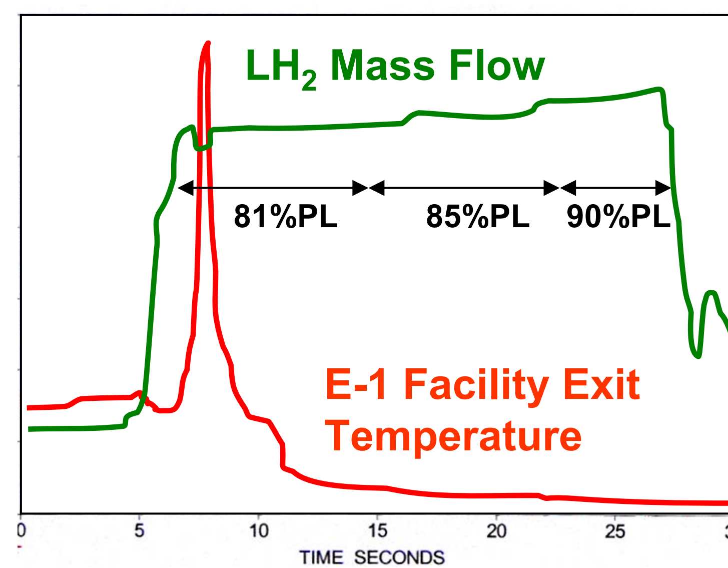
Propellant Flowline Simulations

Pre-Test Bleed of E-1 Liquid Hydrogen Runline

- Test Preparation Procedure:
  1. Slowly chill-down the runline walls to the cryogenic propellant temperatures of 39°R (19K)
  2. Pre-test bleed the runline to flush out any remaining heated fluids
  3. Conduct test



- Problem Encountered:
  - LH_2 runline delivered a transient warm slug to test article during initial startup of engine
  - Warm slug affects engine performance (Thrust & Isp)



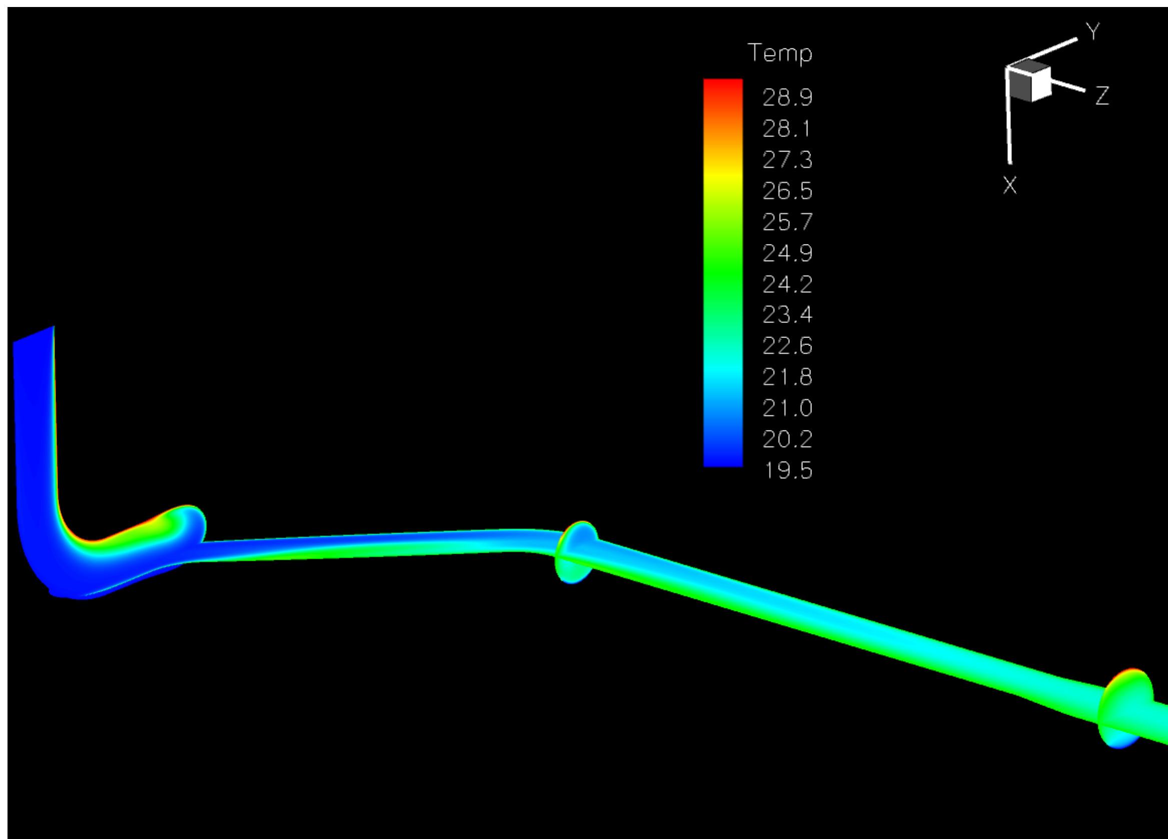
- Fundamental Questions:
  1. What is the source of the warm slug of LH_2?
  2. Can the warm slug be prevented through modification of the testing procedures or does it require facility modifications?

Propellant Flowline Simulations

Pre-Test Bleed of E-1 Liquid Hydrogen Runline

- Using CFD, evaluated efficiency of the pre-test bleed (13 lbm/sec) in purging runline of warm fluid.

Outflow from LH_2 Tank into the E-1 Runline

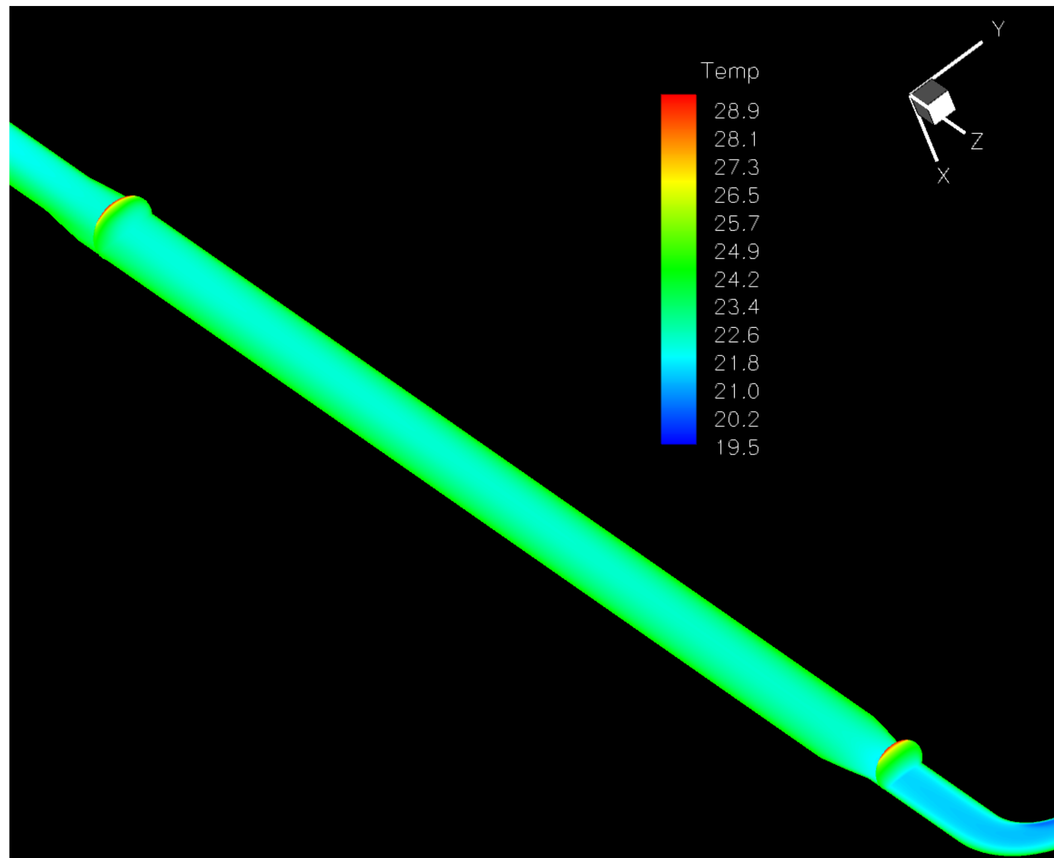


Propellant Flowline Simulations

Pre-Test Bleed of E-1 Liquid Hydrogen Runline

- Using CFD, evaluated efficiency of the pre-test bleed (13 lbm/sec) in purging runline of warm fluid.

Transition to/from the 16-inch/12-inch Diameter Runlines



Propellant Flowline Simulations

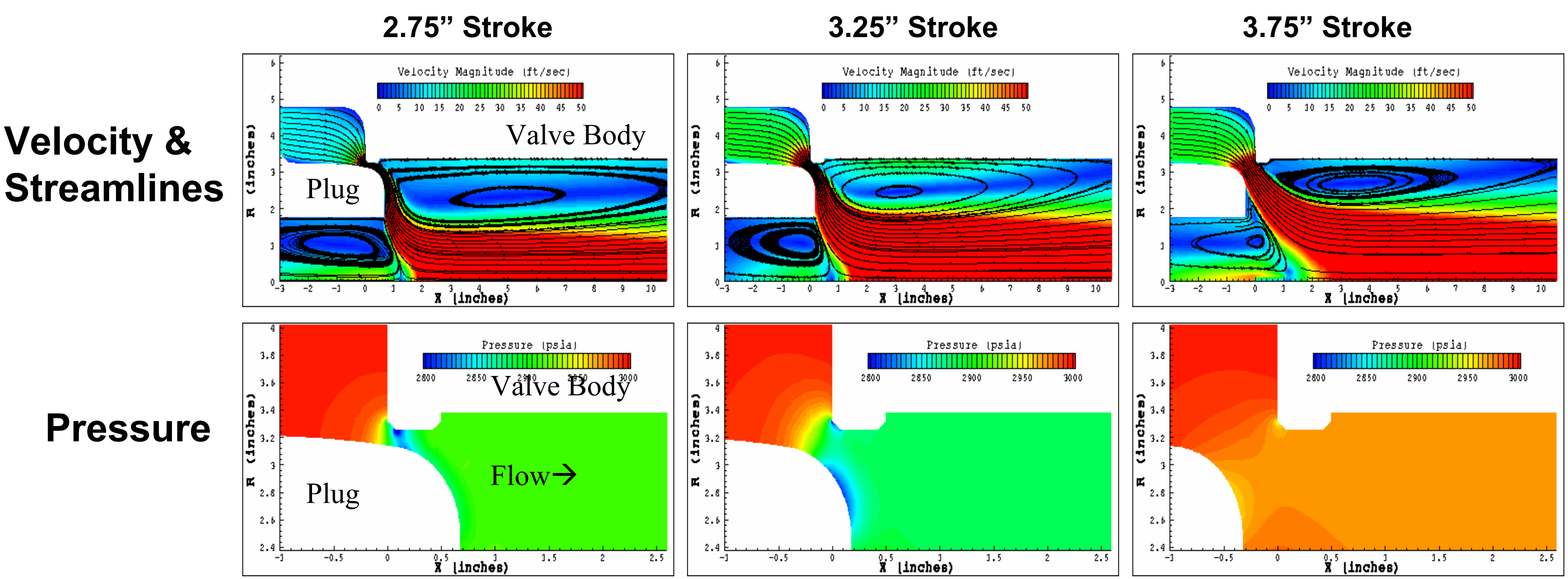
Pre-Test Bleed of E-1 Liquid Hydrogen Runline

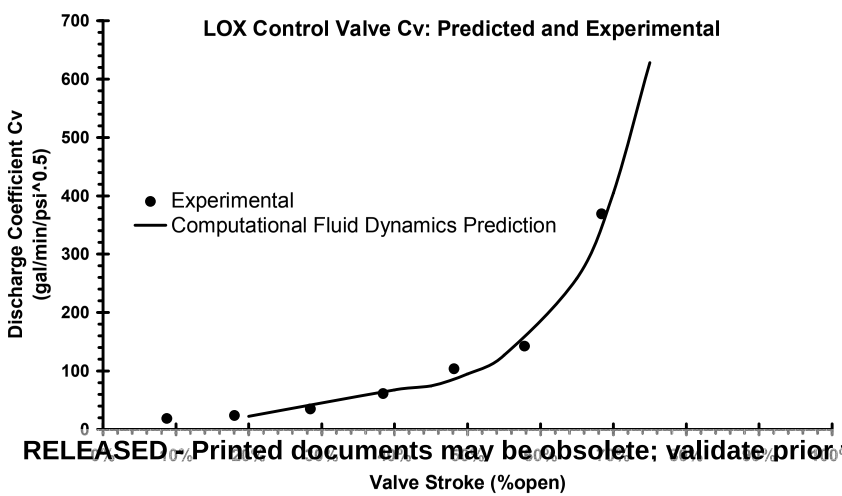
- CFD analysis showed that the pre-test bleed flow was <u>sufficient</u> to flush the warm LH_2 from the duct.
- Residual amounts of LH_2 remaining in low-speed recirculation regions were not sufficient to cause the warm-slug observed during the tests.
- Further analysis showed that the cause of the warm slug was due to radiant head loads to the vacuum jacketed run-lines occurring during the time between the pre-test bleed and the test start (~3 minutes).
- Reduced time-delays between pre-test bleed and test start reduced the mass and temperature of the warm LH_2 slug.

Propellant Control Elements (Valve Dynamics)

Propellant Control Valve Simulations

Modified LOX Control Valve





- CFD Used to Predict the Flow Field & C_v Curve for a Modified LOX Control Valve
- Yields a Good Understanding of How the Flow Field Changes as the Valve Opens & Affects C_v curve
- Analysis Reveals Areas Where Cavitation May Occur as Well as Areas of High Velocity That Are Important When the Working Fluid is LOX

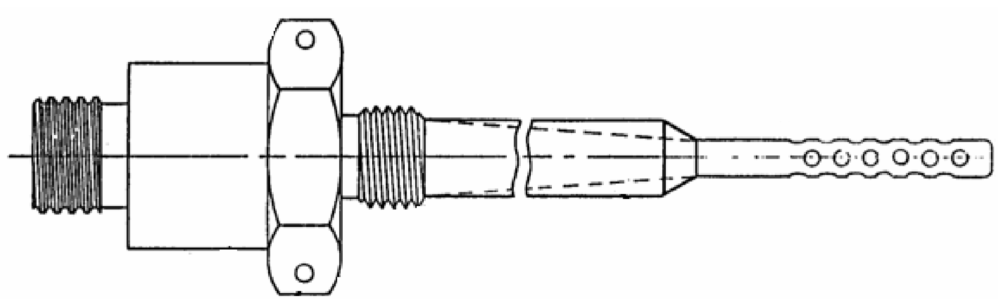
Propellant Flow Measurement Devices

Flow Measurement Device Optimization - RTD

- The primary purpose of this effort was to assess Optimal Solution's Sculptor software in performing:

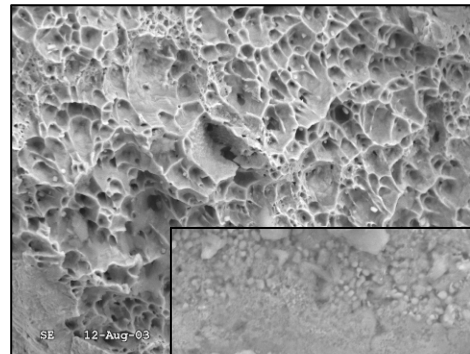
    1. Manual shape deformation without the need for CFD grid regeneration.
    2. Perform CFD-based optimization for a relevant NASA Stennis case.

- **RTD** (resistance temperature detector) probe was selected as the primary test case due to their premature structural failures on the LOX & LH2 propellant feed-lines of the NASA Stennis E1 test facility.

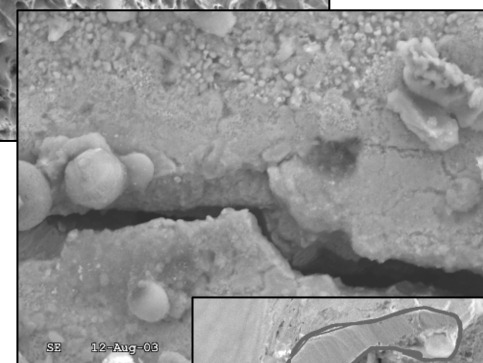


RTD Optimization - Background

- SEM analysis of the failed RTDs by W. Jordan of Louisiana Tech revealed several possible causes of failure in the low temperature environment:



Ductile tensile overload close to the yield strength



Reversed bending resulting in cracking at base of probes on opposite sides

Fatigue failure due to vibration in the system (not test cycles)

- The major factors are believed to be the ductile tensile overloading and reversed bending due to drag on the RTD.

RTD Optimization - Background

- The ductile tensile overloads are attributed to excessive drag on the RTDs.
  - Solution: Optimize RTD geometry by minimizing flow-induced drag
- Reversed bending and vibration failures could be attributed to unsteady vortex shedding being coupled with the natural frequency of the RTDs.
  - Solution: Optimize RTD geometry to alter vortex shedding behavior
- The reversed bending could also be a result of periodic opening/closing of facility valves.

RTD Optimization – Base Case Configuration

- Base case RTD geometry is a circular cylinder mounted inside the SSC E1 test facility's LOX propellant feedline.

RTD Geometry:

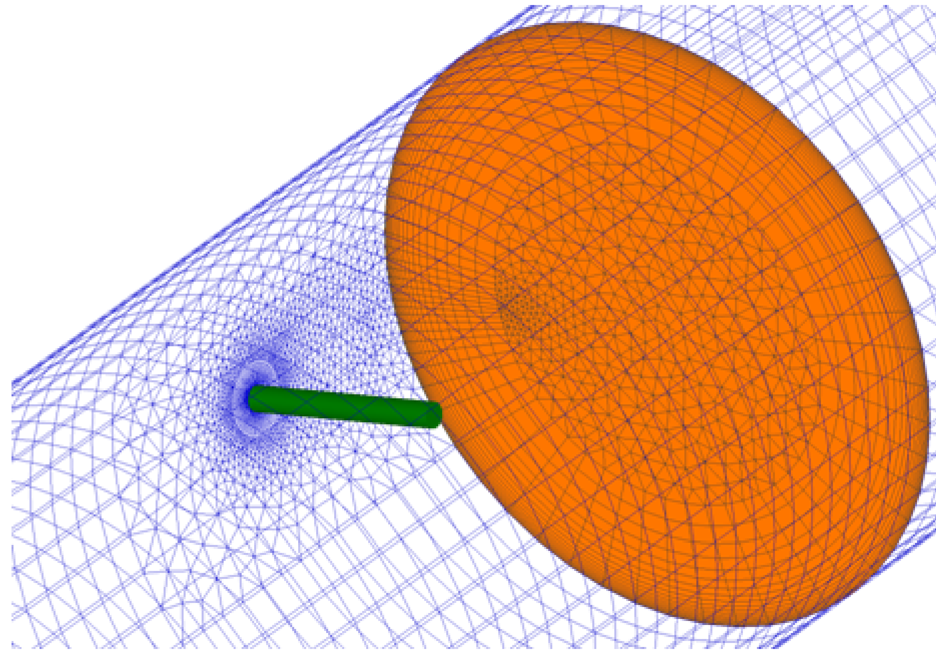
D=0.34 in
L=3.25 in

Pipe Geometry:

D=8.3 in

NIST LOX Conditions:

ρ=71.362 lbm/ft^3
T=200R
μ=1.32e-4 lbm/ft-sec



- E1 LOx test conditions conducive for the phenomenon of <u>"lock-in" flow-induced vibrations</u> (f_s within +/- 30 % of f_n).

u=20.4 ft/sec → Re_{RTD}=3.14e5 & Re_{pipe}=7.64e6 → St=0.2=f_s*D/u

f_s=143 Hz → within 18% of f_n=175 Hz

RTD Optimization – Manual Shape Deformations

- Sculptor's arbitrary shape deformation (ASD) tools were used to manually deform base case RTD into 3 test geometries without the need for re-gridding:

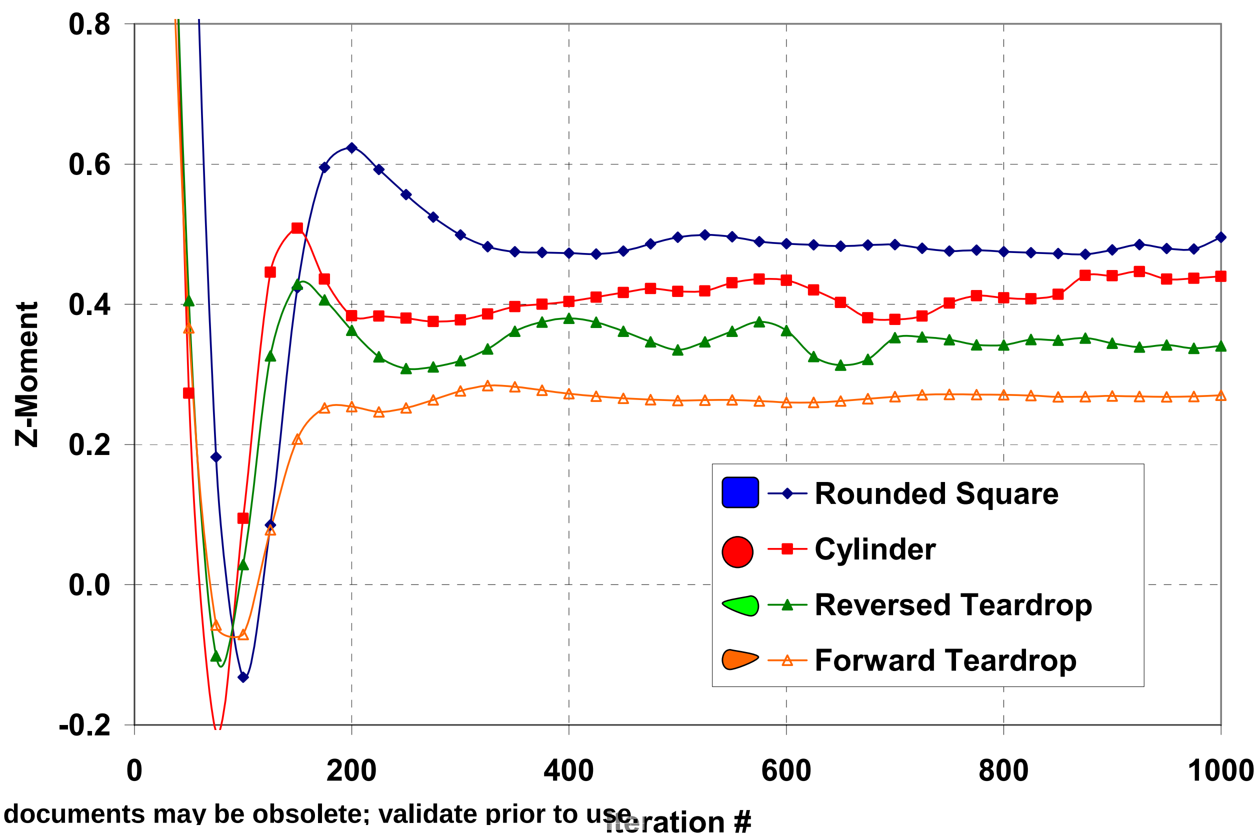
    1. Rounded Rectangular Cylinder
    2. Forward Facing Teardrop
    3. Rearward Facing Teardrop

- Steady-state simulations were performed for each design change and the Z-moment on the RTD was monitored.

RTD Optimization – Manual Shape Deformations

- Results were in agreement with physical expectations.

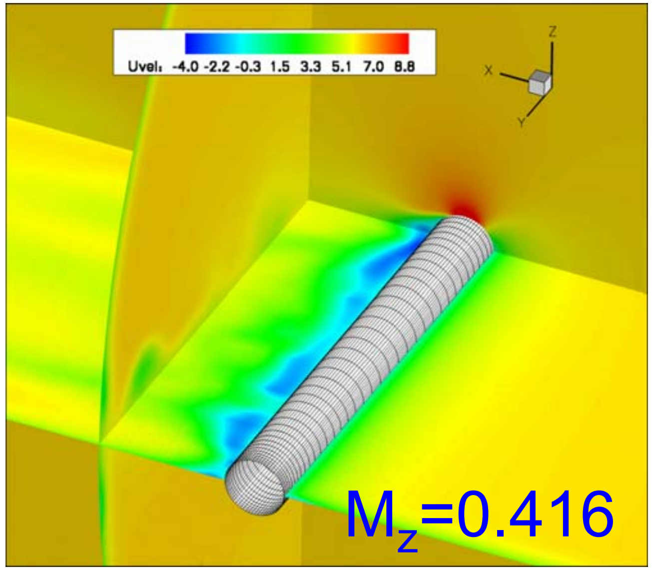
- 33% reduction in the Z-moment was obtained with the forward facing teardrop (pseudo-airfoil)



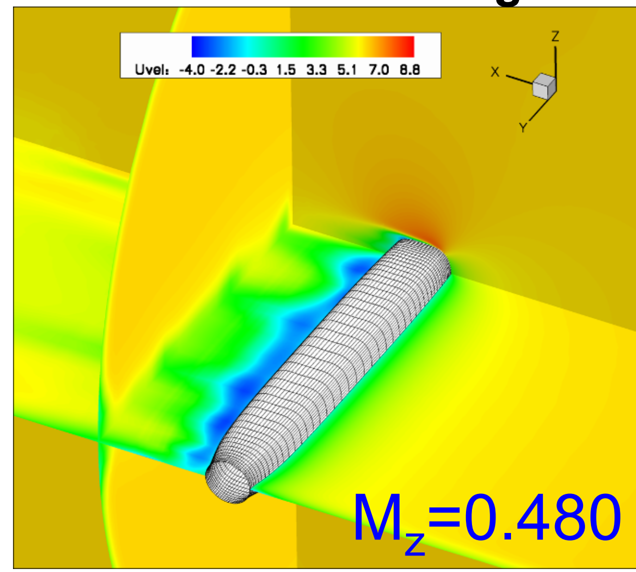
RTD Optimization – Manual Shape Deformations

RTD Z-moments are proportional to the size of the wake region especially near the tip

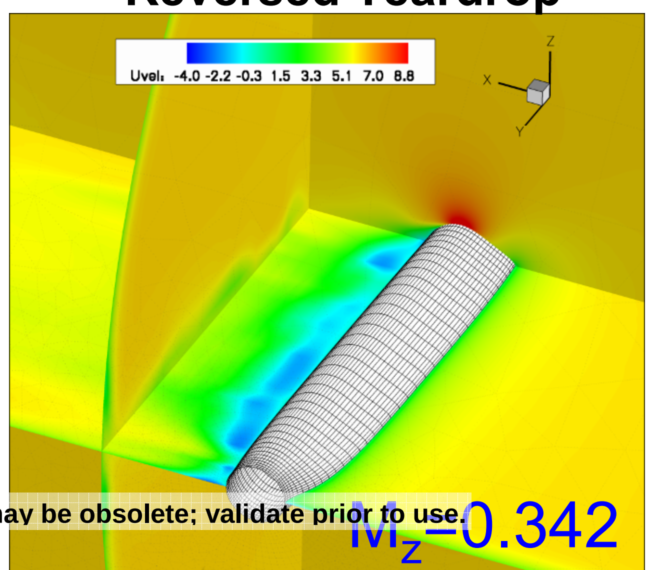
Base Case



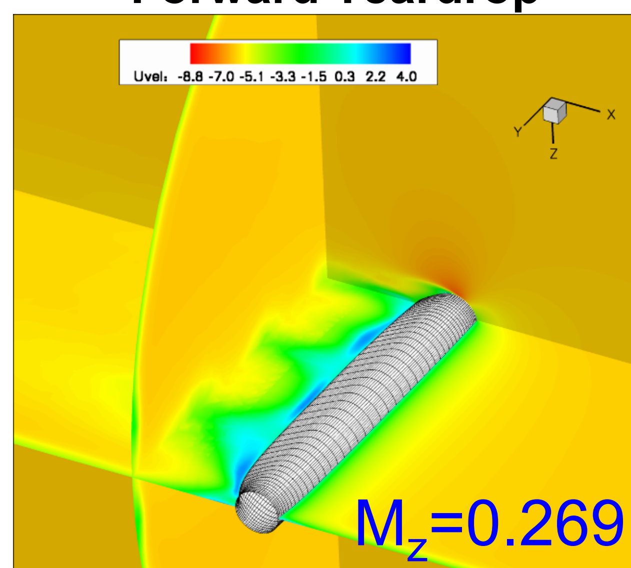
Rounded Rectangle



Reversed Teardrop

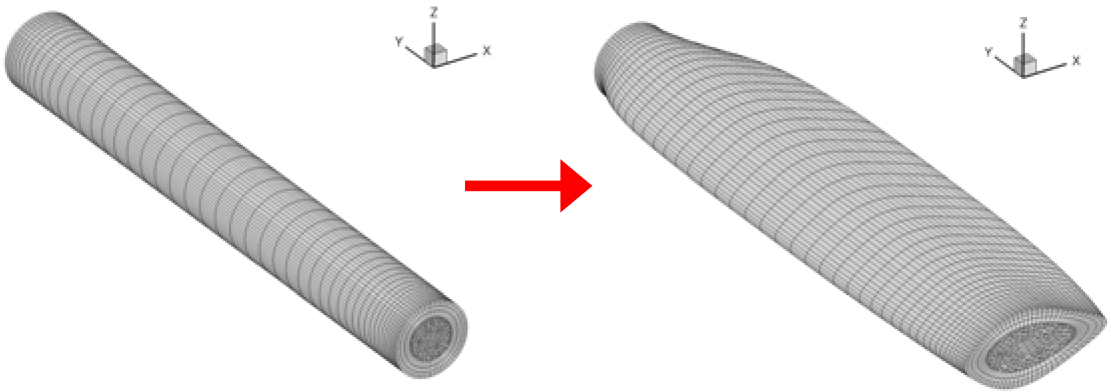


Forward Teardrop

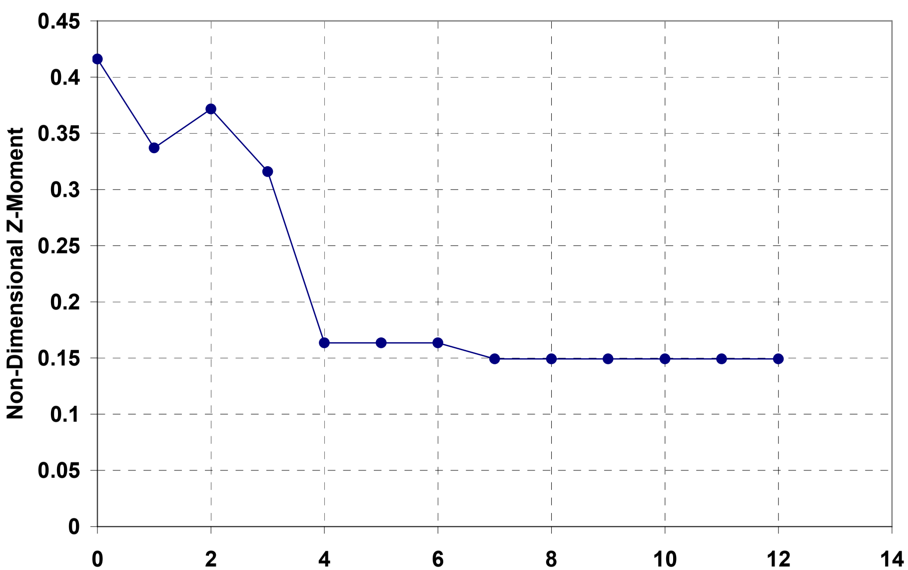


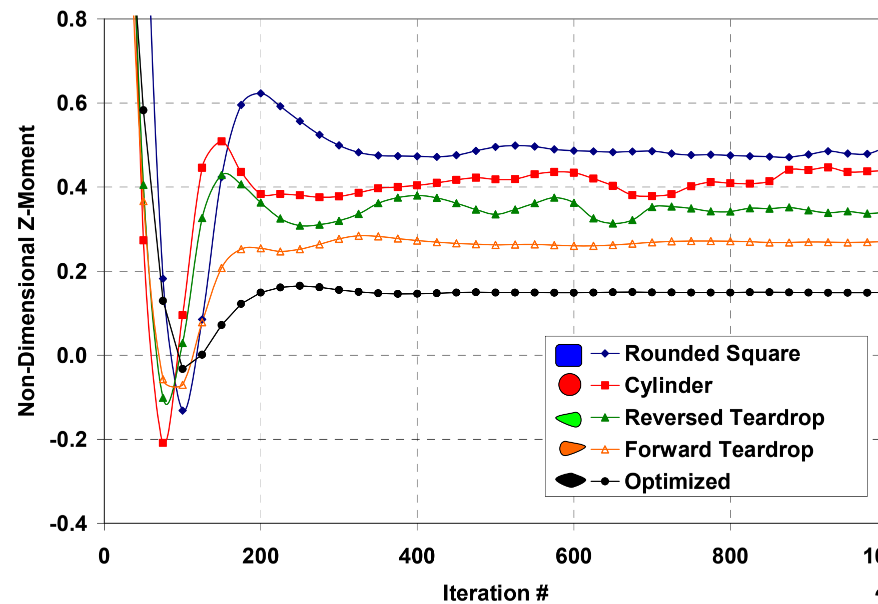
RTD Optimization – Implementation of Gradient-Based Optimizer

- Sculptor successfully reached a steady-state optimum RTD geometry



64% reduction
in steady-state Z-Moment

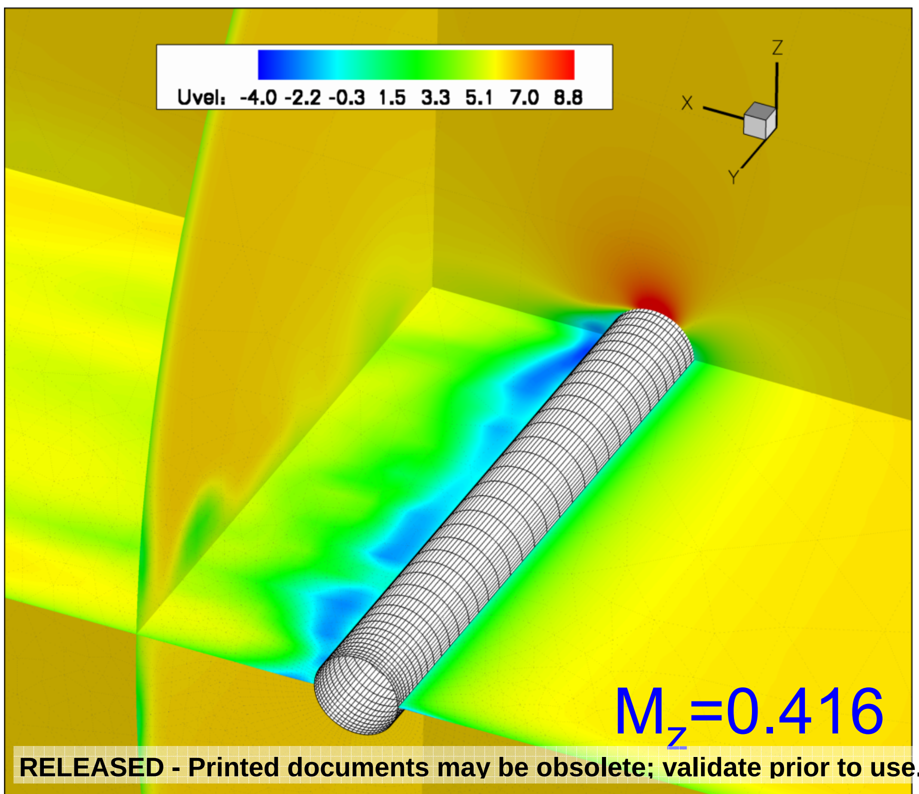




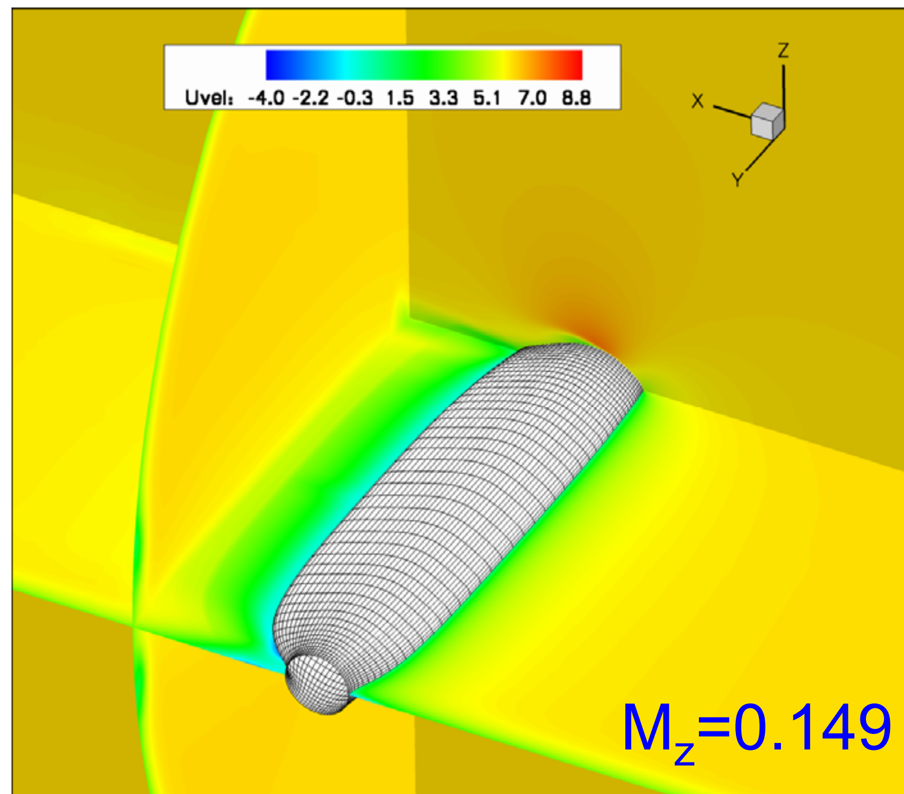
RTD Optimization – Implementation of Gradient-Based Optimizer

- Steady-state optimized RTD produced a smaller and more symmetrical wake giving a lower drag coefficient.
- Further analysis (angle of attack, swirl, etc.) would need to be conducted before any recommendation can be made for modifying the RTD.

Base Case



Optimized Geometry

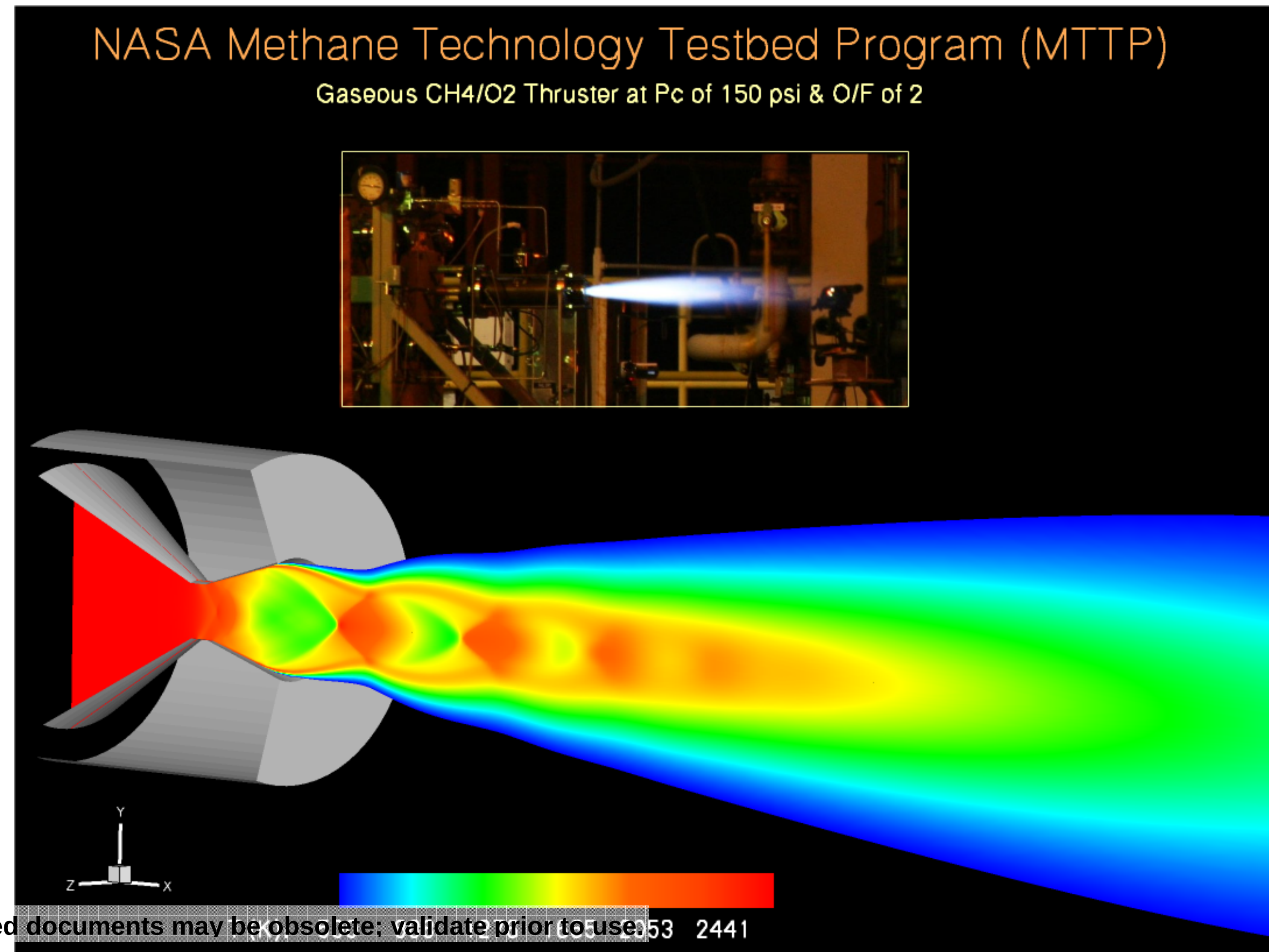


Rocket Plume Modeling

(Hydrocarbon Plumes and Stage Testing)

Methane Technology Testbed Program (MTTP) Plume Simulations

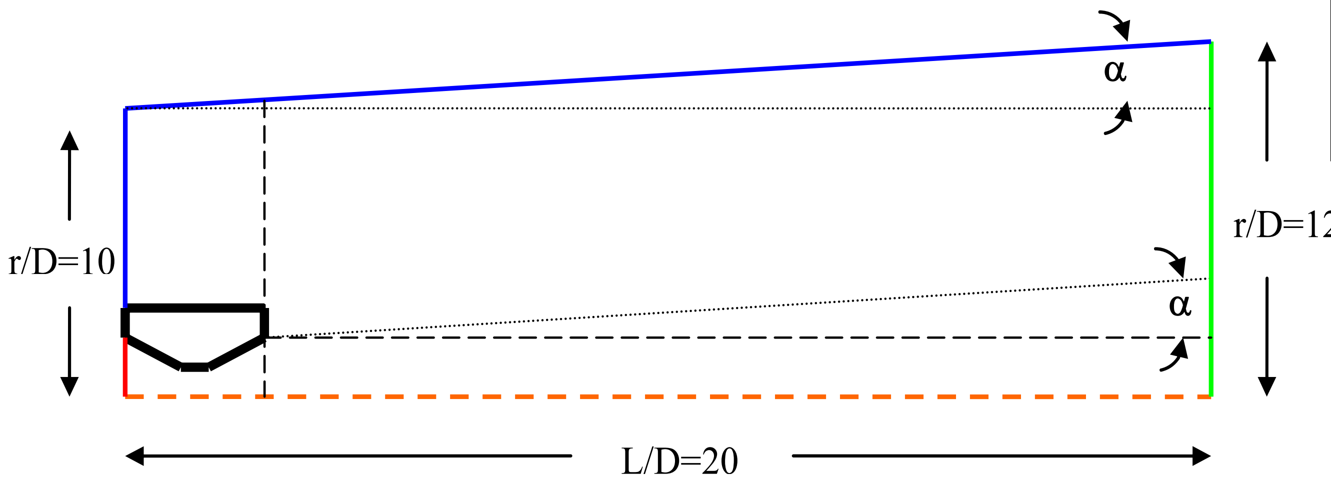
- Develop reliable CFD methodologies for modeling HC plumes
- Provide support for plume diagnostic efforts



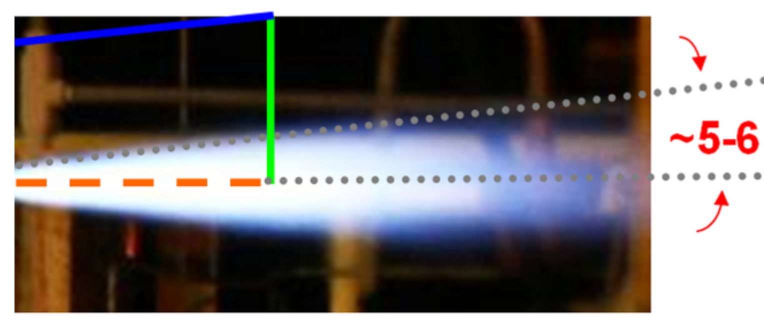
MTTP Plume Simulations – CFD Domain Definition

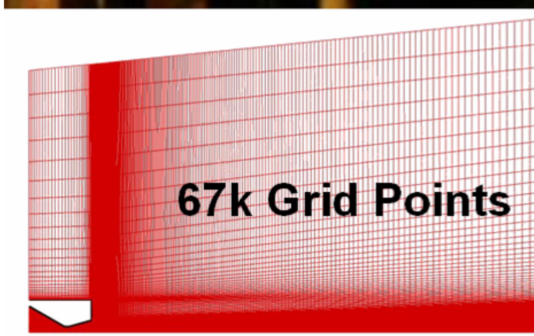
Operating Conditions

P_c=150 psia
O/F=2.0 (Phi ~ 2.0)



- Inlet Boundary
- Freestream Boundary
- Exit Boundary
- Symmetry Boundary
- Nozzle Boundary
- Anticipated Plume Boundary (α=half angle spreading rate ~ 5-6 degrees)



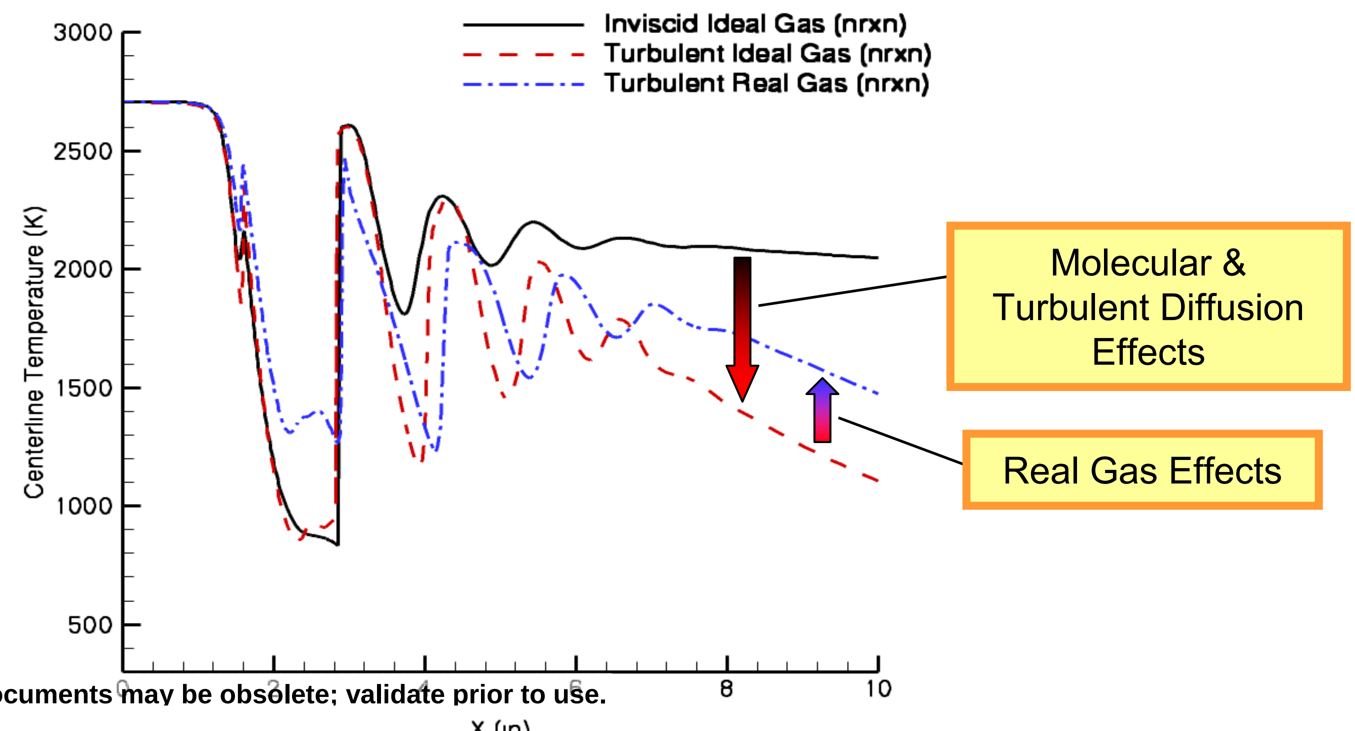


MTTP Plume Simulations – CFD Model Fidelity

- Implemented finer fidelity into the CFD model at an incremental level demonstrated the impact of the modeling assumptions.

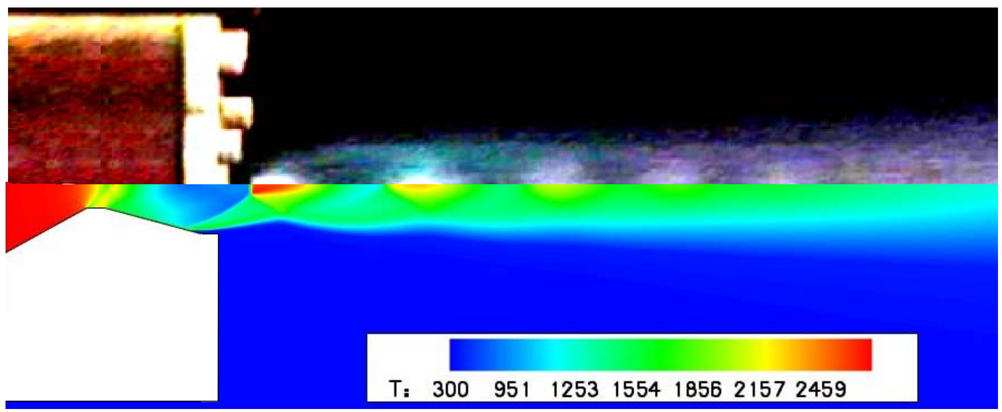
  Inviscid/Ideal Gas → Turbulent/Ideal Gas → Turbulent/Real Gas

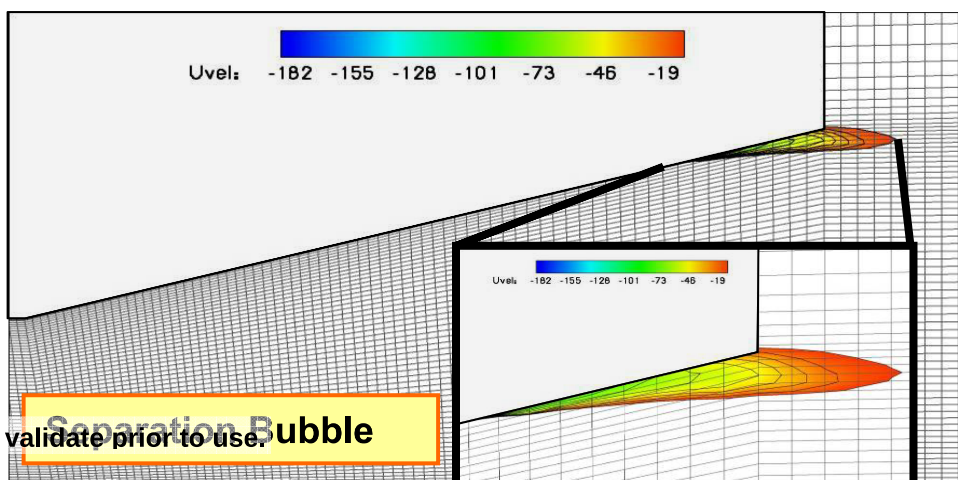
- Shock locations and axial decay in gas properties were impacted by both turbulence (k-epsilon model) and real-gas (13-species) effects.



MTTP Plume Simulations – CFD Model Validation

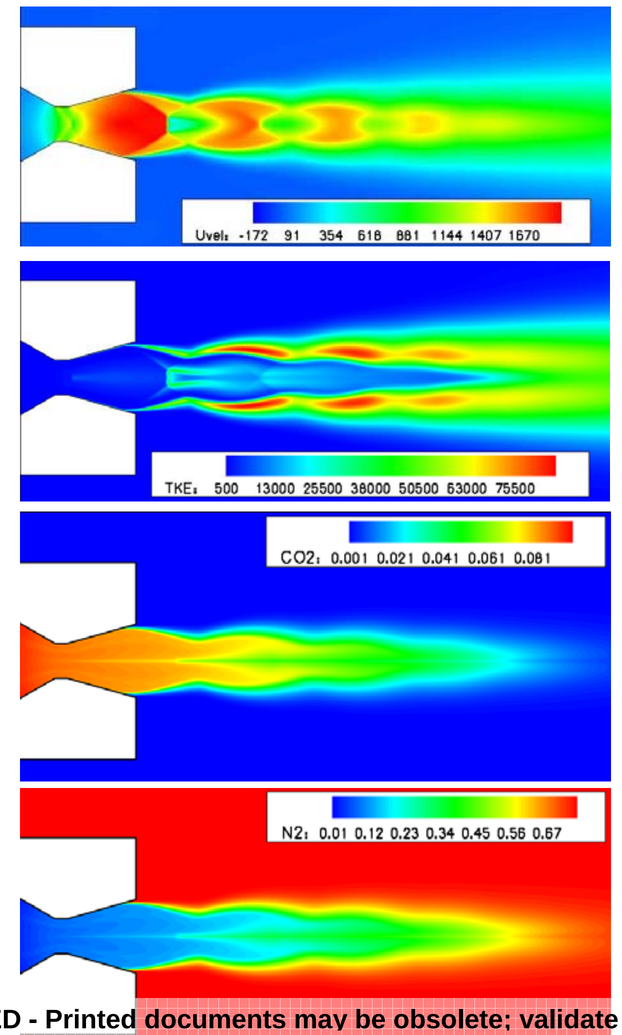
- Real-gas turbulent reacting model predicted correctly
  - Shock-cell locations and sizes
  - Approximate jet spreading rates
  - Observed nozzle flow separation

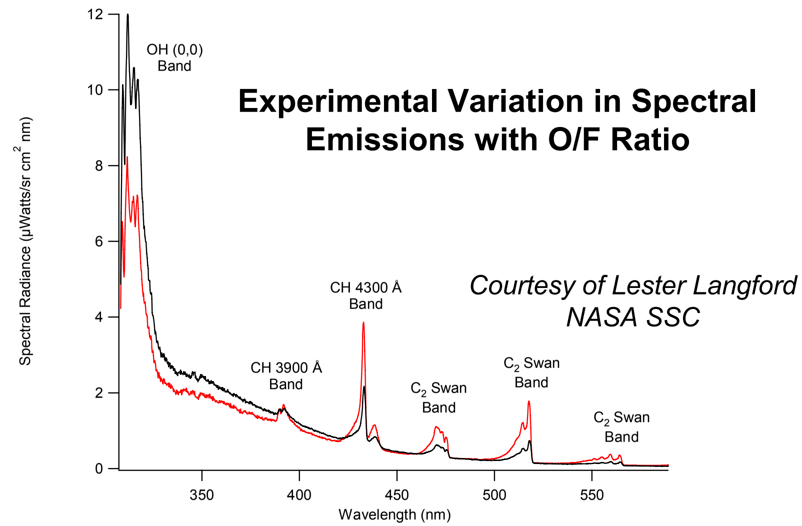


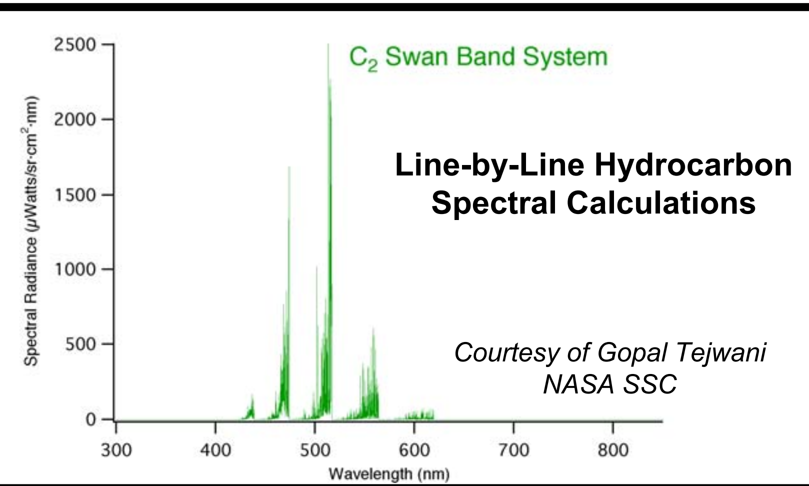


MTTP Plume Simulations – CFD Model Validation

- CFD data was used to support parallel efforts in the experimental plume diagnostics and line-by-line spectral radiation analysis.



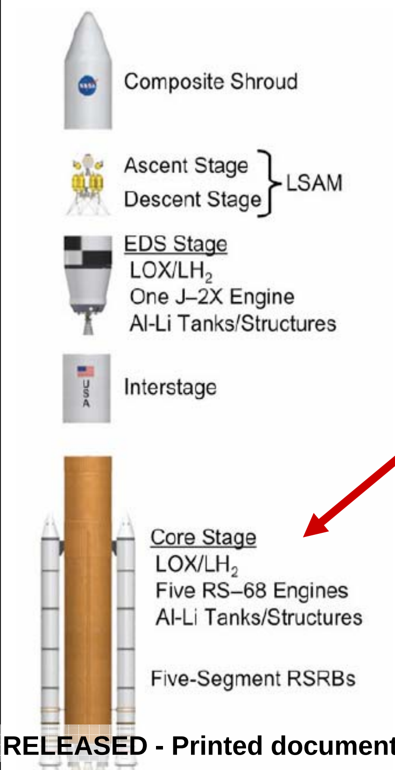




Conceptual ARES Stage Tests - Background

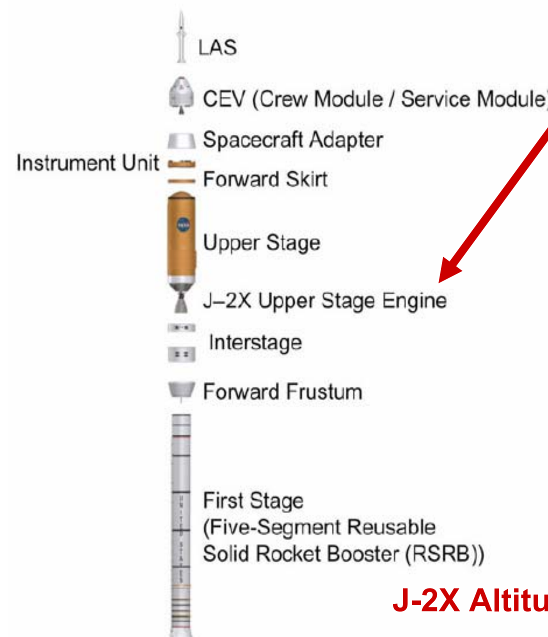
- Two new transport vehicles (**ARES V and I**) have been proposed to support exploration efforts under the newly defined Constellation Program.
- NASA Stennis will play an important role in the testing and certification of the ARES primary power-plants (**RS-68 and J-2X**).

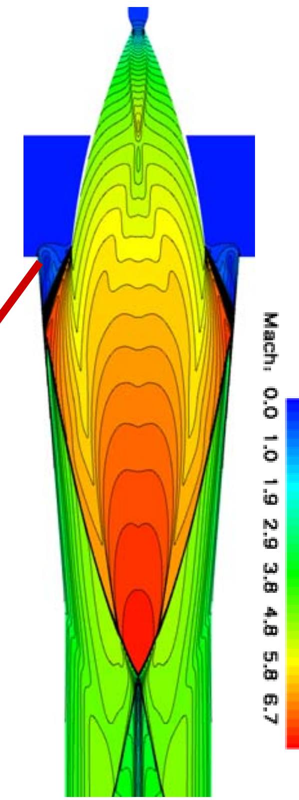
ARES V



RS-68 Test @ B-1
(650 K-lbf)

ARES I





J-2X Altitude Diffuser Simulation
(300 K-lbf)

Conceptual ARES Stage Tests - Background

- In preparation for the Constellation program, proposals for NASA Stennis to conduct ARES V & I stage tests were made.

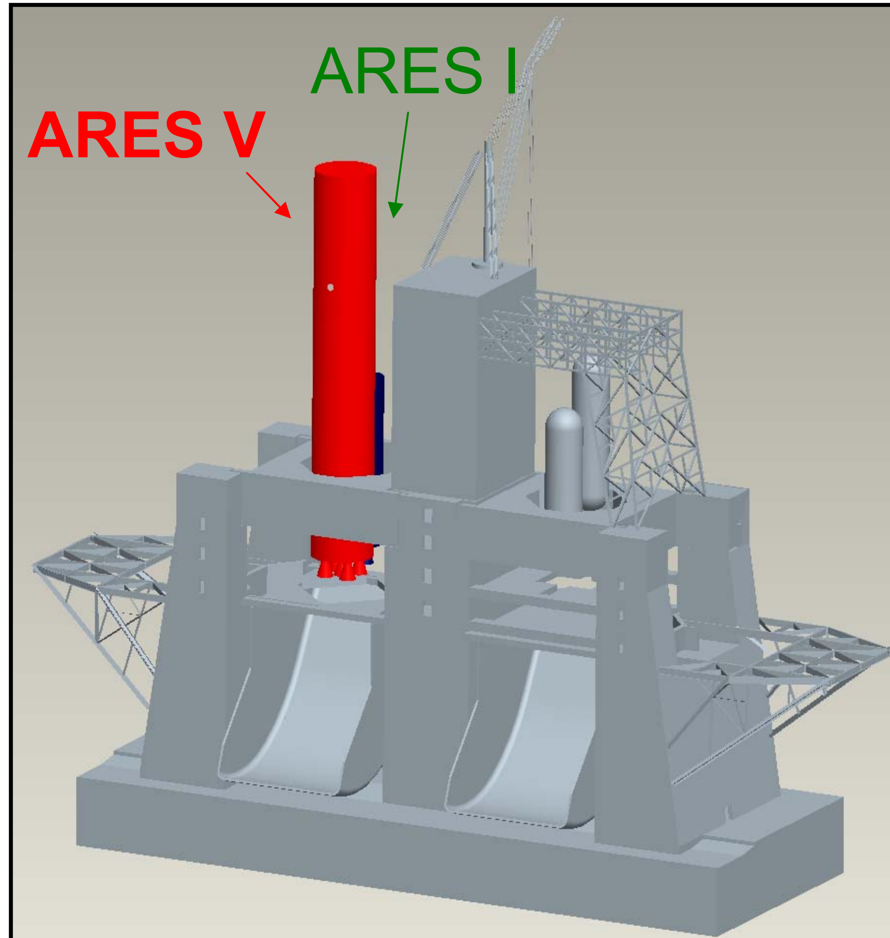
- Due to test schedules and loading/unloading issues of the vehicle stages, the feasibility of conducting **ARES V stage tests with the ARES I stage present on the B-2 test stand** was brought into question.

ARES V – 3.25 M-lbf LOx/H_2
ARES I – 0.30 M-lbf LOx/H_2

Conceptual ARES Stage Tests – Potential Issues

- **Forward alignment of the conceptual <u>ARES V</u> could cause:**
  1. Undesirable plume deflection
  2. Excessive plume heating (deflector & aspirator)
  3. Acoustic/vibrational damage to test articles
- **Aft alignment of the conceptual <u>ARES I</u> could cause:**
  1. Excessive deflector heating due to reduced nozzle/deflector separation distance

PRO-E CAD Model of the Proposed Test Configuration

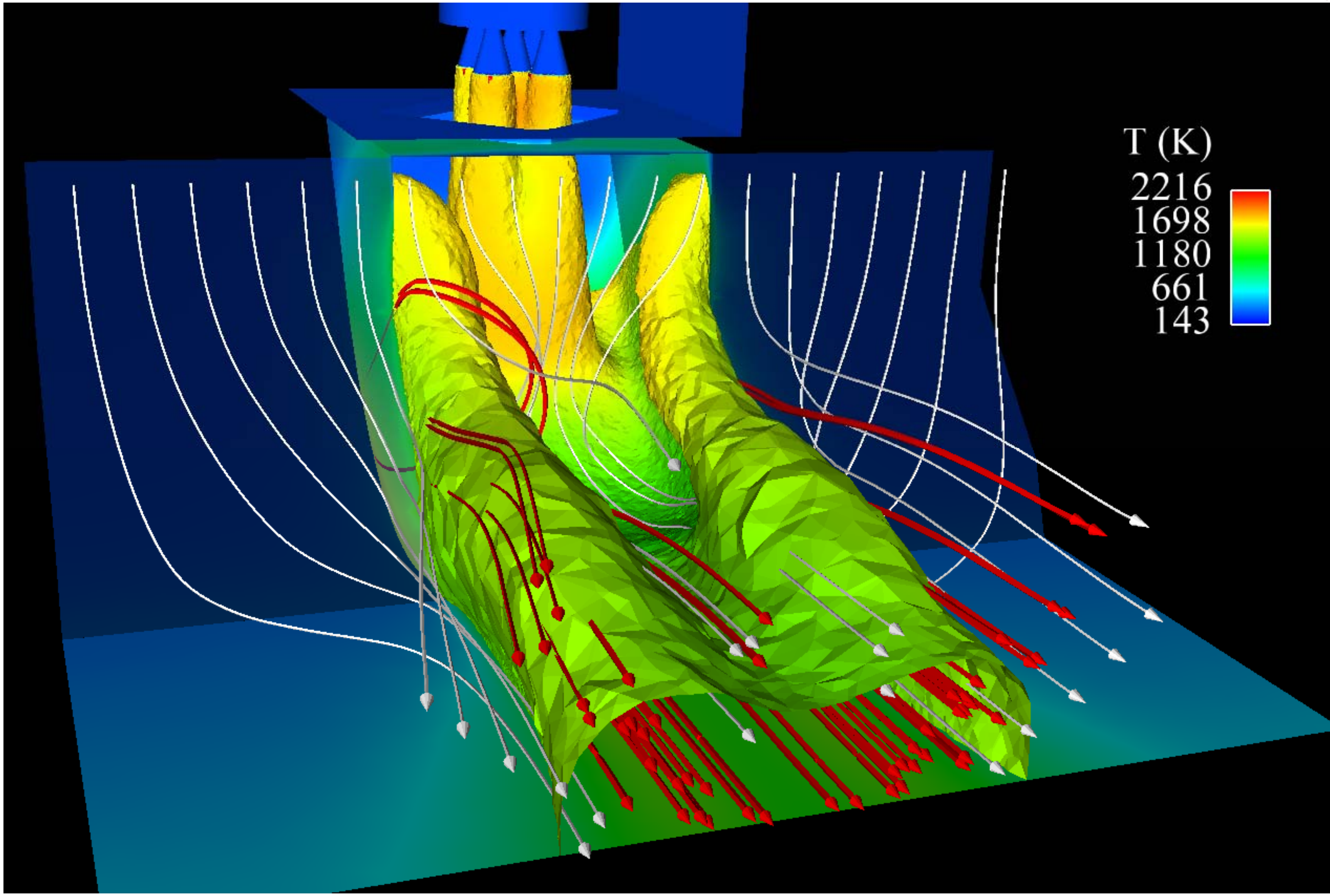


❖ No CFD model of the B-2 test stand existed that would enable us to analyze and address some of these issues.

Conceptual ARES Stage Tests – CFD Methodology

- 4.3 million unstructured grid cells (partitioned to run on 90 CPUs)
- Ideal-gas, chemically frozen flow
- ***Dry-plume***
  - ❑ CFD modeling of two-phase deflector water cooling through thousands of ~1/8" diameter holes on this scale is currently not feasible
    - ➢ Grid requirements to resolve flow is beyond current technology
    - ➢ Two-phase physics are being incorporated in future version of the CRUNCH code under a current SBIR contract with CRAFT-Tech that will enable approximate modeling of the cooling flow.
  - ❑ Basic structure of wet-plume will be similar to the dry-plume
  - ❑ CFD dry-plume data can be used to guide engineering level calculations (correlations/experience) for future cooling modifications.

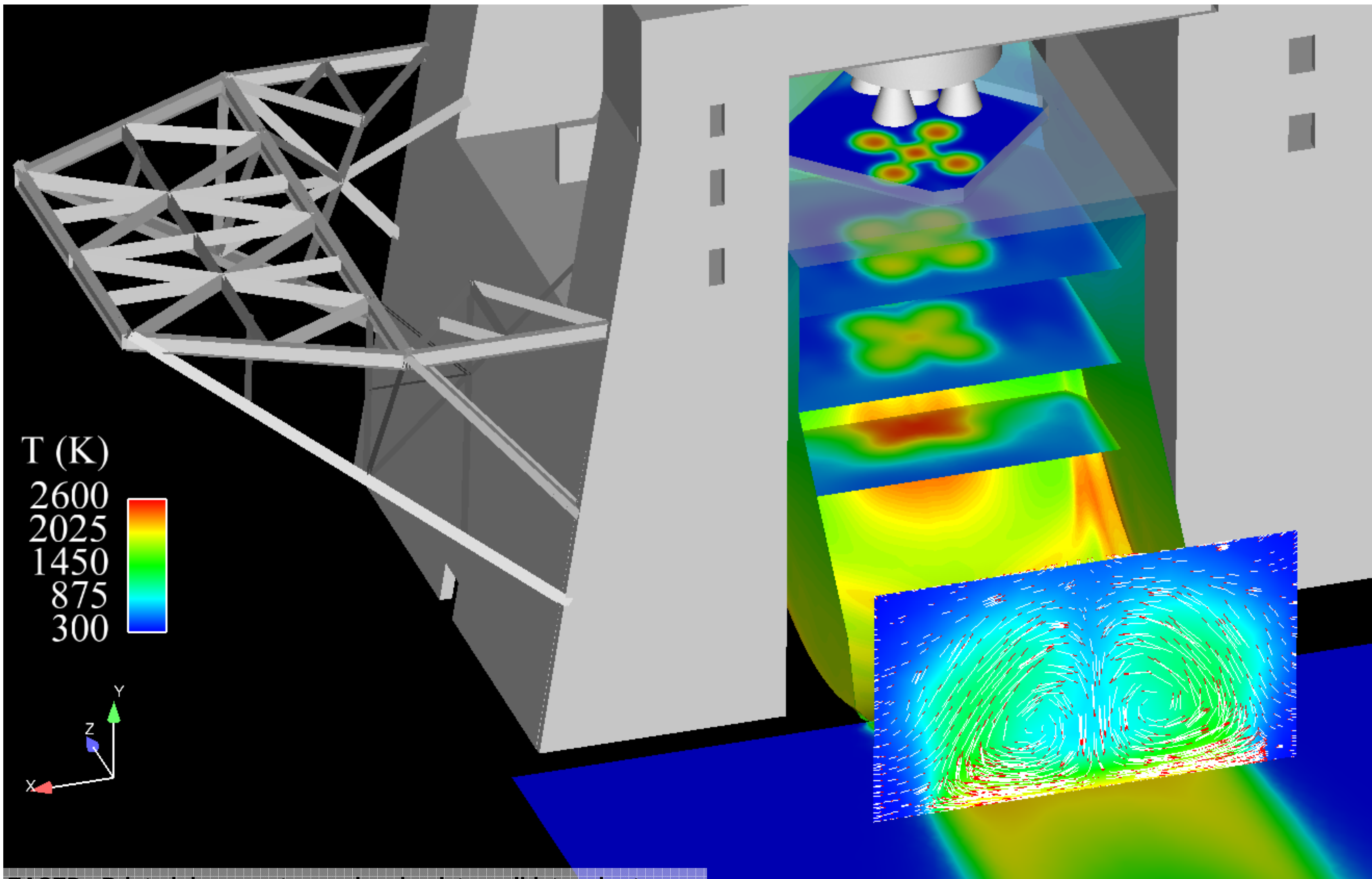
Conceptual ARES Stage Tests – Results



- Test article, stand, and ground contoured by Temperature
- Iso-thermal surface @ 1000 K colored by Velocity
- Engine streamlines (red)
- Plume entrainment streamlines (white)

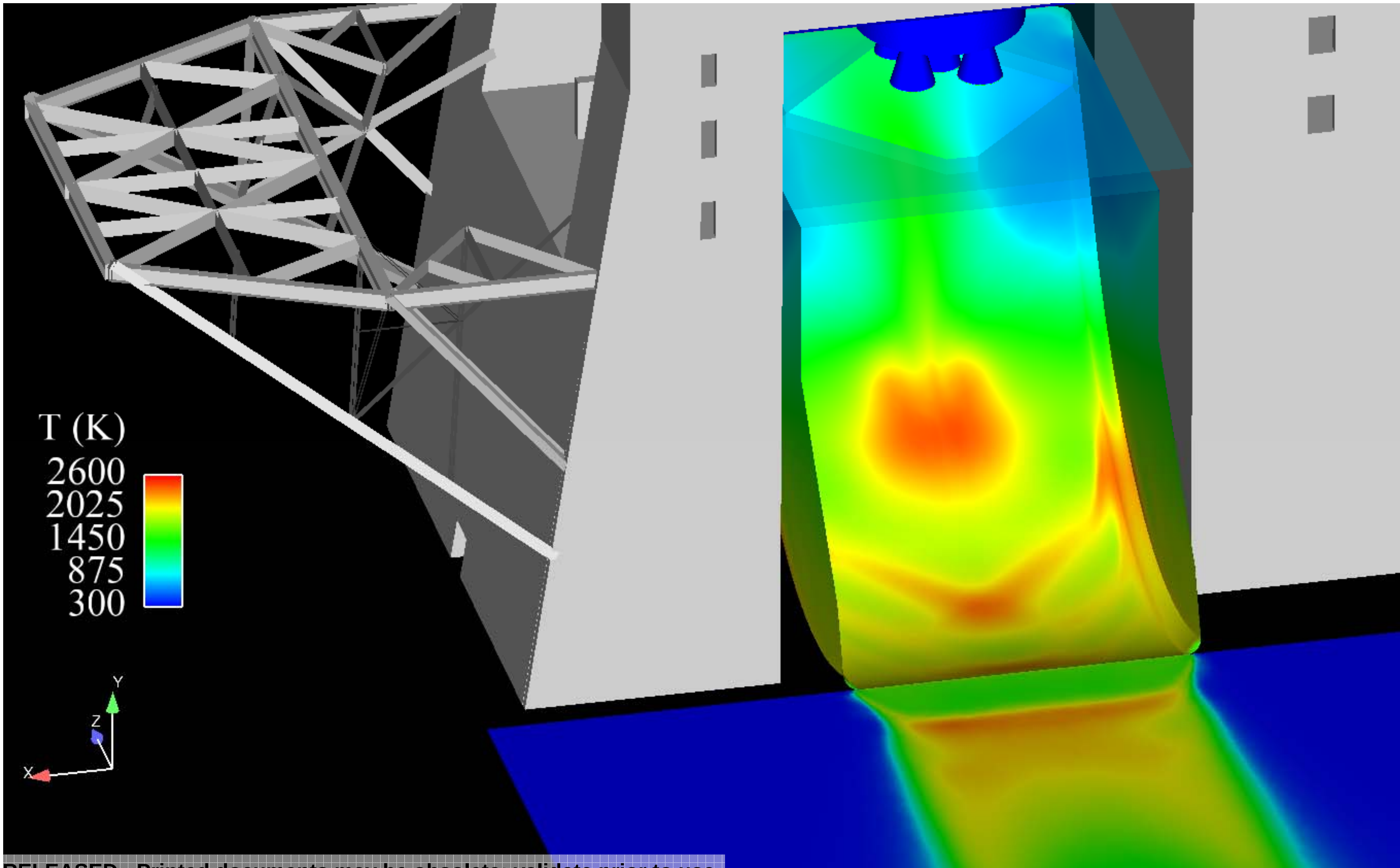
Conceptual ARES Stage Tests – Results

- Time-averaged plume cross-section temperature contours



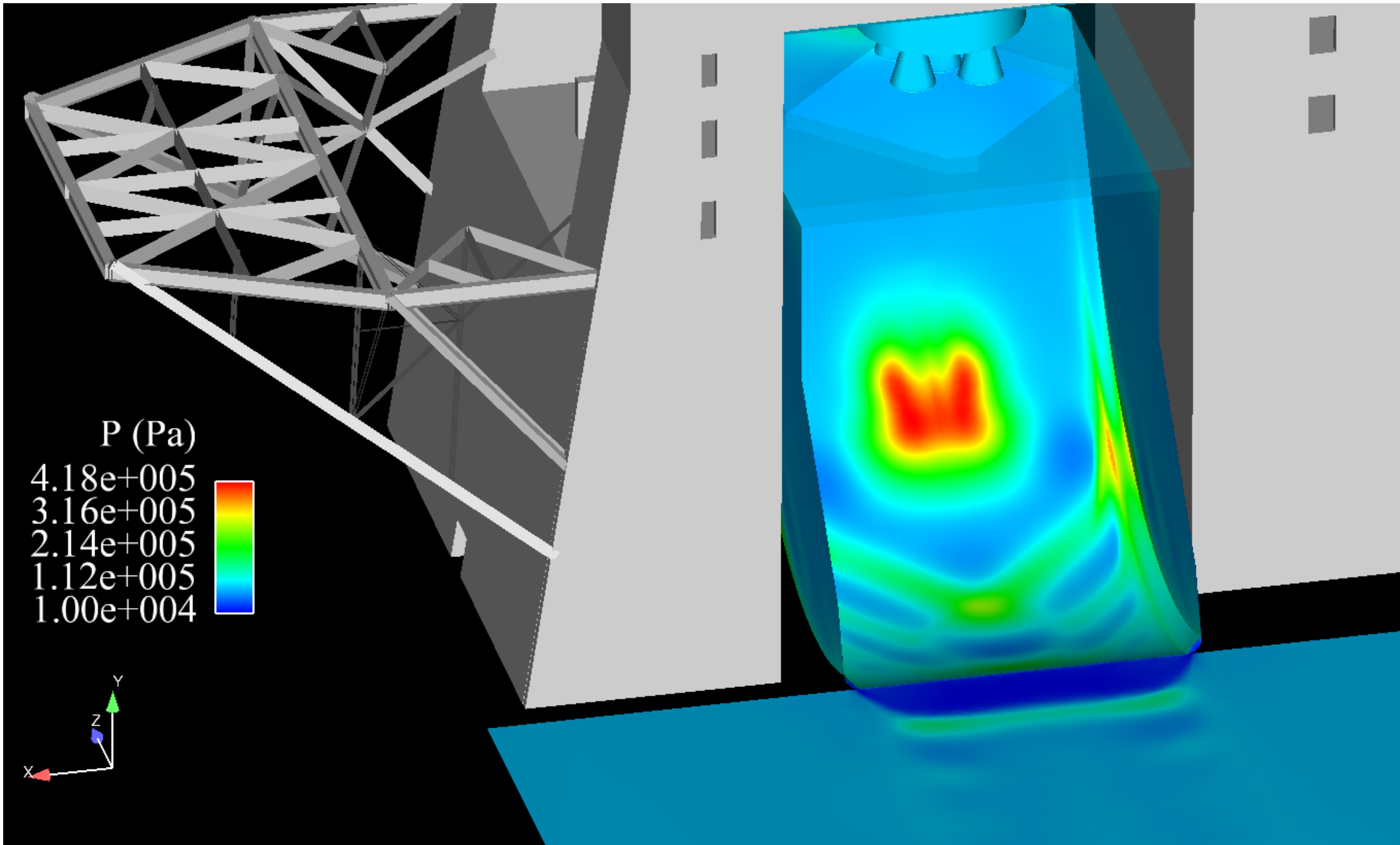
Conceptual ARES Stage Tests – Results

- Time-averaged un-cooled wall surface temperatures



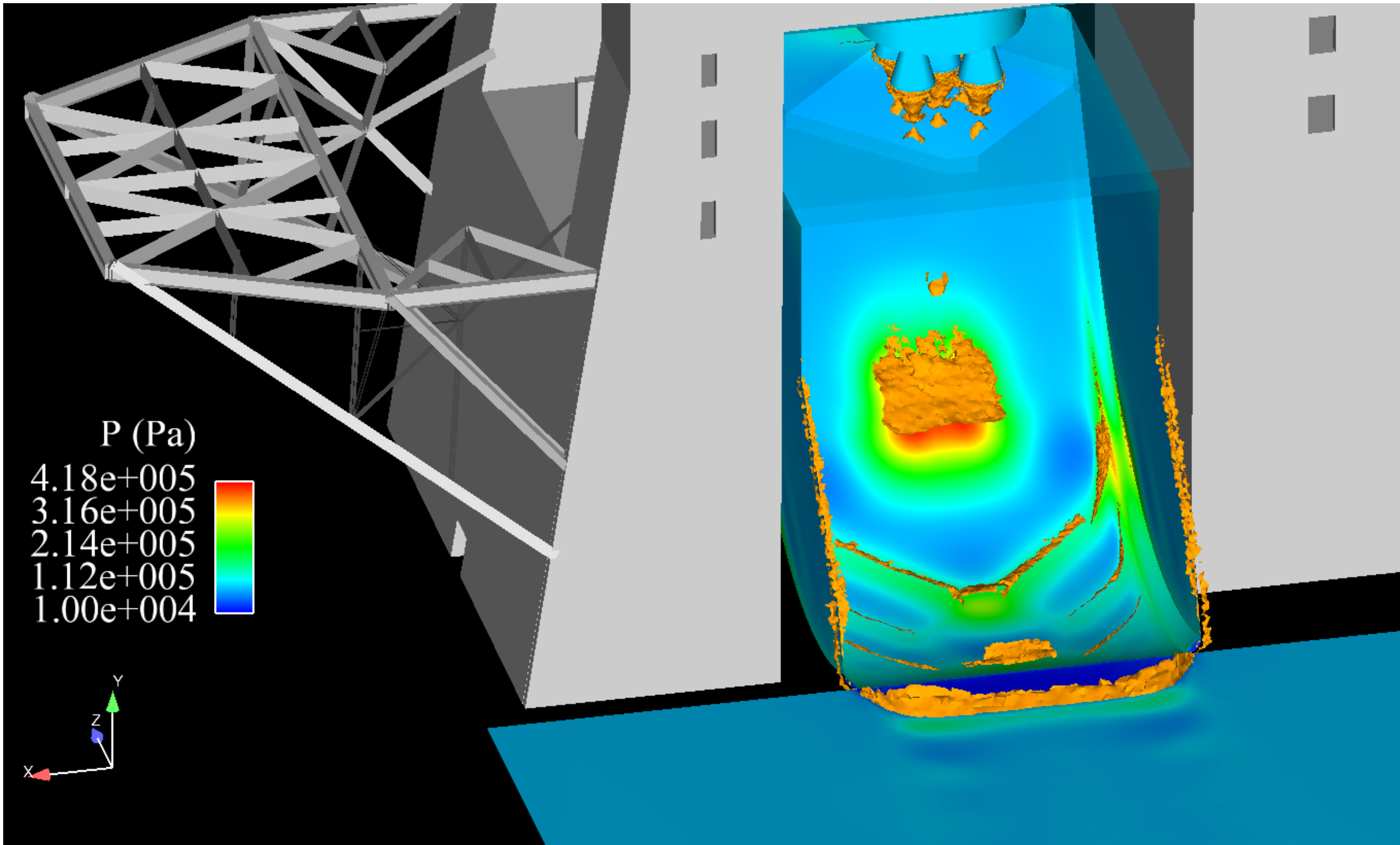
Conceptual ARES Stage Tests – Results

- Time-averaged un-cooled wall surface pressures



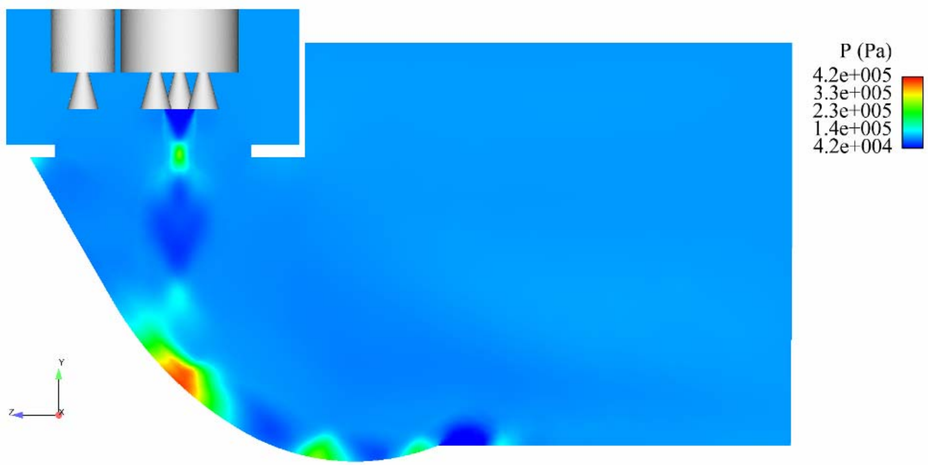
Conceptual ARES Stage Tests – Results

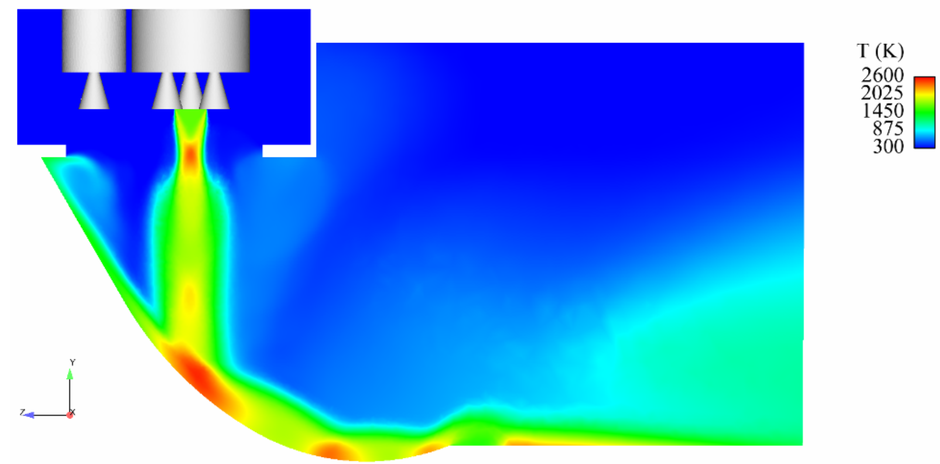
- Time-averaged un-cooled wall surface pressures & shock surfaces

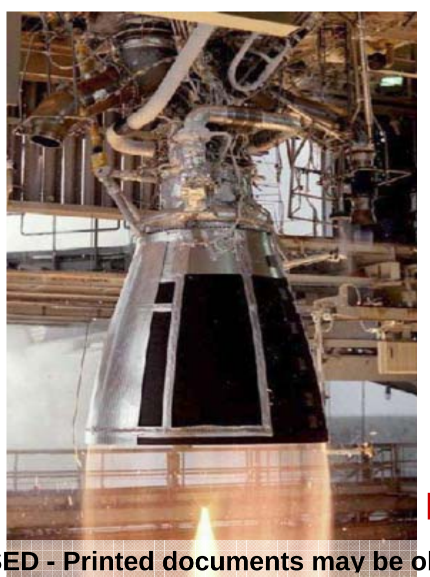


Conceptual ARES Stage Tests – Results

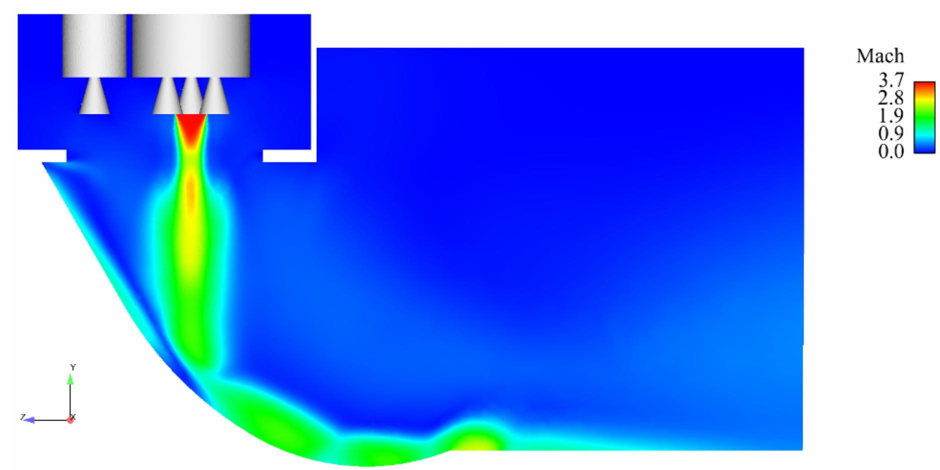
- Time-averaged centerline (x-slice) contours





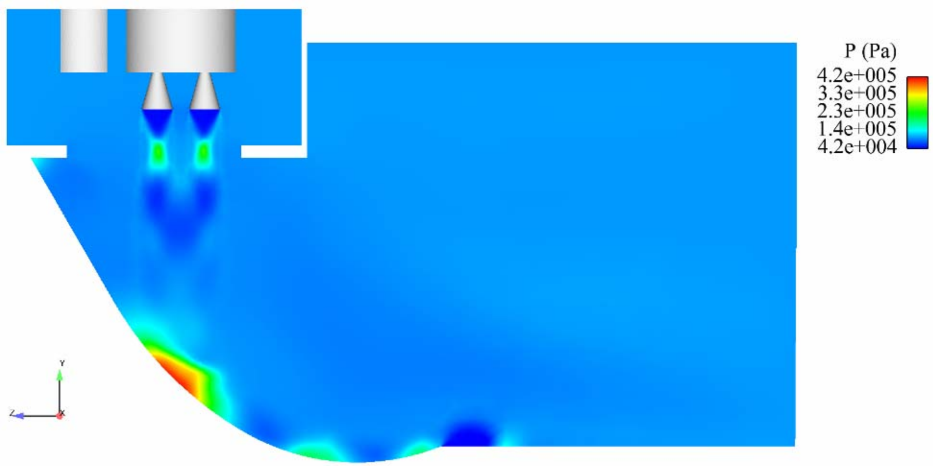


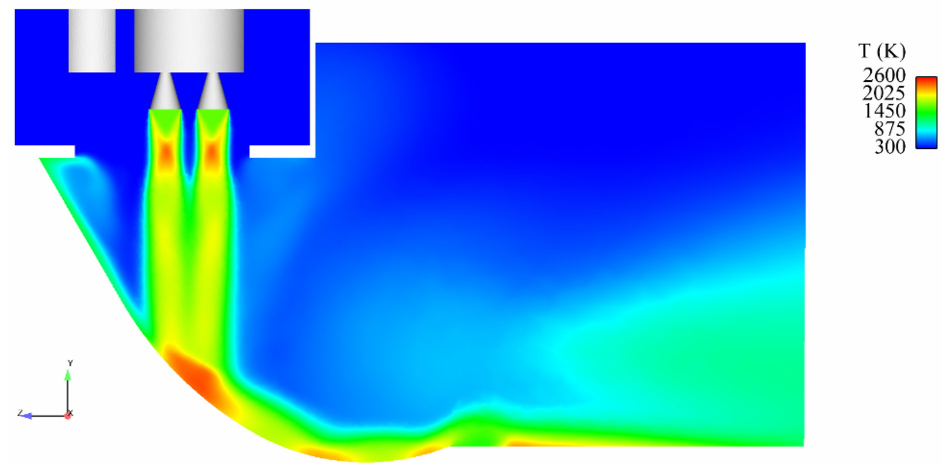
RS-68 Test @ B-1
(660 K-lbf)

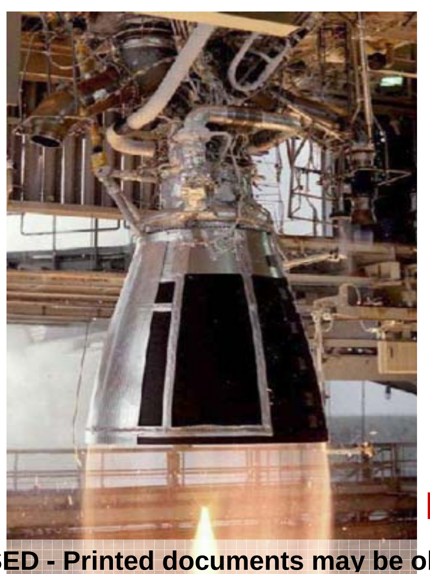


Conceptual ARES Stage Tests – Results

- Time-averaged off-center (x-slice) contours







RS-68 Test @ B-1
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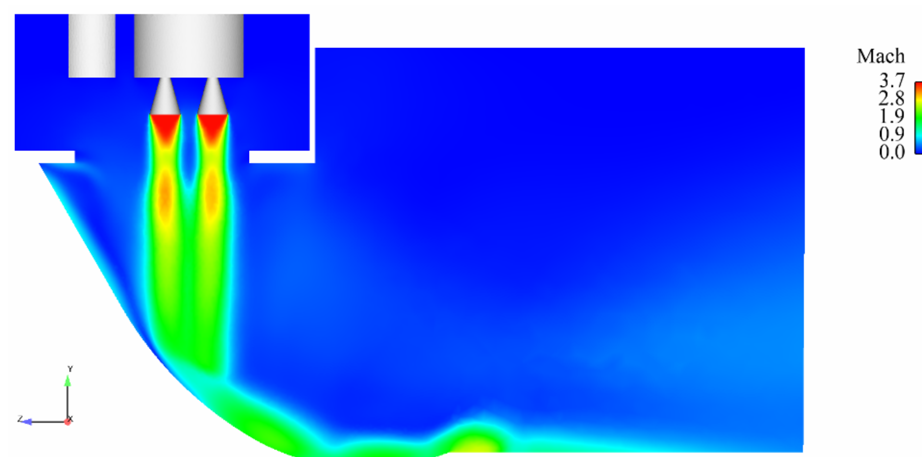

Conceptual ARES Stage Tests – Value Added

Capabilities/Competency:

- Provided the <u>unique capability</u> of modeling and analyzing the B-2 test stand flow-field at full-scale.
- Provided the <u>experience base</u> for future CFD plume modeling of NASA Stennis test stands.

Learnings/Insight:

1. Provided a <u>physical understanding</u> of the ARES V plume dynamics and its impingement characteristics in terms of placement on the deflector, size and shape, and un-cooled temperatures/pressures.
    - This will prove to serve as a valuable guide for future engineering calculations & acoustic/vibrational studies

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Concluding Remarks

- NASA Stennis Space Center is the nation's lead facility for full-scale liquid rocket engine testing.
- Testing at the component, engine and stage levels are essential for maintaining current space flight capabilities and reducing the associated risks.
- Computational modeling support of the test operations at Stennis is continually growing in demand.
- The Stennis modeling community is constantly looking to apply new validated technologies in the day-to-day working environment.