Computation of Unsteady Flow in Flame Trench For Prediction of Ignition Overpressure Waves

Dochan Kwak and Cetin Kiris
NASA Ames Research Center
October 2010

These slides will be presented at Seoul National University and Hanyang University in Seoul, Korea during the week of October 25, 2010.
The material in this presentation has been widely disseminated in the following publications:

1. Kiris, C., Chan, W., Kwak, D., and Housman, J. A., “Time-accurate Computational Analysis of the Flame Trench,” The *Fifth International Conference on Computational Fluid Dynamics*, Seoul, Korea, July 7-11, 2008.
2. Kiris, C., Housman, J., Schauerhamer, D., Gusman, M., Chan, W., and Kwak, D., “Time-Accurate Computational Analysis of the Flame Trench Applications,” 21st International Conference on Parallel Computational Fluid Dynamics, Moffett Field, CA, USA, May 18-22, 2009.
3. Housman, J.A., Kiris, C., and Kwak, D., “Time-Accurate Computational Analysis of a Dual-time Stepping Method for Simulating Ignition Overpressure Waves,” ICCFD6, St. Petersburg, Russia, July 12-16, 2010
4. Kiris, C., Housman, J.A., and Kwak, D., “Space/Time Convergence Analysis of a Ignition Overpressure in the Flame Trench,” CFD Review 2010, World Scientific, 2010

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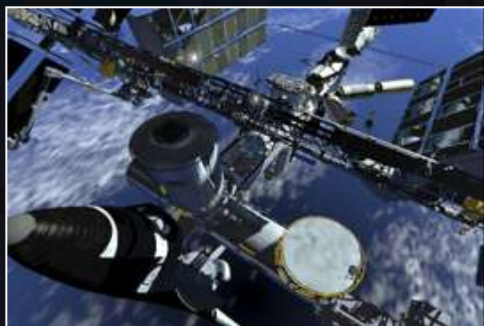
Technical Challenges of Space Exploration

Performance, Safety, Reliability, Cost

ISS



Human in Space

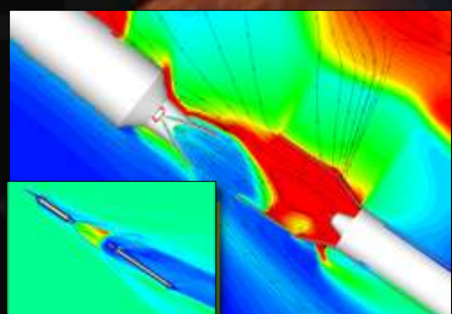
In-space Travel

(Earth Departure Stage)

Crew Exploration Vehicle (CEV)

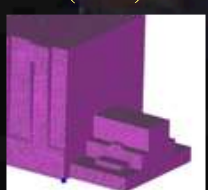
Martian Base

Ascent & Risk Assessment



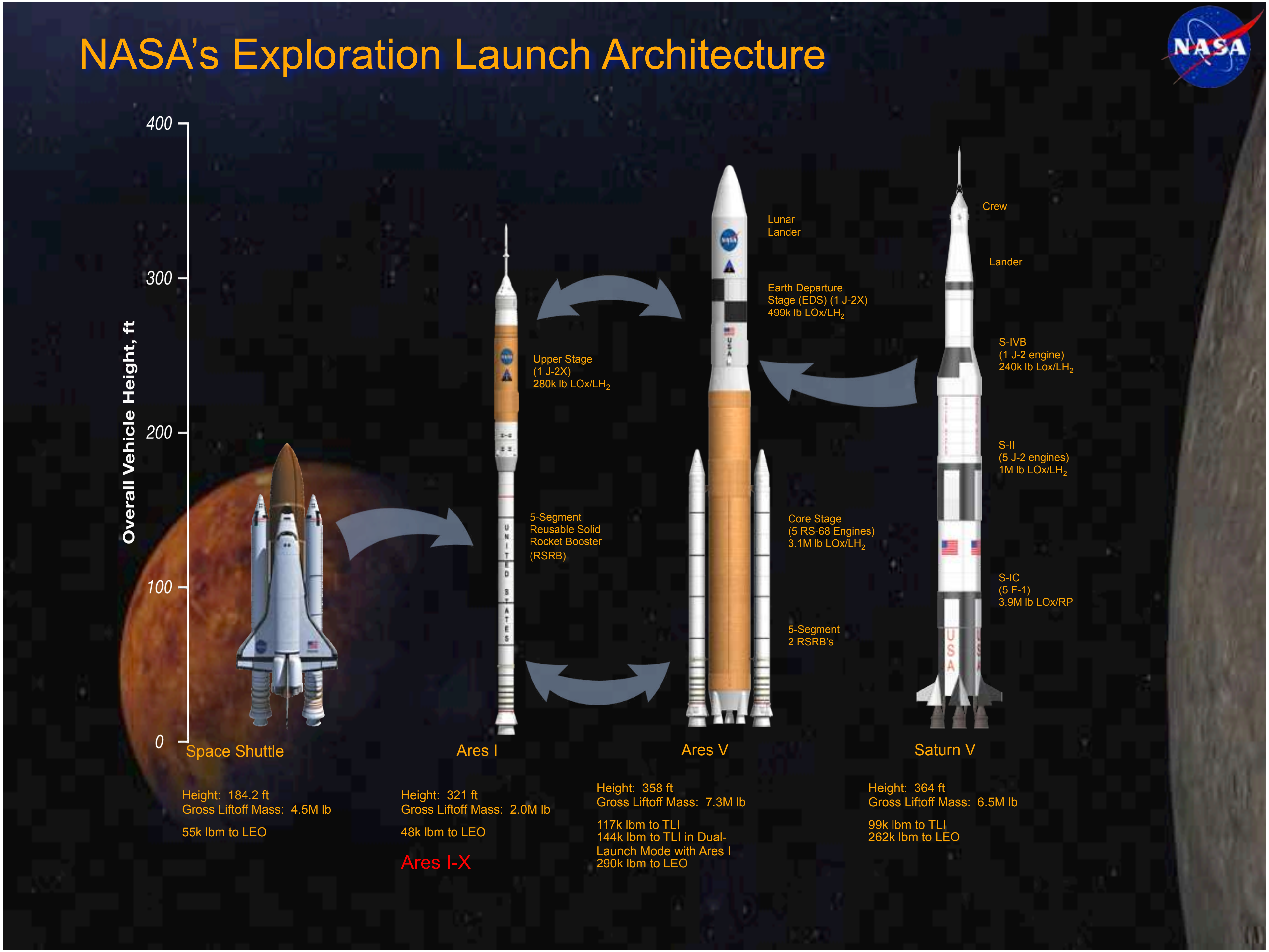
Ground Operation & Lift Off

T0 (VAB)



T0+1.9 sec

Return to Earth: EDL


NASA's Exploration Launch Architecture
NASA
Overall Vehicle Height, ft
400
300
200
100
0
Crew
Lander
Lunar Lander
Earth Departure Stage (EDS) (1 J-2X) 499k lb LOx/LH_2
Upper Stage (1 J-2X) 280k lb LOx/LH_2
S-IVB (1 J-2 engine) 240k lb Lox/LH_2
S-II (5 J-2 engines) 1M lb LOx/LH_2
5-Segment Reusable Solid Rocket Booster (RSRB)
Core Stage (5 RS-68 Engines) 3.1M lb LOx/LH_2
S-IC (5 F-1) 3.9M lb LOx/RP
5-Segment 2 RSRB's
Space Shuttle
Ares I
Ares V
Saturn V
Height: 184.2 ft
Gross Liftoff Mass: 4.5M lb
55k lbm to LEO
Height: 321 ft
Gross Liftoff Mass: 2.0M lb
48k lbm to LEO
Ares I-X
Height: 358 ft
Gross Liftoff Mass: 7.3M lb
117k lbm to TLI
144k lbm to TLI in Dual-Launch Mode with Ares I
290k lbm to LEO
Height: 364 ft
Gross Liftoff Mass: 6.5M lb
99k lbm to TLI
262k lbm to LEO

Today's talk: CFD applications to launch environment focusing on unsteady flow in flame trench and prediction of ignition overpressure

Outline

- Introduction / Background
  - Major Sources of Unsteady Loads on Launch System
  - Flow in Flame Trench
  - Historical background
- Prediction of Ignition Overpressure Waves
- CFD Procedures
  - Solver
  - Benchmark Case for Validation
- Application Examples
  - STS-1 and STS-124 Analysis
  - Ares-1X
- Summary and Discussions

Introduction: Major Sources of Unsteady Loads on Launch Systems

1. Ignition Over Pressure (IOP)

   Primary source of transient load on flame trench, launch structure and vehicle at launch

   - High-accuracy simulation of start-up process was first performed at Ames in conjunction with Ares-1X

2. Plume aero-acoustics

   Can impose significant vibration load on vehicle and payload during ascent

   - Experimental correlation based on a single rocket is being used: NASA SP-8072 (1971)

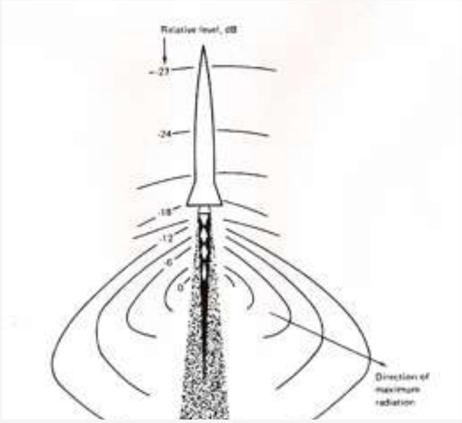
3. Vibration due to turbopump

   Can generate damaging vibration on engine and the whole launch vehicle during ignition, lift-off and ascent

   - Prediction tool not available to quantify cavitation

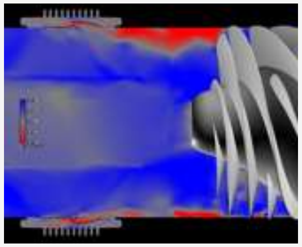
4. Combustion-related vibrations, such as thrust oscillation and combustion instability

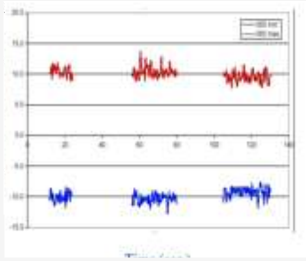
IOP



Sketch of overall sound pressure contour from exhaust plume

SSME Low Pressure Fuel Pump: instantaneous pressure map & measured pressure fluctuation upstream of the pump ➔

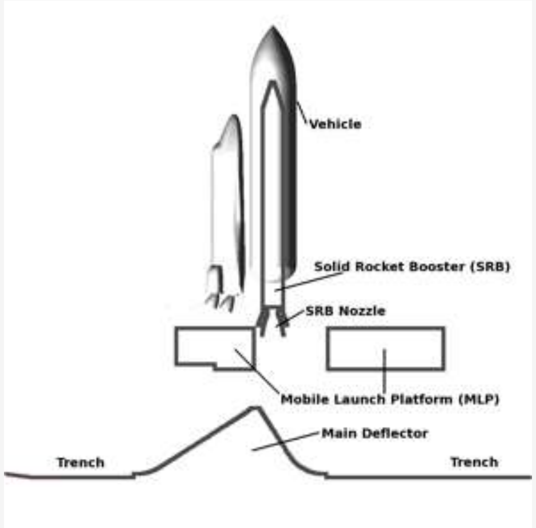




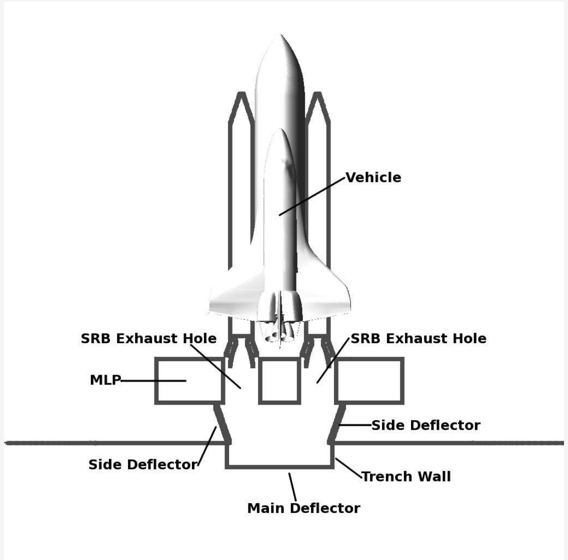
Introduction: Unsteady Flow in Flame Trench

IOP Wave Physics

- During ignition, the exhaust plume injects mass into the confined volume of the flame trench under the Mobile Launch Platform (MLP).
- This additional mass displaces the air within the trench causing a piston-like action.
- Compression waves then travel up and down the trench generating a series of strong pressure waves.
- The pressure waves travel back through the MLP exhaust holes towards the launch vehicle, possibly damaging the vehicle and surrounding structure



Shuttle and flame trench: main definition



Side view

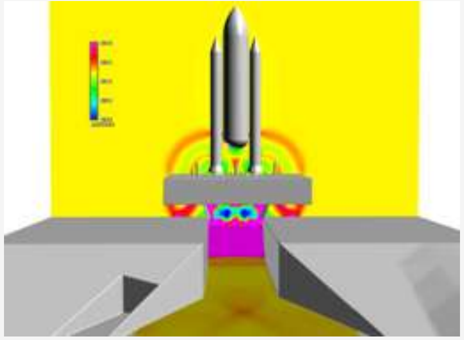
Introduction: Unsteady Flow in Flame Trench

In addition to IOP wave phenomenon, other complex physical processes also occur during ignition and liftoff.

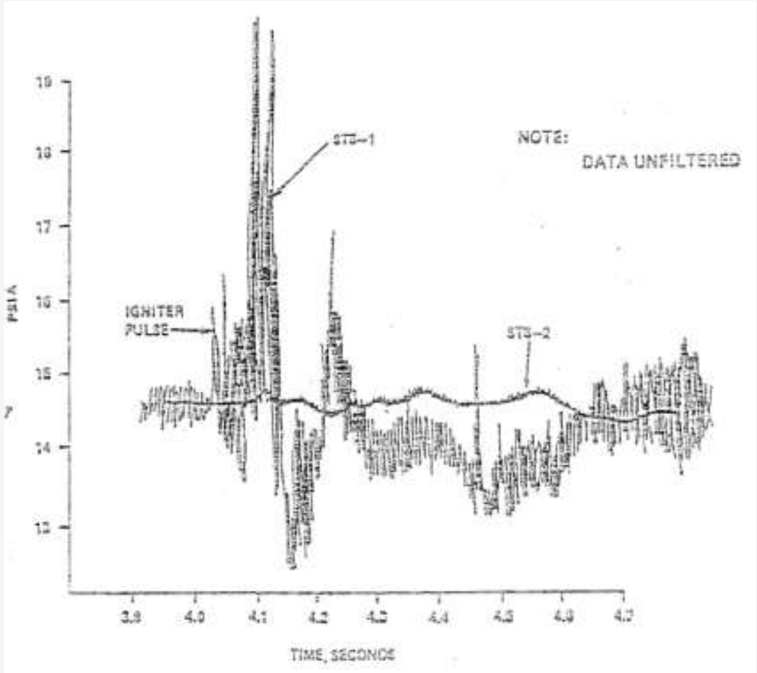
- Transient build up of the chamber stagnation conditions (very fast time scales).
- Multispecies interaction of exhaust gases with the ambient air.
- Fuel rich exhaust gas afterburning (chemical reactions).
- After burning effects of solid aluminum particles in SRB plumes.
- Multiphase interaction of the exhaust gases with the IOP wave suppression system (for example, water jet, water bag etc).

Introduction: Historical Background

- STS-1 & 2 Flight Data Comparison
  - STS-1 data shows very high ignition pulse
  - STS-2 shows the impact of water suppression system



CFD simulation of IOP with Shuttle, Kiris et al.
STS-1 April 12, 1981



STS-1&2 IOP Flight Data

Introduction: Historical Background

- STS-124 Trench Wall Damage

  During the launch of space shuttle Discovery on May 31, 2008, flame trench wall was damaged.

  Debris shown in the photo is the residue from this damage.

  Repairs are done before space shuttle Atlantis' STS-125 mission to NASA's Hubble Telescope.

Debris scattered near Launch Pad 39A at NASA's Kennedy Space Center after May 31, 2008 launch of space shuttle Discovery

Damaged wall

Debris scattered outside the perimeter of Launch Pad 39A

Prediction of Ignition Over Pressure (IOP) Waves

- Objectives of CFD Simulation
  - Characterize/ quantify IOP wave for new and existing launch vehicles (as a part of the entire ascent simulation).
  - ➢ IOP trend analysis can contribute to launch pad design.

- Approach
  - Evaluate current capabilities and develop high-fidelity methods/tools
    Algorithm and solution procedure
    Space time resolution requirements
  - Idealized test case
    2-D impinging jet: Experiment by JAXA
  - STS-1 case
  - Single-phase applications (Ares-1X)
  - Multi-phase modeling issue (STS-4)

  (Currently collaborating with JAXA to develop numerical methods, enhance supercomputing performance, and develop advanced multi-phase flow modeling)

CFD Procedures

- State-of-the-art CFD technology
  - Grid generators, solvers (and associated algorithms) are generally available (either in-house or commercial codes).
  - Engineering-level physical models are also available for steady state solutions.
  - Prediction capability is limited to small regions, primarily in steady-state (generally good for interpolation).
  - Supercomputers at Petaflops level are becoming more available, requiring to look into parallel efficiency, data management…
    - Jaguar at ORNL (224,000 cores)
    - Pleiades at NASA Ames (81,000 cores, theoretical peak of 973.3TF)
    - …and others
- Current Procedure
  - Rigorous error estimate/control methods, validation procedures are not available – "Best Practices" are current approach.

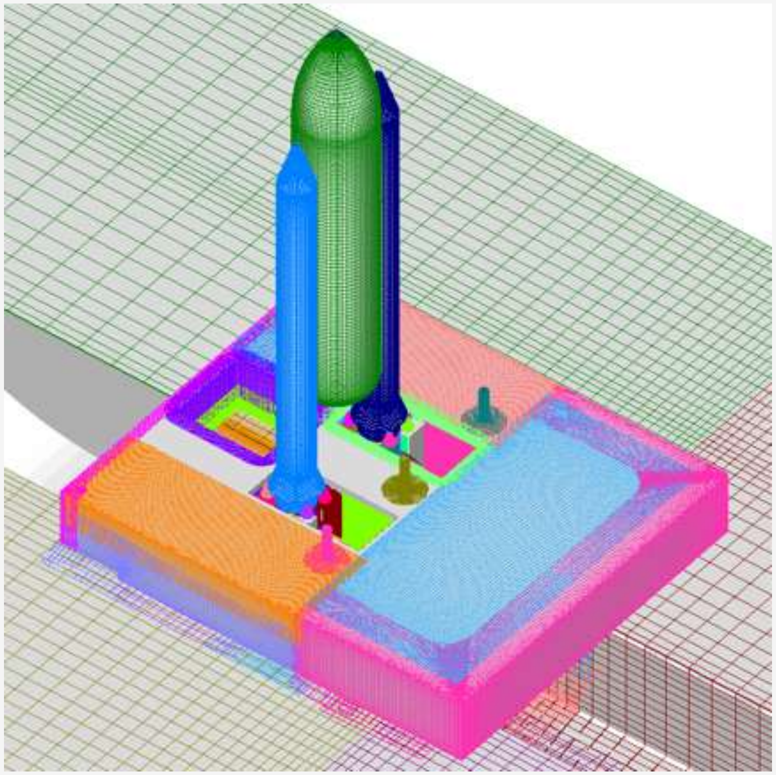
➢ Next, will demonstrate how space and time resolution requirements are determined for IOP simulation.

Computational Model and Flow Solver

- Computational Model and Grid:

  Overset grid:

  - e.g. STS-1 Shuttle configuration
    - 2 SRB's and external tank
    - 129 overset grids
    - 92 Million grid points
- Flow Solver : OVERFLOW-2
  - Compressible Navier-Stokes flow solver
  - Automatic domain connectivity including grid splitting for parallel computations
  - Spalart-Allmaras Turbulence Model
  - Diagonalized Beam-Warming scalar pentadiagonal scheme for LHS terms
  - Second-order in time with sub-iteration procedure (20 subiterations)
  - Physical time step used : 8.0e-5 seconds
- Assumptions
  - Single species calculations
  - Single Phase (no water effects)



Governing Equations

Reynolds Averaged Navier-Stokes Equations

$$\frac{\partial Q}{\partial t}+\frac{\partial (F-F_v)}{\partial x}+\frac{\partial (G-G_v)}{\partial y}+\frac{\partial (H-H_v)}{\partial z}=0$$

$$Q=\begin{bmatrix}\rho\\ \rho u\\ \rho v\\ \rho w\\ E\end{bmatrix}\quad F=\begin{bmatrix}\rho u\\ \rho u^2+p\\ \rho uv\\ \rho uw\\ \rho uH\end{bmatrix}\quad G=\begin{bmatrix}\rho v\\ \rho vu\\ \rho v^2+p\\ \rho vw\\ \rho vH\end{bmatrix}\quad H=\begin{bmatrix}\rho w\\ \rho wu\\ \rho wv\\ \rho w^2+p\\ \rho wH\end{bmatrix}$$

Governing Equations

$$F_v = \begin{bmatrix} 0 \\ \tau^{xx} \\ \tau^{xy} \\ \tau^{xz} \\ u\tau^{xx} + v\tau^{xy} + w\tau^{xz} - q_1 \end{bmatrix} G_v = \begin{bmatrix} 0 \\ \tau^{yx} \\ \tau^{yy} \\ \tau^{yz} \\ u\tau^{yx} + v\tau^{yy} + w\tau^{yz} - q_2 \end{bmatrix} H_v = \begin{bmatrix} 0 \\ \tau^{zx} \\ \tau^{zy} \\ \tau^{zz} \\ u\tau^{zx} + v\tau^{zy} + w\tau^{zz} - q_3 \end{bmatrix}$$

$$\tau^{ij} = (\mu + \mu_T)\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}(\mu + \mu_T)\delta_{ij}\frac{\partial u_k}{\partial x_k} \qquad \vec{q} = -(\kappa + \kappa_T)\ \nabla T$$

$$\mu = 1.45e-06\left(\frac{T^{1.5}}{T+110}\right) \text{kg/(m.s) (Sutherland's Law)} \qquad \kappa = \frac{C_P\ \mu}{\Pr} \ \text{(Pr - Prandtl Number)}$$

μ_T - Turbulent Eddy Viscosity κ_T - Turbulent Thermal Conductivity

(Computed from turbulence model)

Time Step Sensitivity Analysis

Dual Time Step Formulation in OVERFLOW 2

$$\frac{\partial \hat{Q}}{\partial \tau} + \frac{\partial \hat{Q}}{\partial t} + \frac{\partial (\hat{F} - \hat{F}_v)}{\partial \xi} + \frac{\partial (\hat{G} - \hat{G}_v)}{\partial \eta} + \frac{\partial (\hat{H} - \hat{H}_v)}{\partial \zeta} = 0$$

Generalized Coordinate Transformation

$\xi \equiv \xi(x,y,z),\ \eta \equiv \eta(x,y,z),\ \zeta \equiv \zeta(x,y,z)$

$\hat{Q} = J^{-1}Q$, where J^{-1} is the Jacobian of the transformation

$$\hat{F} = J^{-1}(\xi_x F + \xi_y G + \xi_z H) \qquad \hat{F}_v = J^{-1}(\xi_x F_v + \xi_y G_v + \xi_z H_v)$$

$$\hat{G} = J^{-1}(\eta_x F + \eta_y G + \eta_z H) \qquad \hat{G}_v = J^{-1}(\eta_x F_v + \eta_y G_v + \eta_z H_v)$$

$$\hat{H} = J^{-1}(\zeta_x F + \zeta_y G + \zeta_z H) \qquad \hat{H}_v = J^{-1}(\zeta_x F_v + \zeta_y G_v + \zeta_z H_v)$$

Time Step Sensitivity Analysis

Discretizations can be done, e.g. by fully-discrete formulation

$$\left[I + \frac{3}{2}\frac{\Delta\tau}{\Delta t} + J\,\Delta\tau\left(\frac{\partial \hat{R}}{\partial Q}\right)\right]\Delta Q^m = -J\,\Delta\tau\left(\frac{3\hat{Q}^m - 4\hat{Q}^n + \hat{Q}^{n-1}}{2\Delta t} + \hat{R}^m\right)$$

High-order RHS

$$\begin{aligned}\hat{R}^m &= (\tilde{F}^m_{j+1/2} - \tilde{F}^m_{j-1/2}) + (\tilde{G}^m_{k+1/2} - \tilde{G}^m_{k-1/2}) + (\tilde{H}^m_{l+1/2} - \tilde{H}^m_{l-1/2}) \\ &\quad - (\hat{F}^m_{v,j+1/2} - \hat{F}^m_{v,j-1/2}) - (\hat{G}^m_{v,k+1/2} - \hat{G}^m_{v,k-1/2}) - (\hat{H}^m_{v,l+1/2} - \hat{H}^m_{v,l-1/2})\end{aligned}$$

Approximate LHS

$$\left(\frac{\partial \hat{R}}{\partial Q}\right) \approx \left[\delta_\xi\left(\hat{A} - \hat{A}_v\right) + \delta_\eta\left(\hat{B} - \hat{B}_v\right) + \delta_\zeta\left(\hat{C} - \hat{C}_v\right)\right]$$

$$\hat{A} = \frac{\partial \hat{F}}{\partial Q},\ \hat{B} = \frac{\partial \hat{G}}{\partial Q},\ \hat{C} = \frac{\partial \hat{H}}{\partial Q}$$

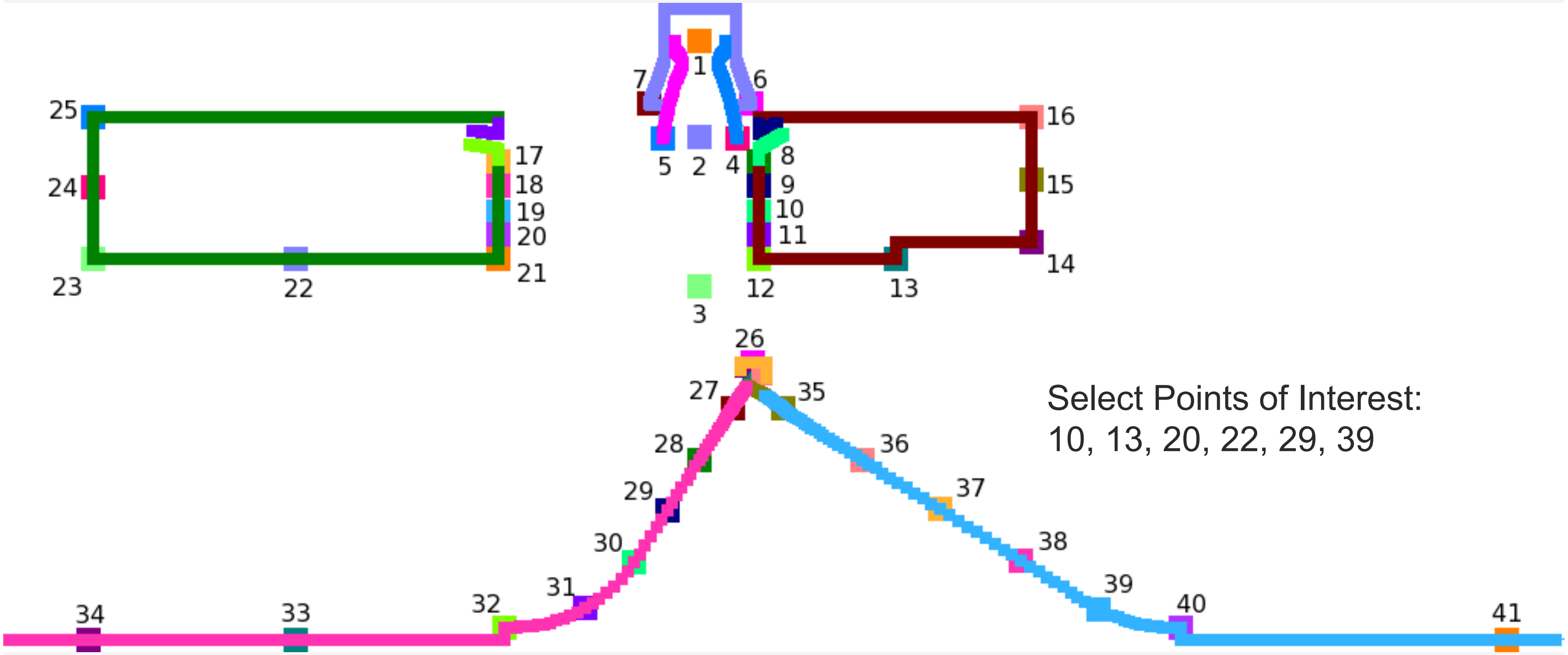
and

$$\hat{A}_v = \frac{\partial \hat{F}_v}{\partial Q},\ \hat{B}_v = \frac{\partial \hat{G}_v}{\partial Q},\ \hat{C}_v = \frac{\partial \hat{H}_v}{\partial Q}$$

Time Step Sensitivity Analysis

Test Problem-2D Flame Trench

Time-Accurate Pressure Point Locations

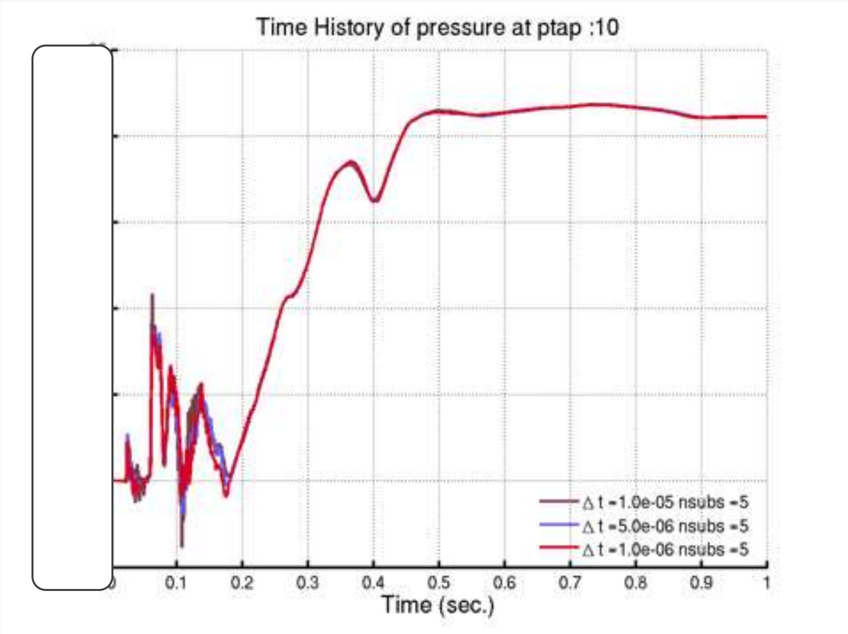


Select Points of Interest:
10, 13, 20, 22, 29, 39

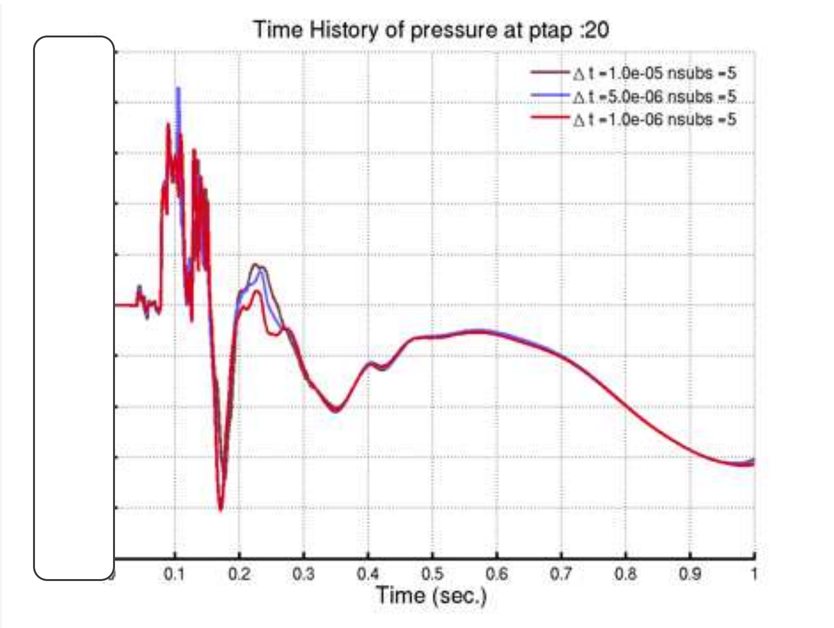
Initial Conditions: Atmospheric Pressure and Density, Zero Velocity.

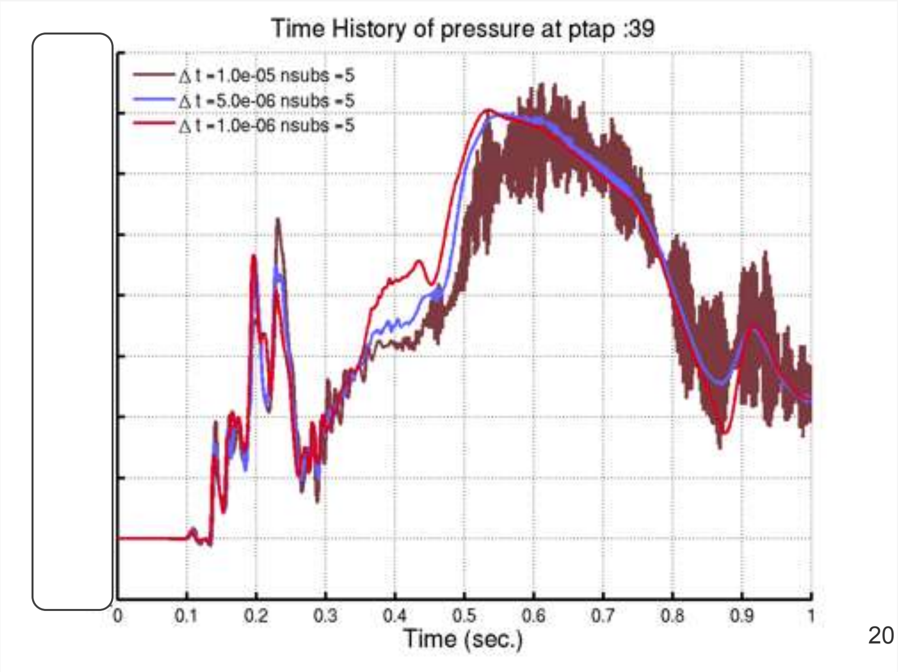
Boundary Conditions: Time-accurate plenum conditions at the nozzle.

Time Step Sensitivity Analysis

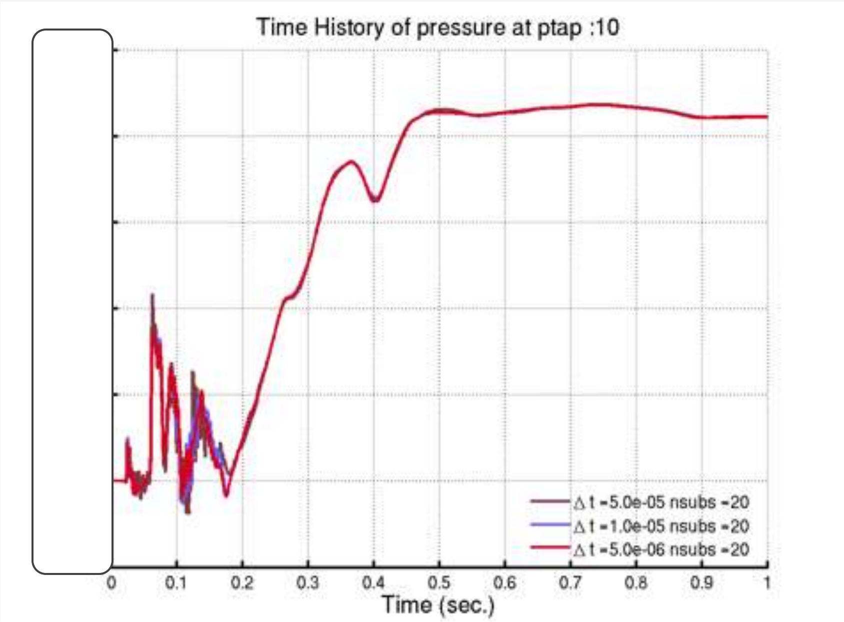


Δt/nsubs	5	10	20	50	100	200
1.0e-04	#	#	#	#	X	X
5.0e-05	#	#	X	X	X	X
1.0e-05	X	X	X	X	X	X
5.0e-06	X	X	X	X		
1.0e-06	X	X				

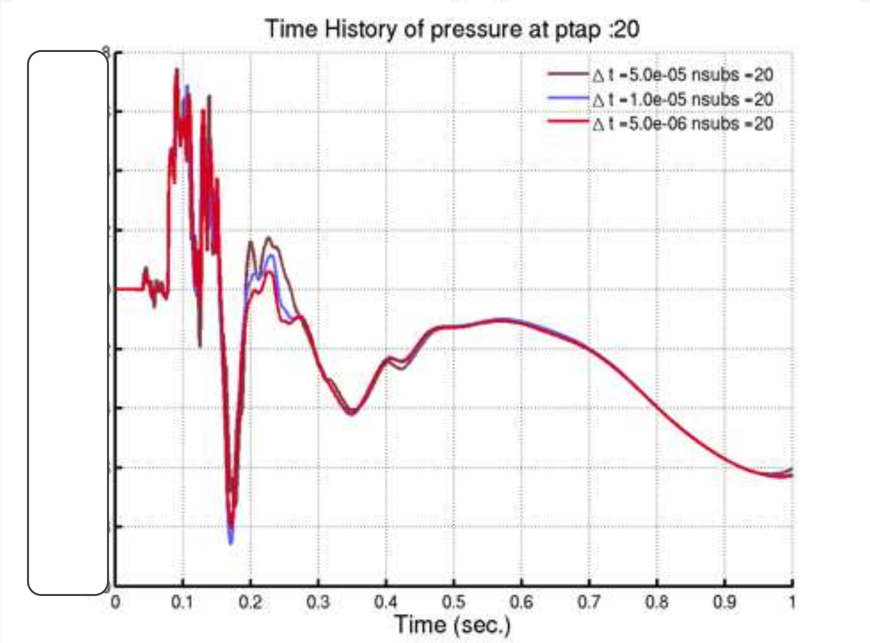


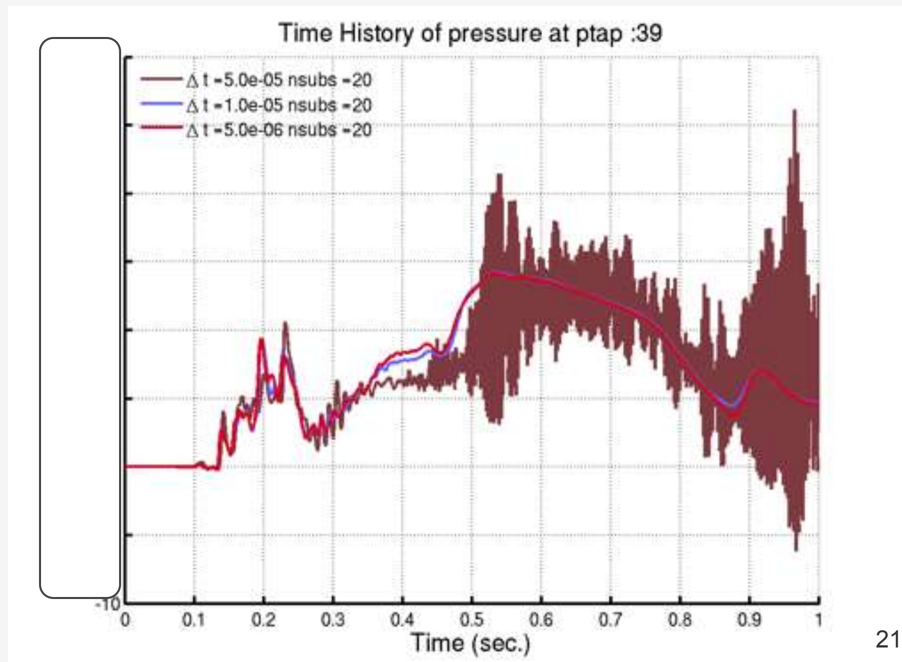


Time Step Sensitivity Analysis

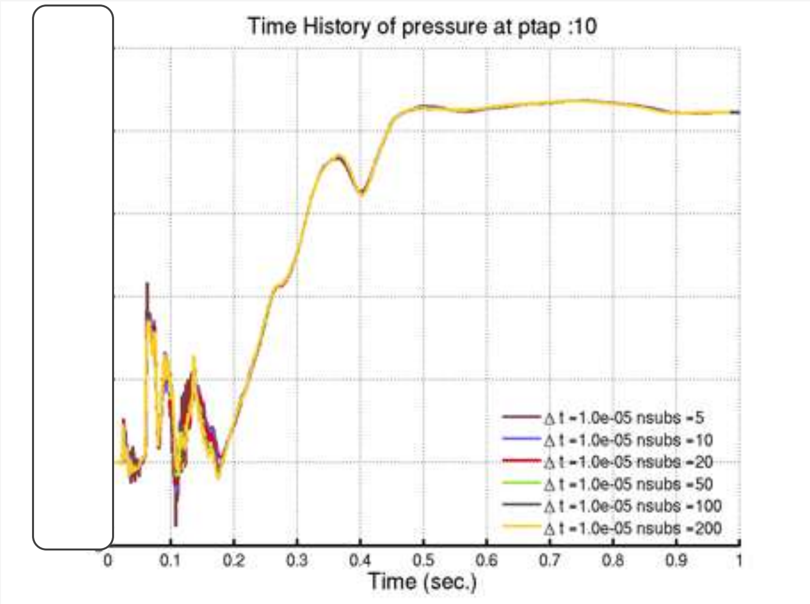


Δt/nsubs	5	10	20	50	100	200
1.0e-04	#	#	#	#	X	X
5.0e-05	#	#	X	X	X	X
1.0e-05	X	X	X	X	X	X
5.0e-06	X	X	X	X		
1.0e-06	X	X				

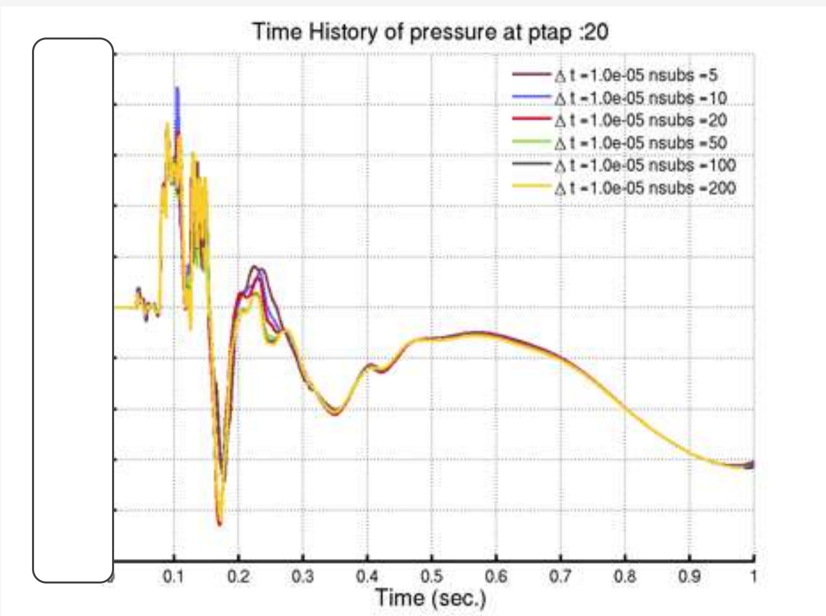


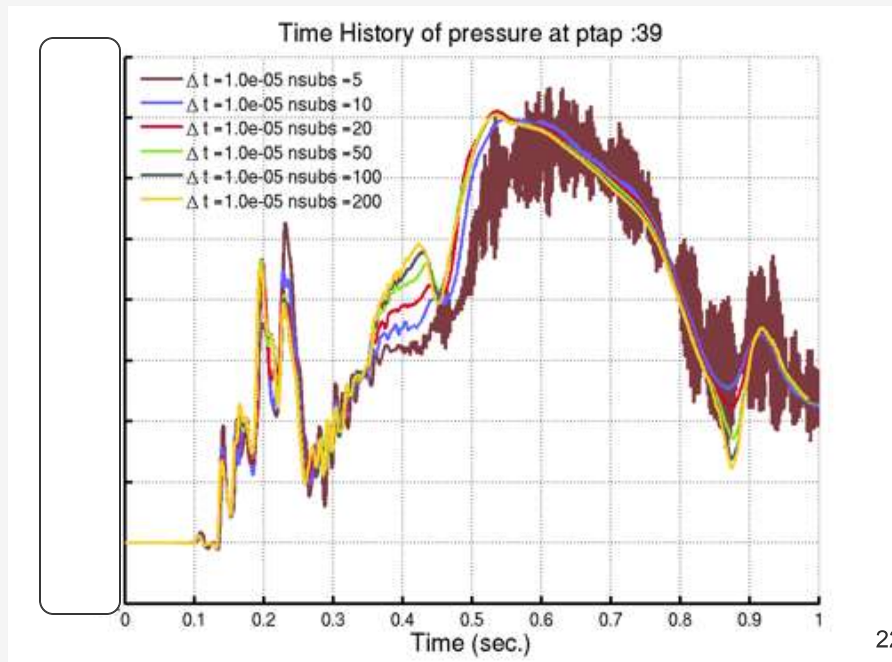


Time Step Sensitivity Analysis



Δt/nsubs	5	10	20	50	100	200
1.0e-04	#	#	#	#	X	X
5.0e-05	#	#	X	X	X	X
1.0e-05	X	X	X	X	X	X
5.0e-06	X	X	X	X		
1.0e-06	X	X				





Time Step Sensitivity Analysis

Analysis is performed using the dual time stepping framework to analyze the sensitivity of unsteady IOP wave propagation with respect to both time step and convergence.

- The largest possible pseudo time CFL numbers should be used for efficiency
- Larger pseudo time CFL numbers were examined, but lead to sub-iteration instabilities.
- Large physical time steps with small pseudo time CFL numbers and a small number of sub-iterations lead to nonphysical results (without numerical instability).
- For a fixed time step and pseudo time CFL, the sub-iterations should be increased until a sub-iteration invariant solution is obtained.

$$1.0e-05 \leq \Delta t \leq 5.0e-05 \quad \text{for } nsubs = 10 \text{ and } 20$$

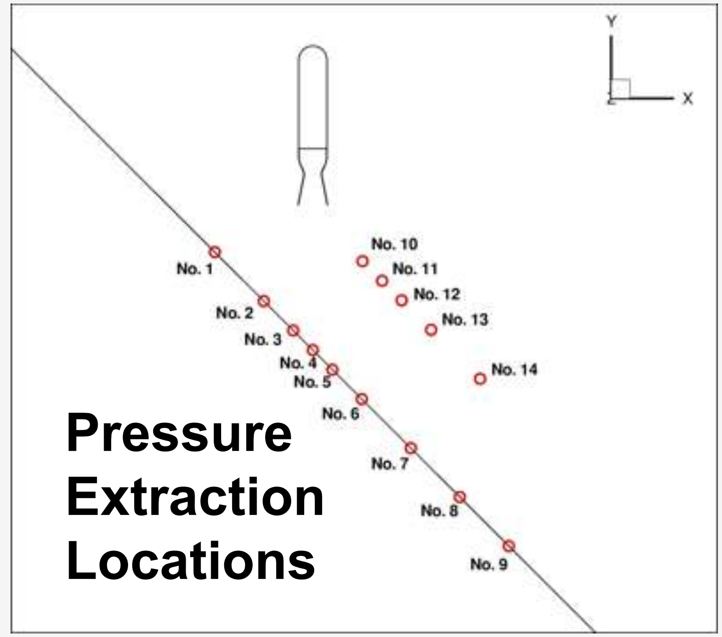
$$5.0e-05 \leq \Delta t \leq 1.0e-04 \quad \text{for } nsubs \geq 50$$

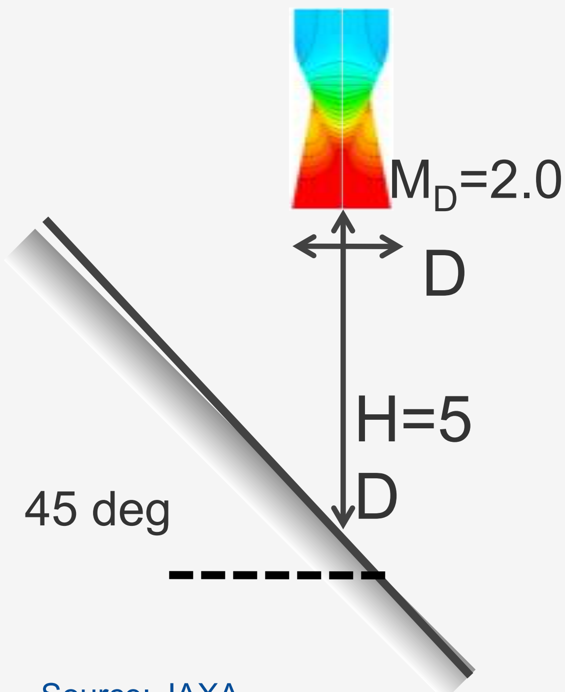
Idealized Test Case for Validation

Test Case Introduced by NASA-JAXA collaboration:

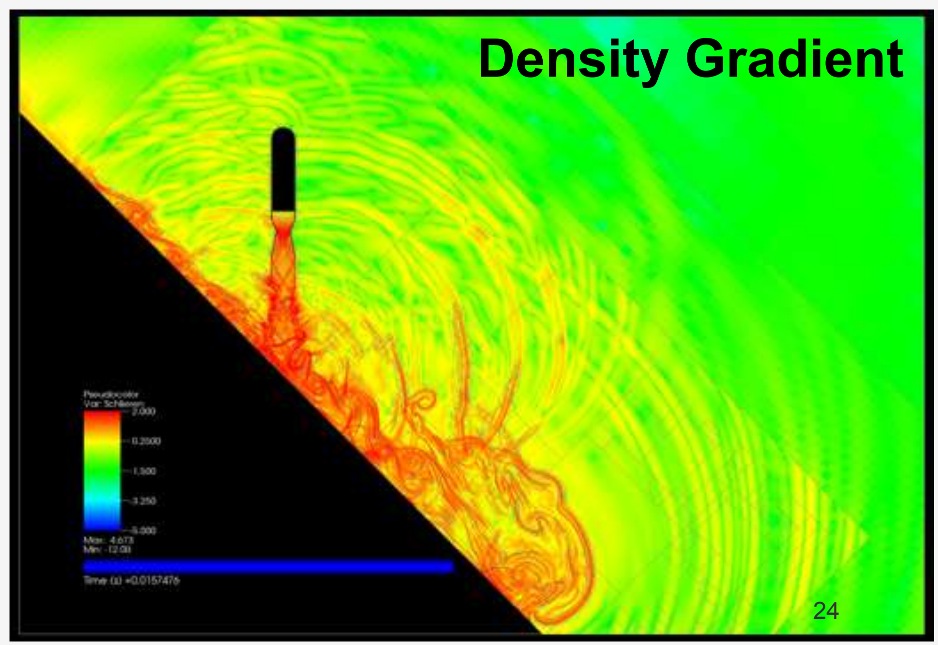
2D Impinging Jet

- Focus on basic methods for capturing IOP and launch acoustics
- Conical Mach 2 nozzle
- Single-species (γ = 1.4)
- Po/Patm = 7.825
- Over inclined flat plate





Source: JAXA



Simulating Ignition Overpressure Waves

Numerical experiments

- Jet Impingement Physics
- Sensitivity Analysis
  - Sub-Iteration
  - Physical Time-Step
  - Space-Time

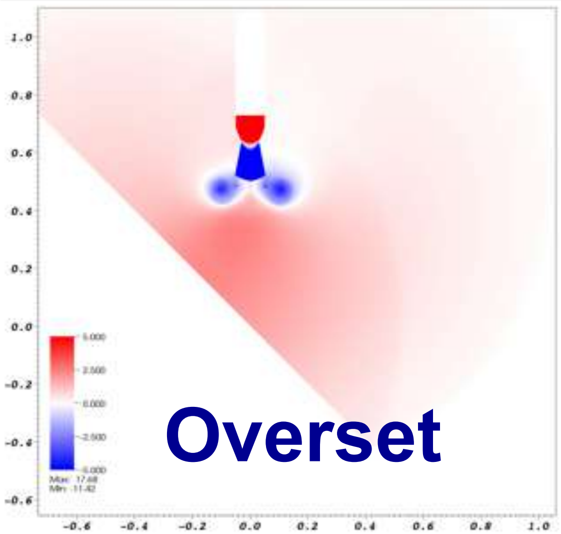
Parameter Matrix

- Seven sub-iteration counts:
  - NSUB = 5, 10, 20, 50, 100, 200, 400
- Six physical time levels:
  - CFL = 1, 2, 5, 10, 50, 100
- Three grid resolution levels:
  - Coarse $\Delta x = 0.005$ m, $1.4e\text{-}05 <= \Delta t <= 1.4e\text{-}04$
  - Medium $\Delta x/2$, $\Delta t/2$
  - Fine $\Delta x/4$, $\Delta t/4$

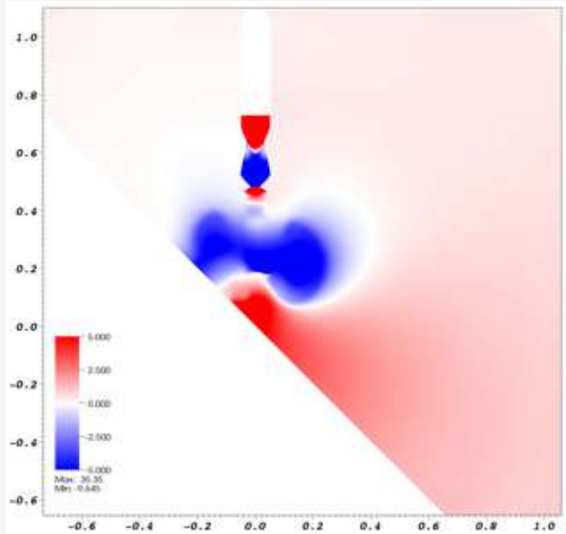
$$\Delta t = \frac{CFL \cdot \Delta x}{Cref}$$

Jet Impingement Time Sequence

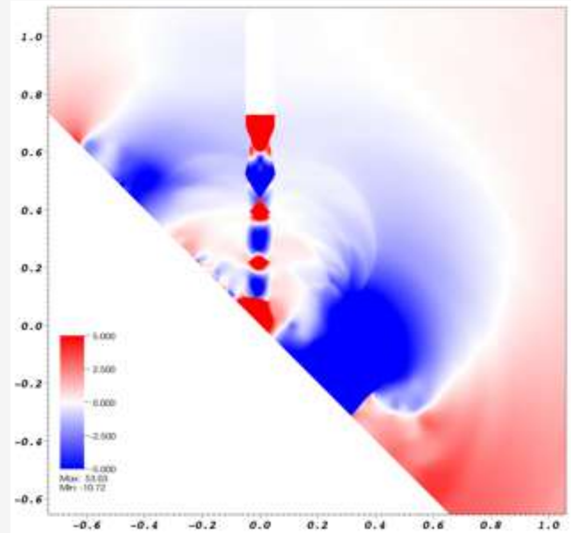
t=0.0036 s



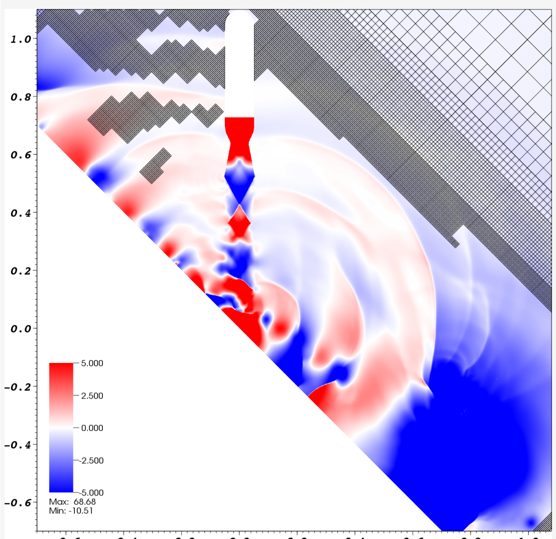
t=0.0072 s



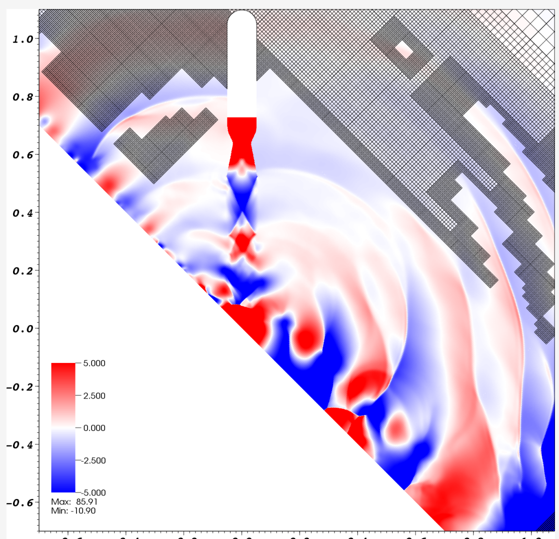
t=0.0108 s



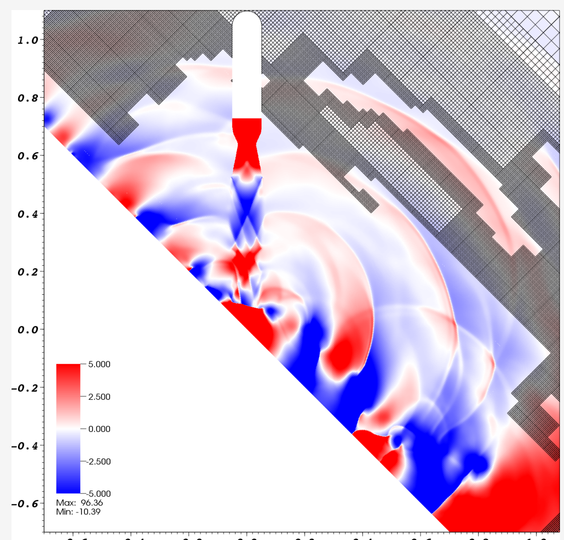
t=0.0144 s



t=0.0180 s

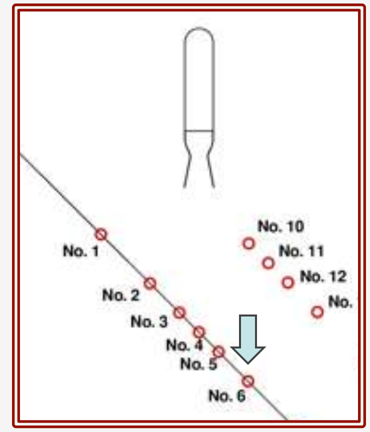


t=0.0216 s

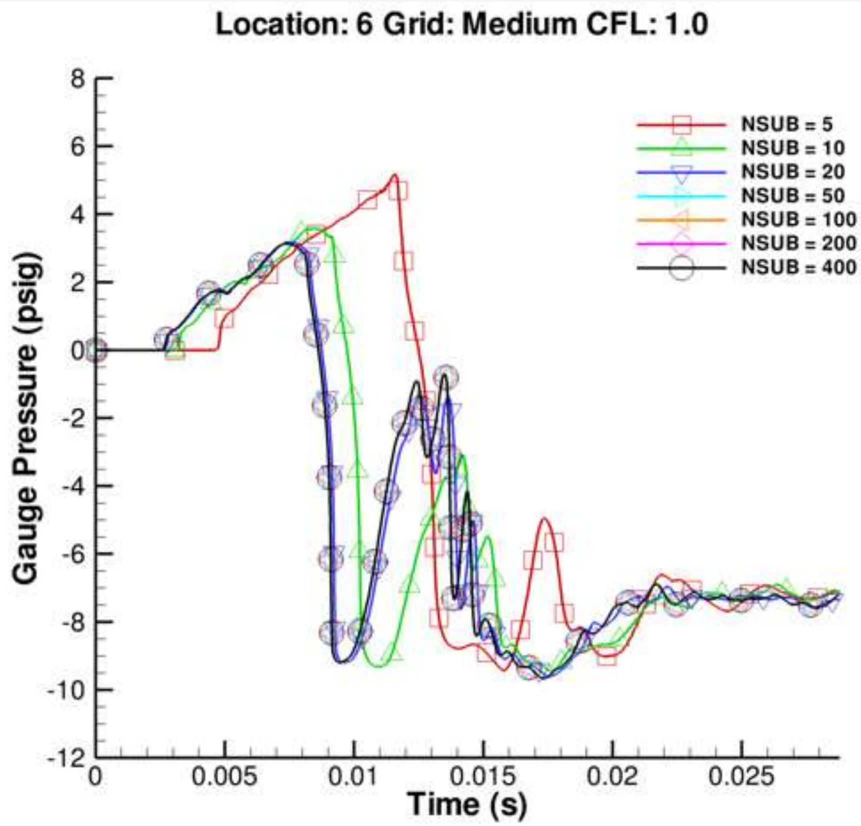


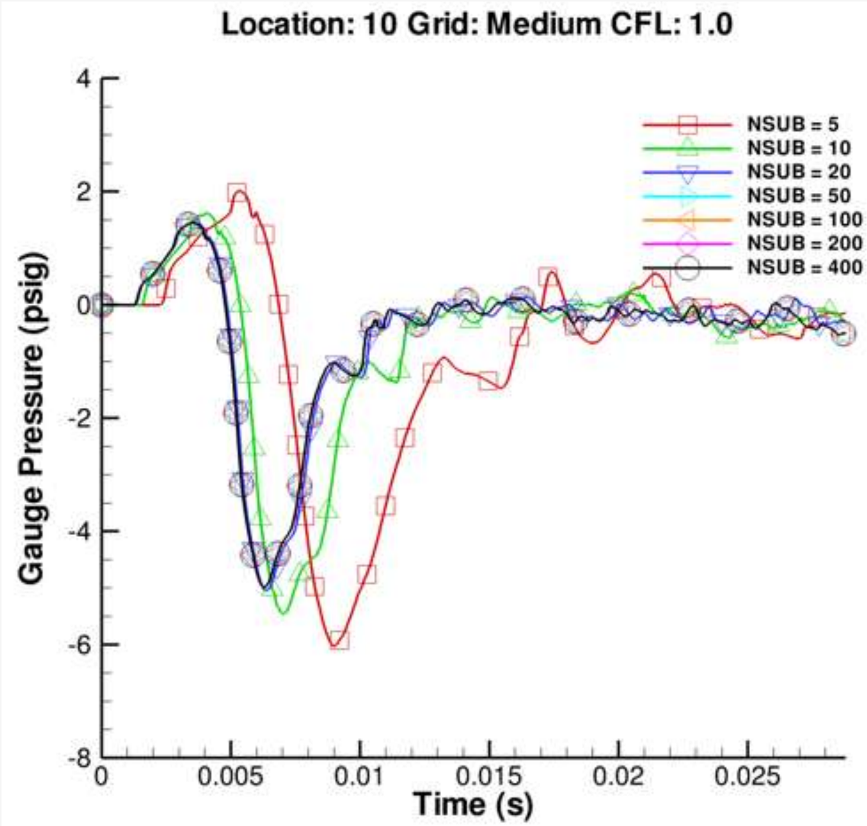
Sub-Iteration Sensitivity Test

Location 6 and 10:
- NSUB >= 20: Appear Converged
- NSUB/CFL >= 20: Sufficient

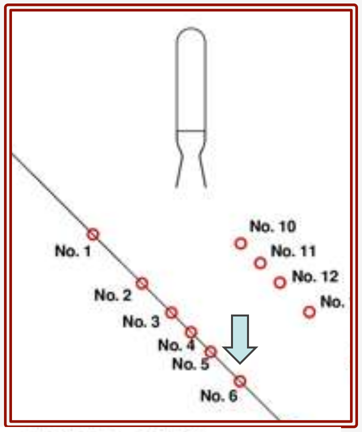


Overset





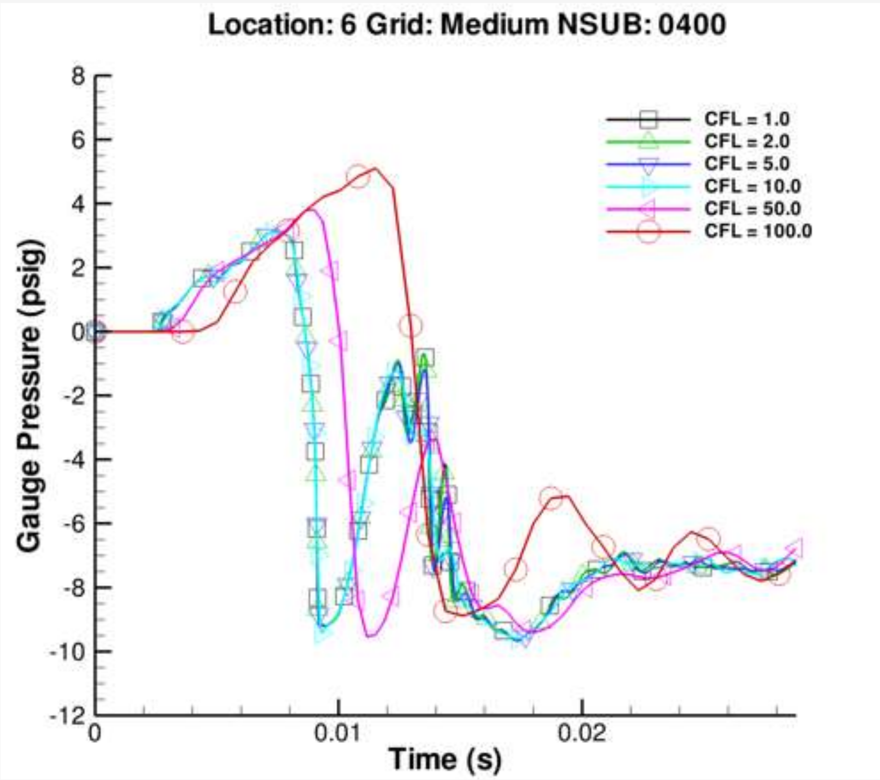
Time-step Sensitivity Analysis

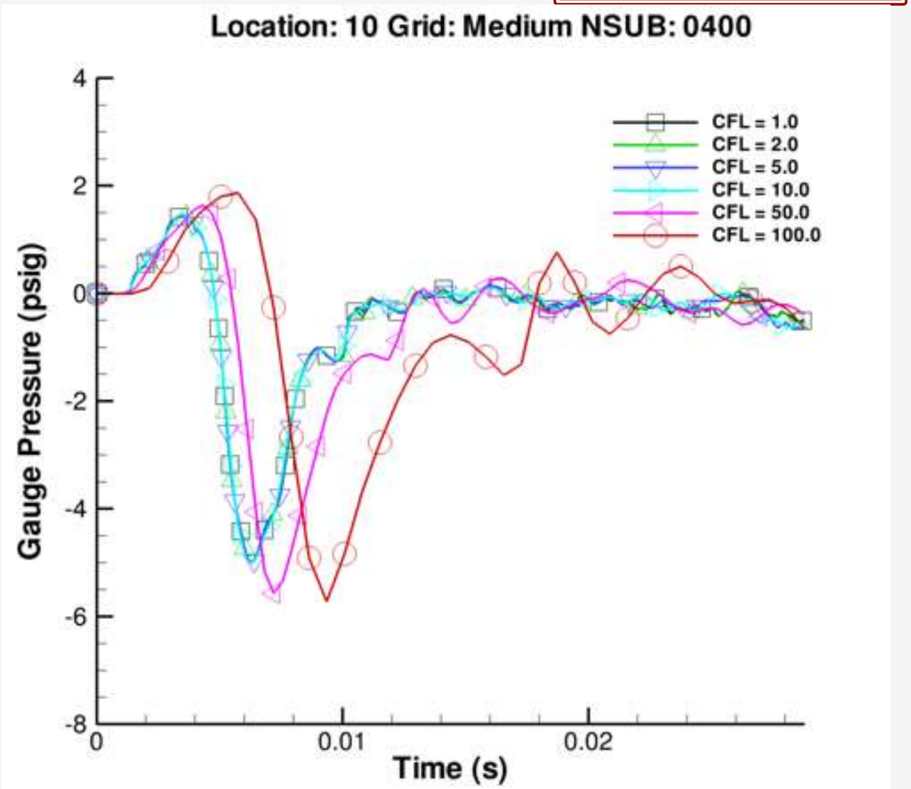


Location 6 and 10:

- CFL <= 10: Appear Converged
- NSUB/CFL >= 40: Sufficient

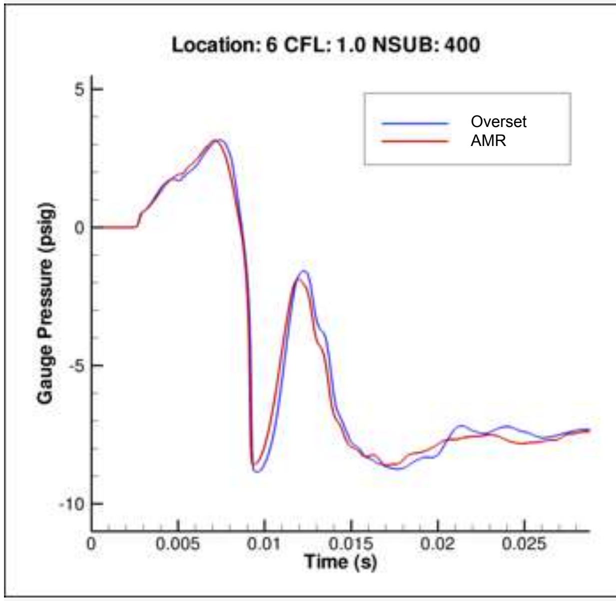
Overset



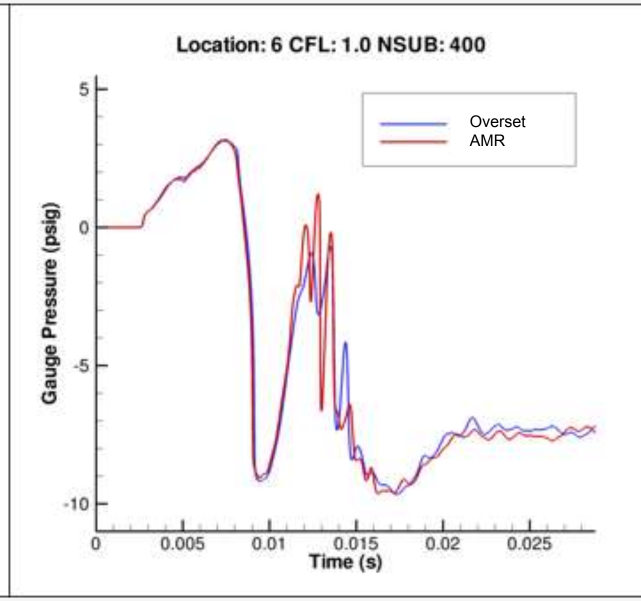


Space-Time Sensitivity Analysis

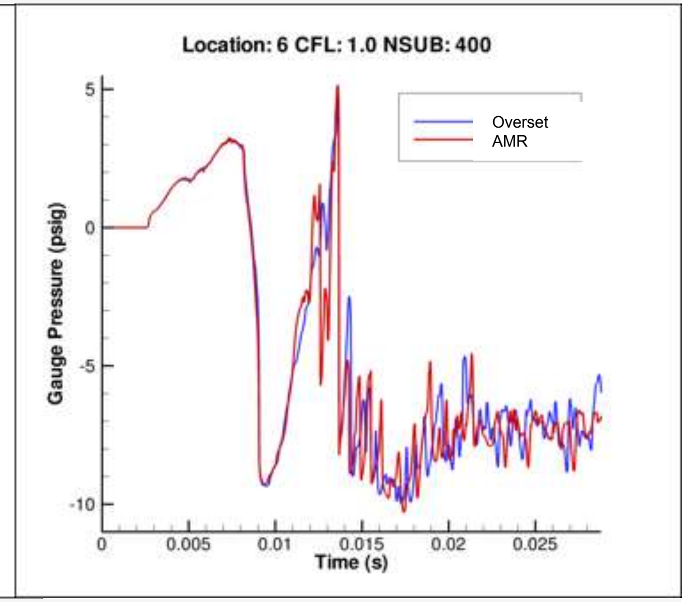
Location 6



Coarse
- Low-frequency



Medium
- Increasing frequency



Fine
- High frequency develops after IOP

Idealized Test Case

- Numerical experiments have been performed for an idealized test problem
  Comparison with experiments will be done as data become available

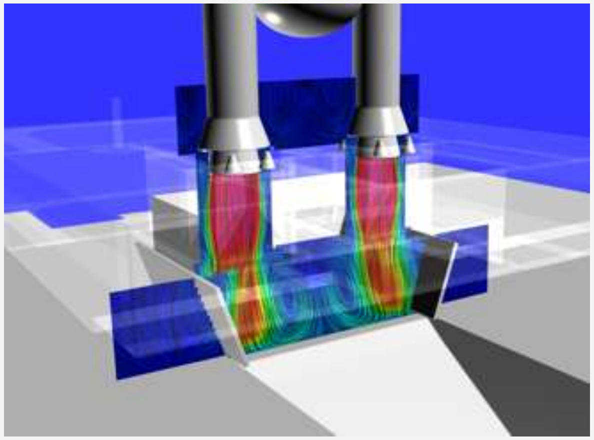
- Preliminary conclusion from the numerical tests:
  - For a fixed ratio NSUB/CFL, the sub-iteration convergence is approximately independent.

  - If time-integrated functionals (e.g. RMS) are of interest, then coarser space-time resolutions may be acceptable.

  - When high-frequency wave content is important (e.g. Min/Max functionals), then viscous effects should be included.

Applications to Shuttle and Ares-1X

- Assumptions for CFD simulations
  - Single species flow with corrected nozzle boundary conditions such the correct thrust, temperature, and Mach number are retained at the nozzle exit.
  - Influence of multispecies gas effects are negligible.
  - Influence of solid aluminum particles in the exhaust gas and afterburning effects are negligible.
  - IOP water suppression system is neglected, thus no multiphase flow effects are included in the present results.
  - All relevant geometric structures are included in the model.
  - Full unsteady RANS simulation is carried out.

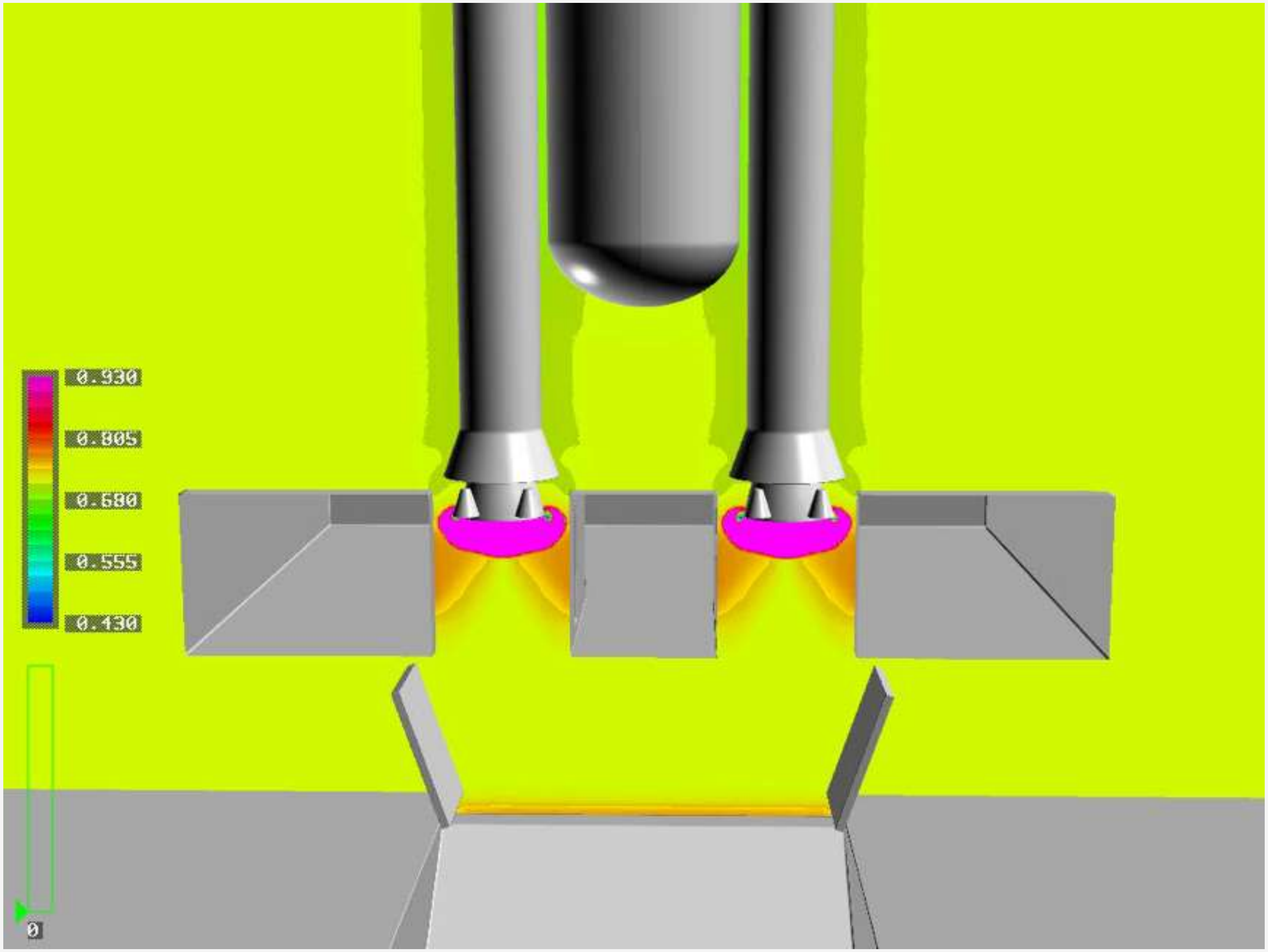


Flow patterns showing fountain effects in impinging plumes

- Required information for CFD simulation
  - Time accurate conservative quantities for a perfect gas at the nozzle plenum.
- Quantities prescribed at the plenum must generate the correct thrust, temperature, and Mach number at the nozzle exit.

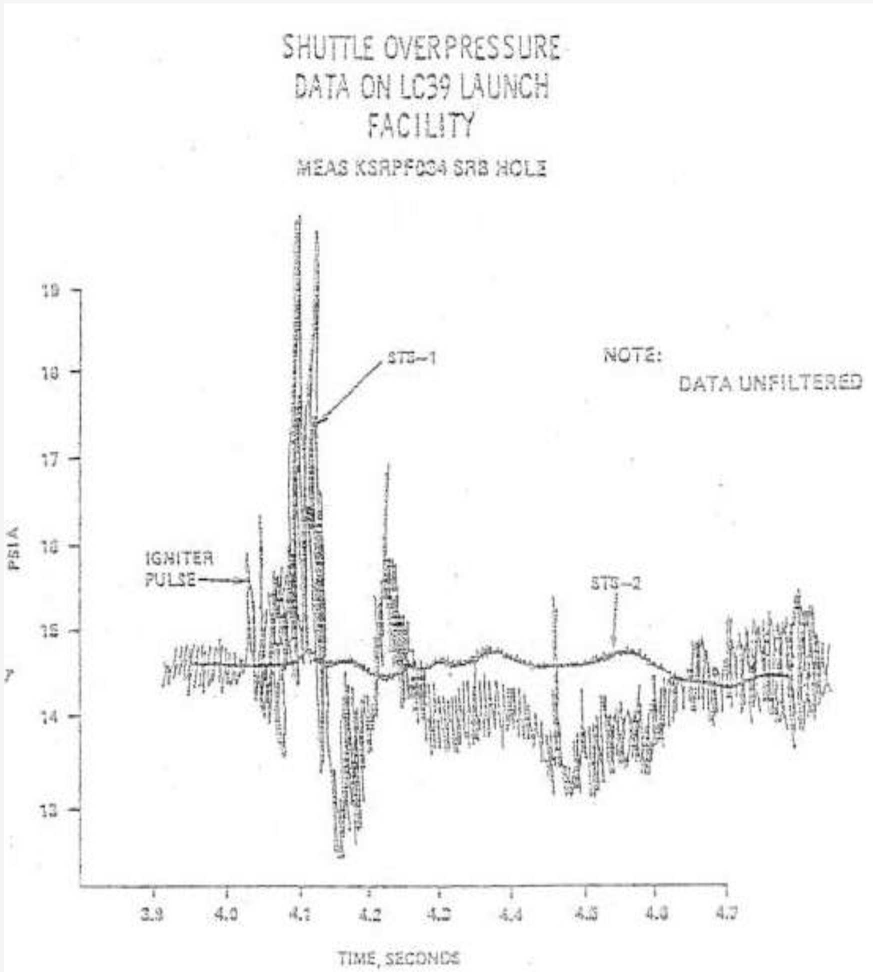
- Given information
  - Pressure and mass flow rate at the nozzle plenum.
  - Mixture exhaust gas properties.
  - Approximate temperature of exhaust gas at the plenum.

Flame Trench Flow Analysis for STS-1

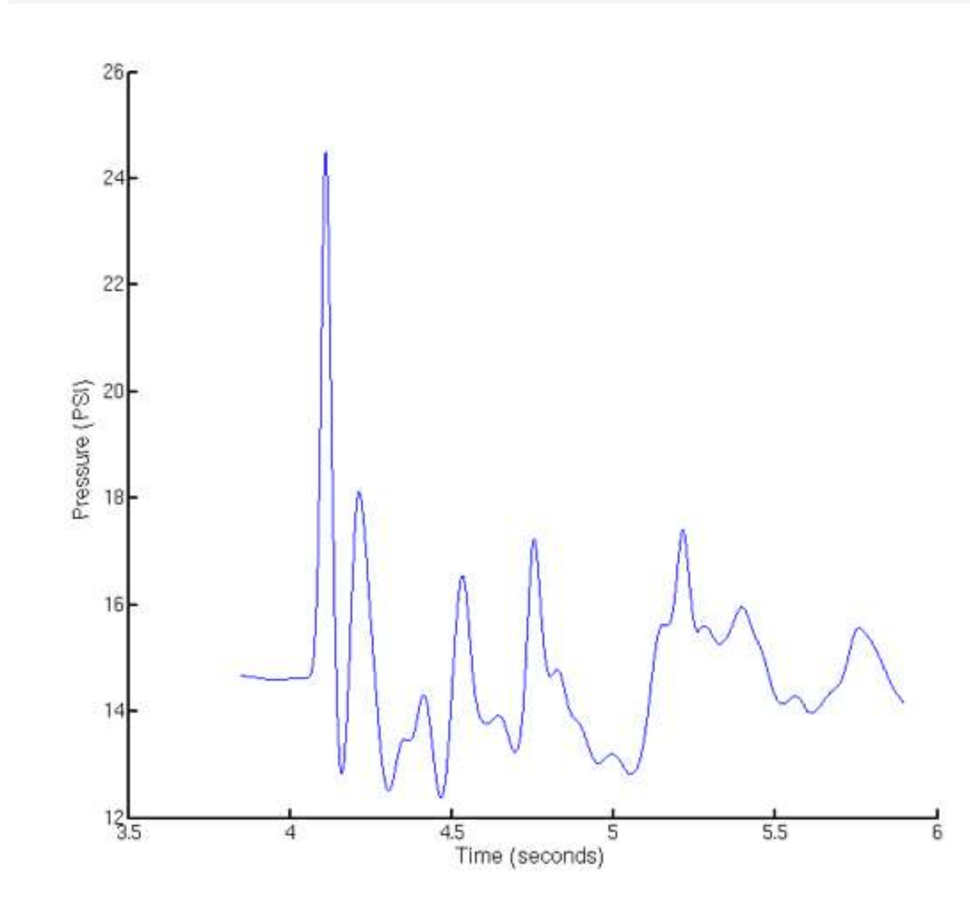


Pressure Contours

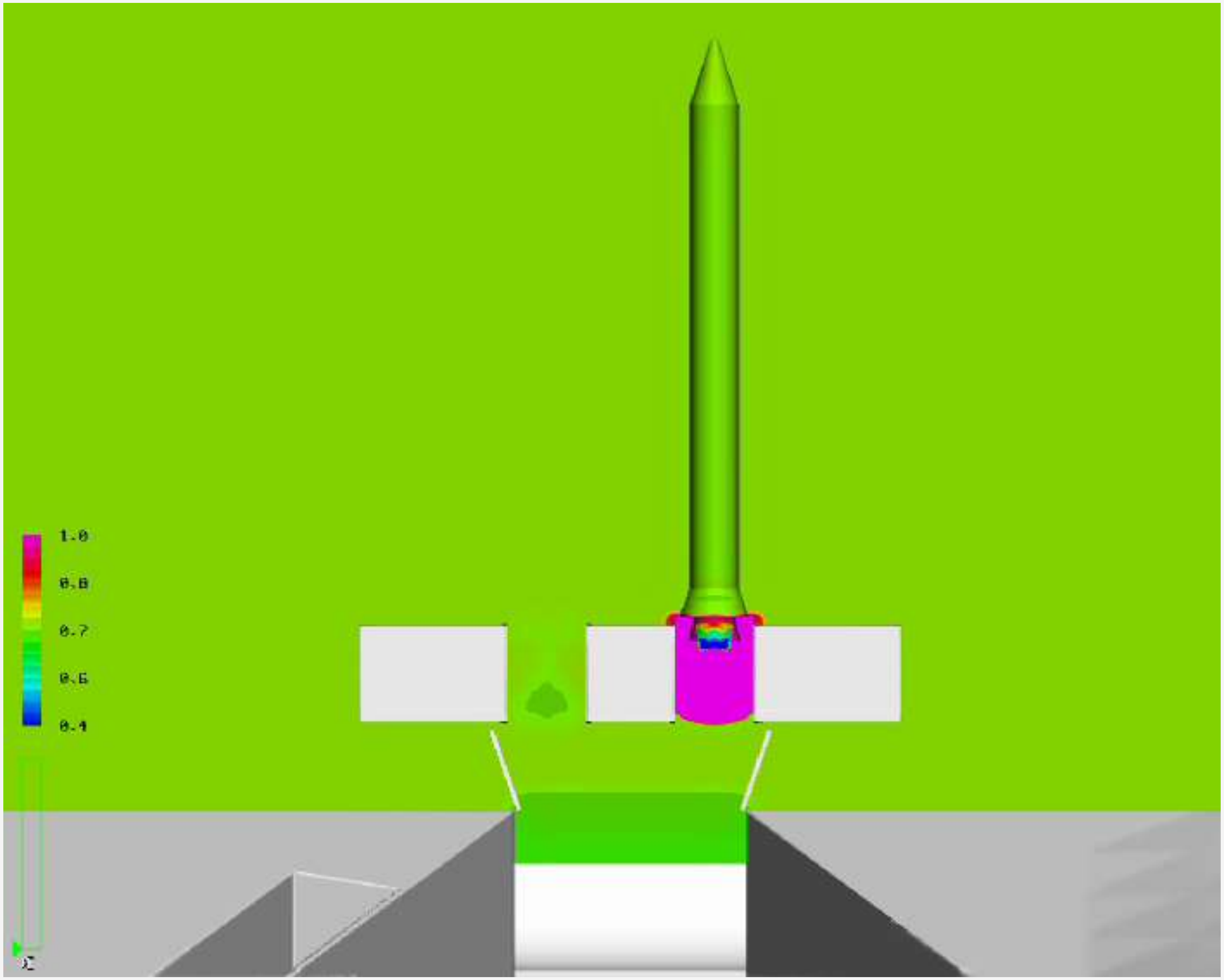
STS-1 IOP Flight Data vs. Computations



Left SRB skirt area ET side

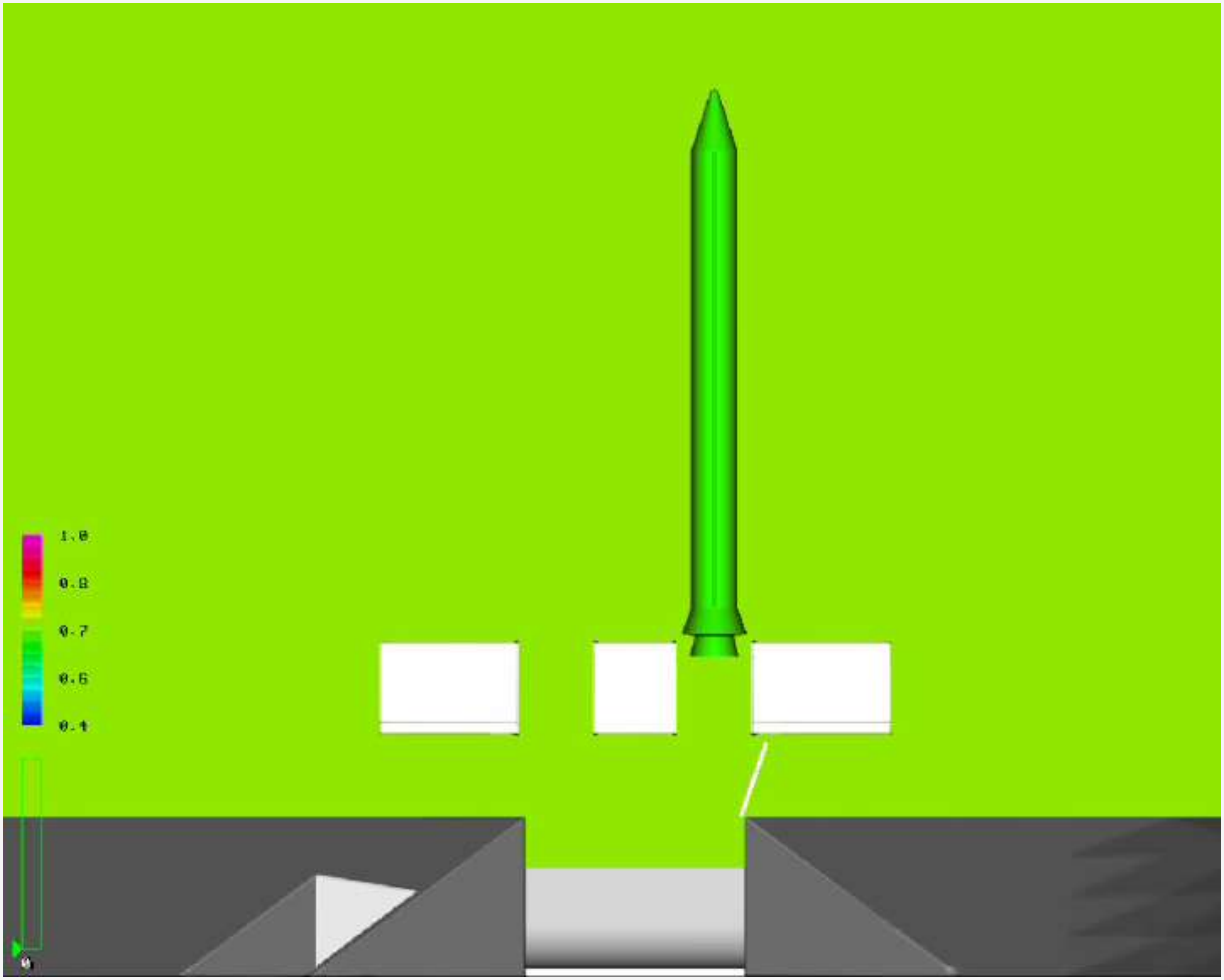


Flame Trench Flow Analysis for Ares-1X



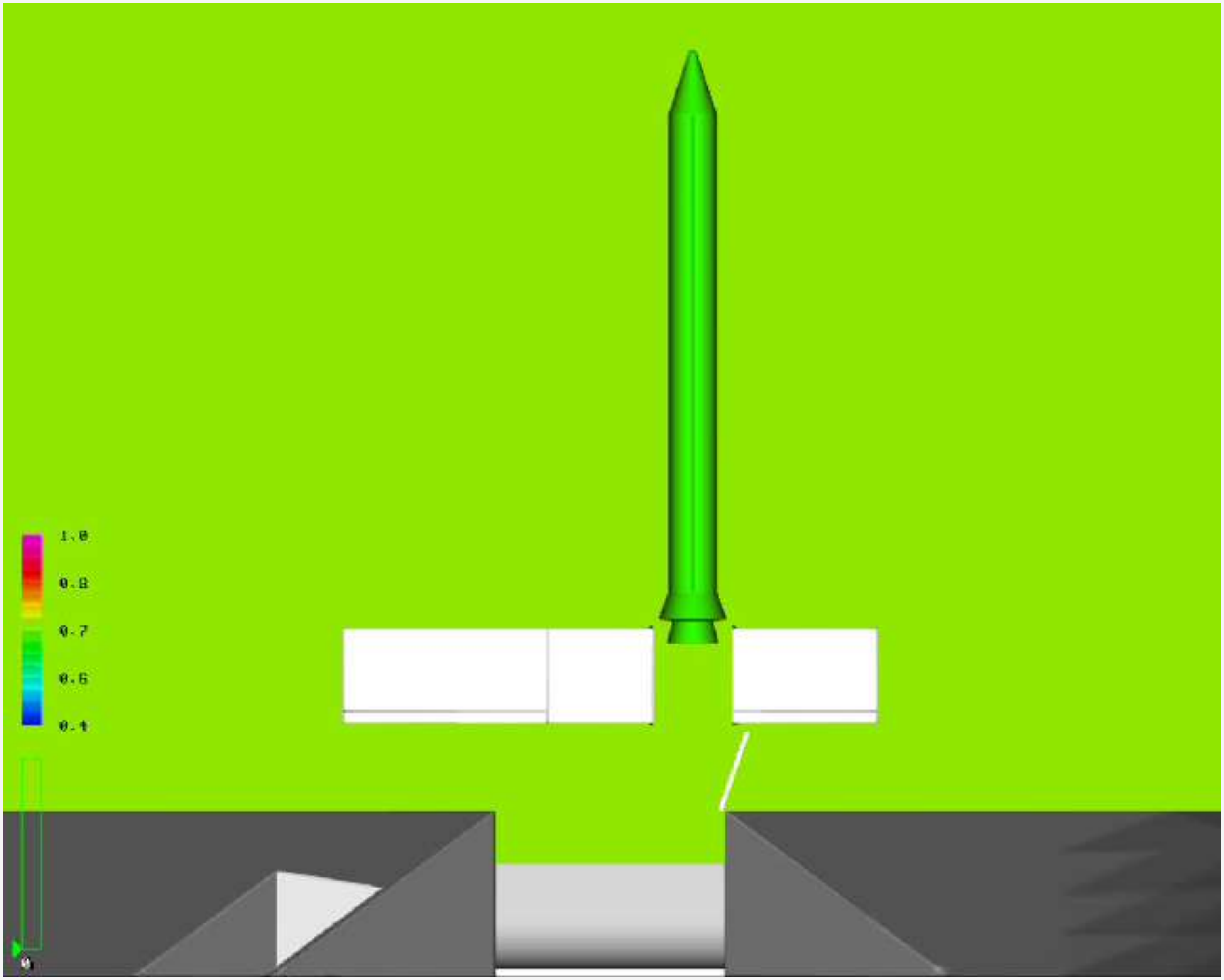
Pressure Contours

Flame Trench Flow Analysis for Ares-1X



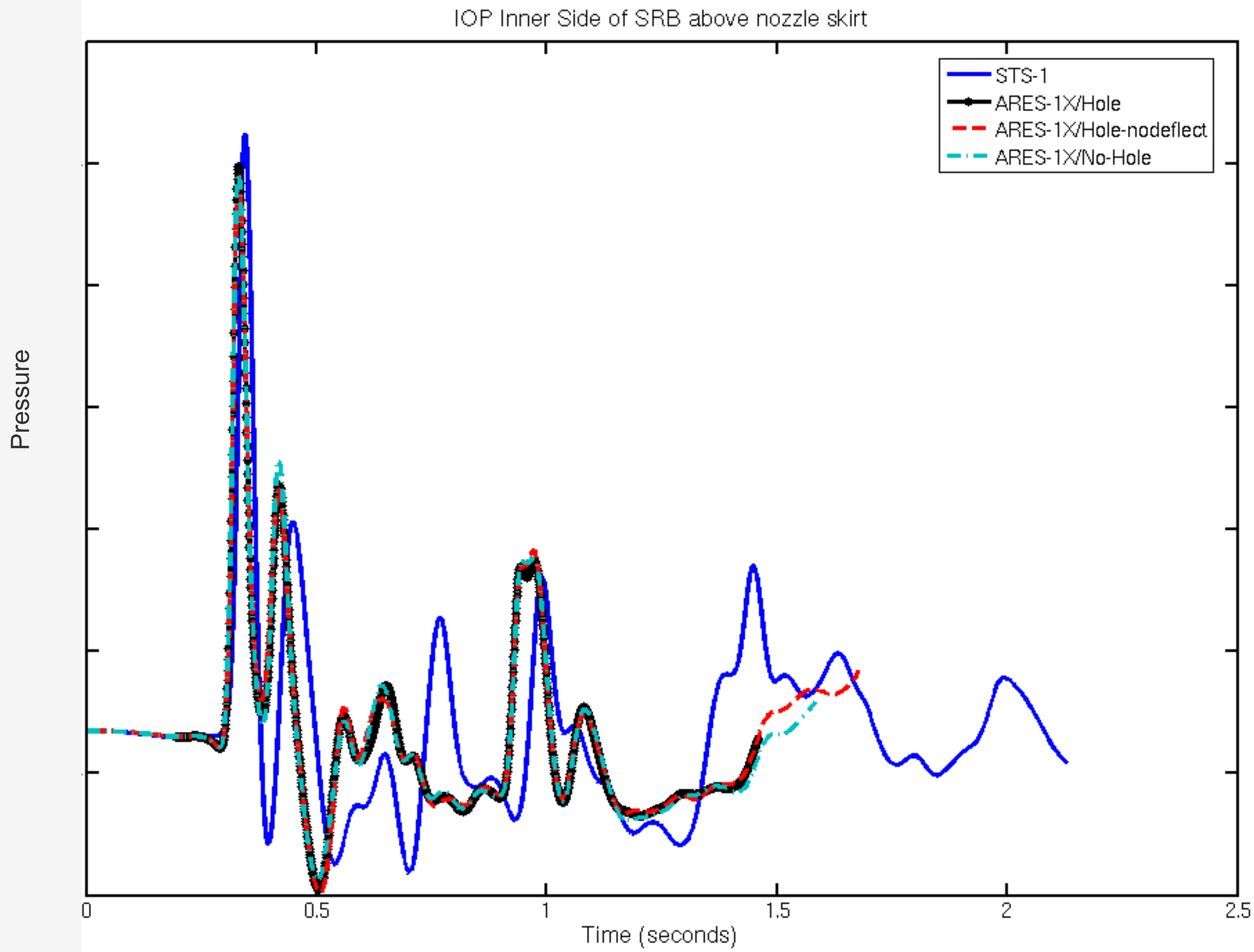
Pressure Contours

Flame Trench Flow Analysis for Ares-1X



Pressure Contours

STS-1 and Ares-1X IOP computations



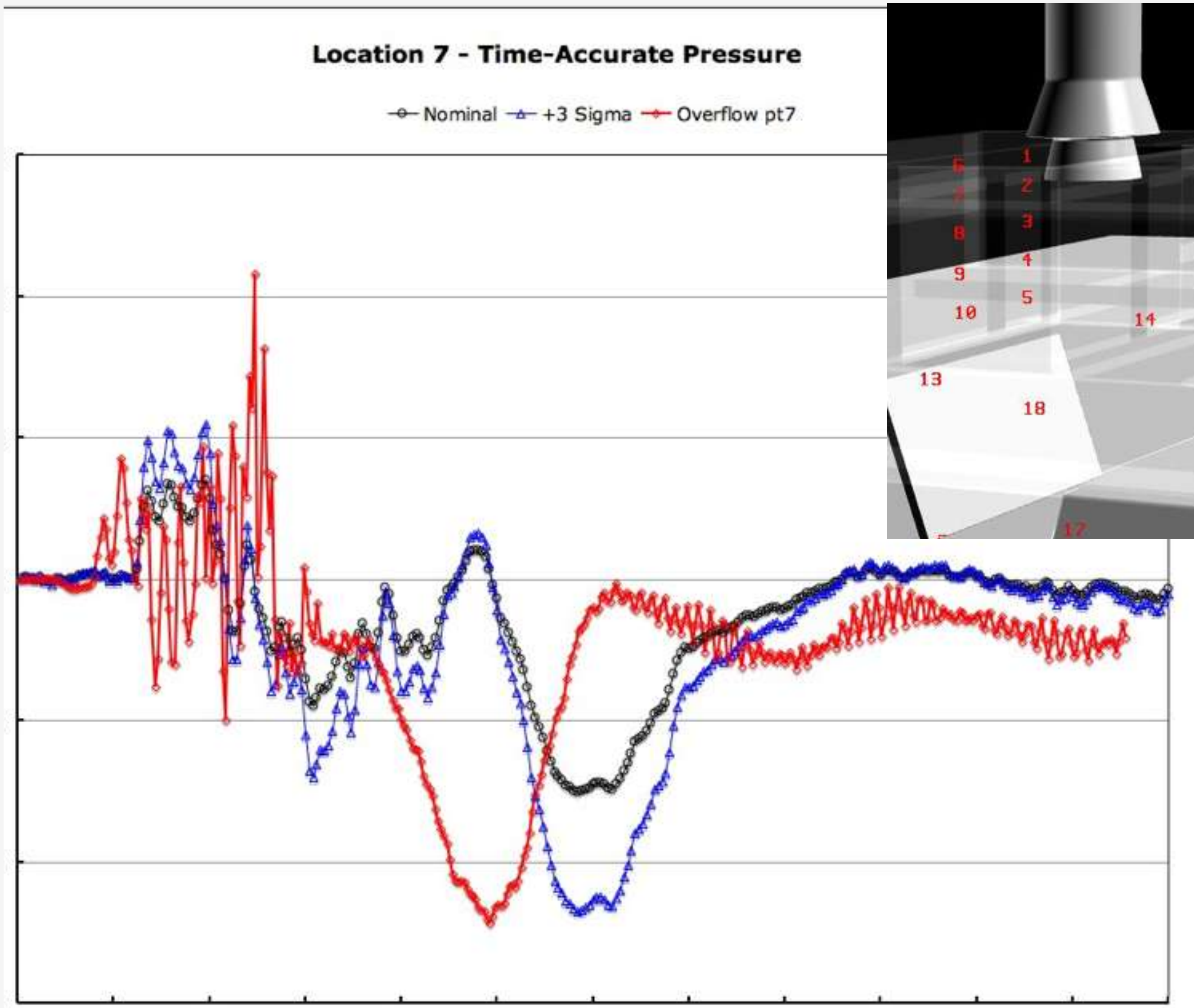
CFD Support for STS-125 Launch Environment

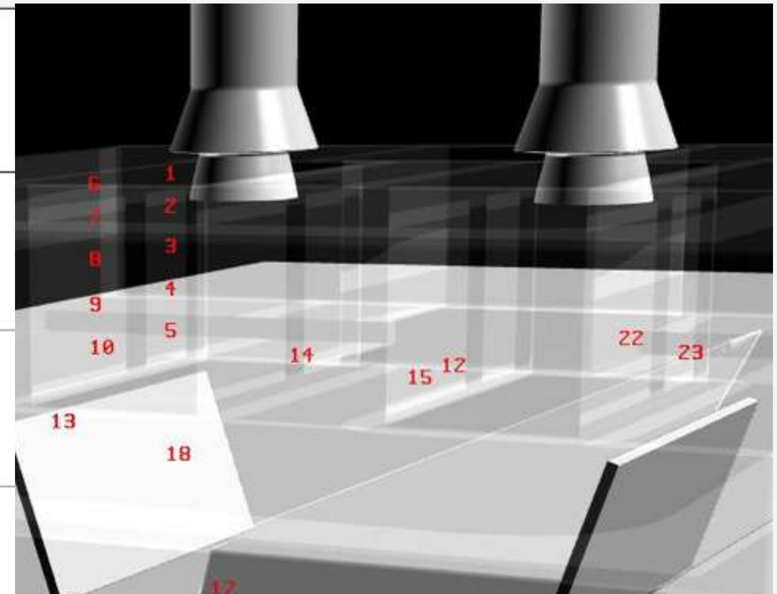
After STS-124 wall damage on May 31, 2008, trench wall had to be repaired before STS-125 mission to Hubble Telescope.

- To quantify flow in flame trench (pressure, temperature etc.)
  - Computations were carried out up to 1.15 seconds by using 504 CPU's (completed in less than 4 days)
  - CFD results were compared against STS-4 flight data.

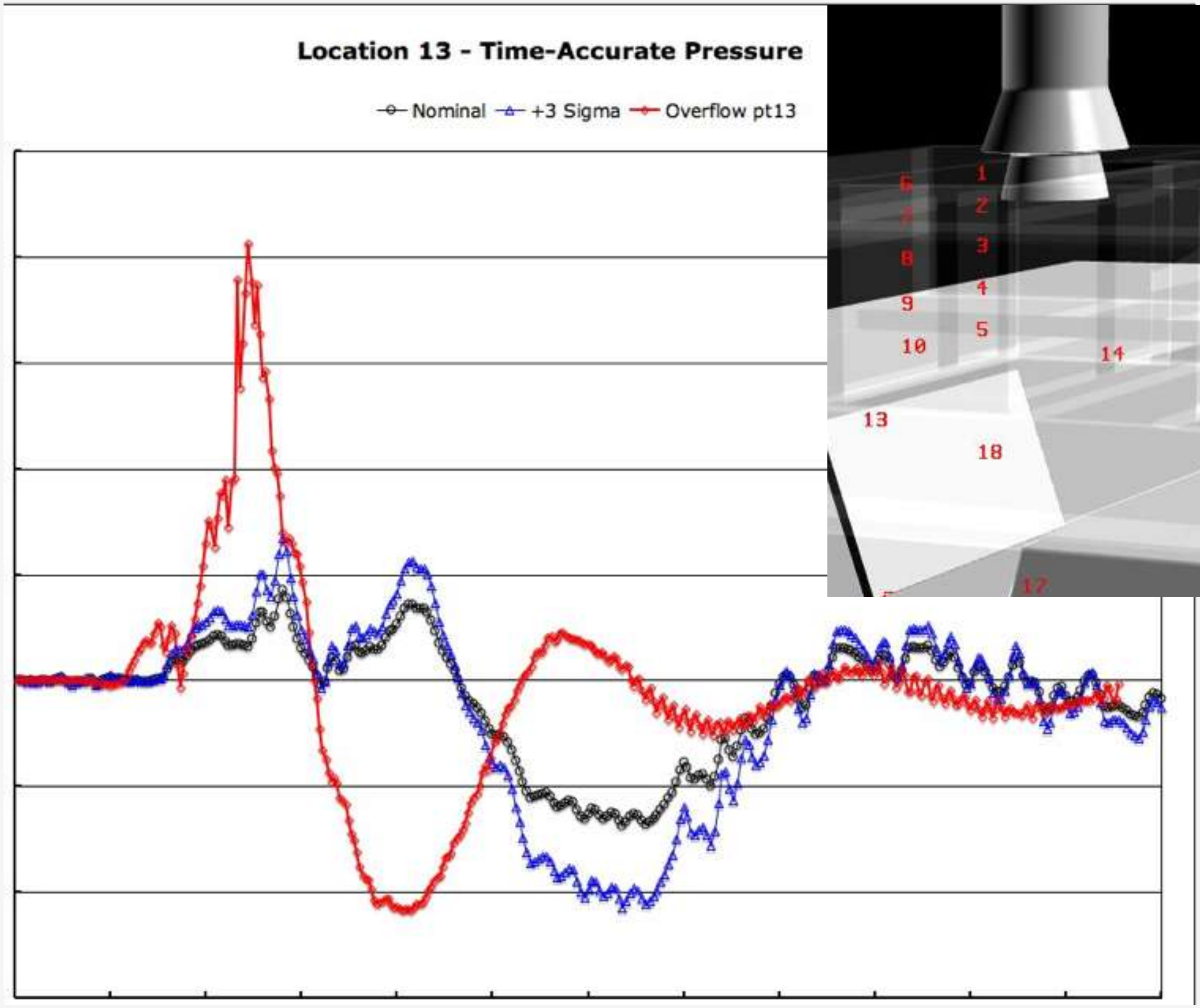
- Single-phase computations produced conservative results compared to STS-4 data.
- Time-dependent computational data were provided to Ground Operations to determine load environment.

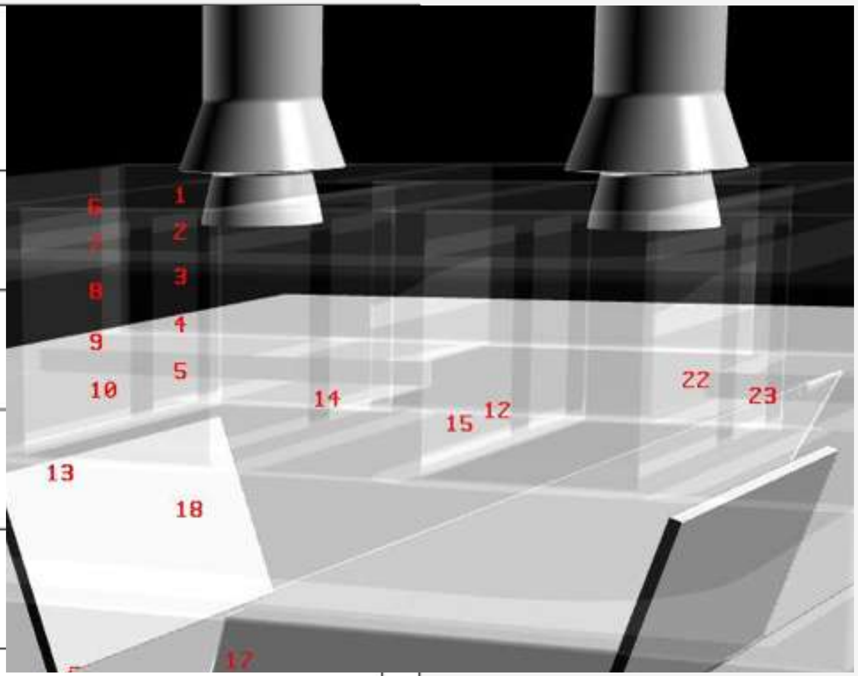
Computed Results (Overflow) vs. STS-4 Data



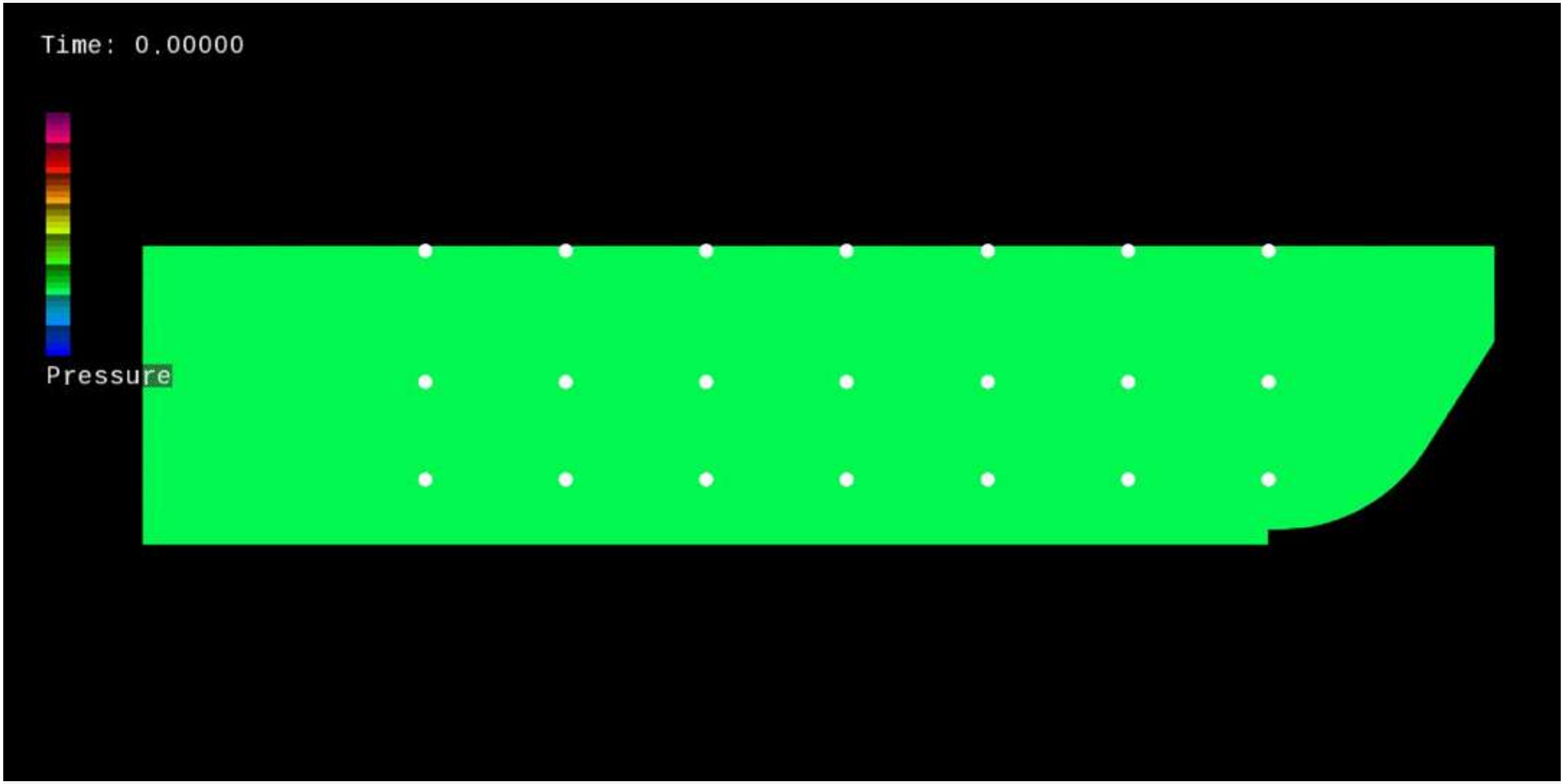


Computed Results (Overflow) vs. STS-4 Data

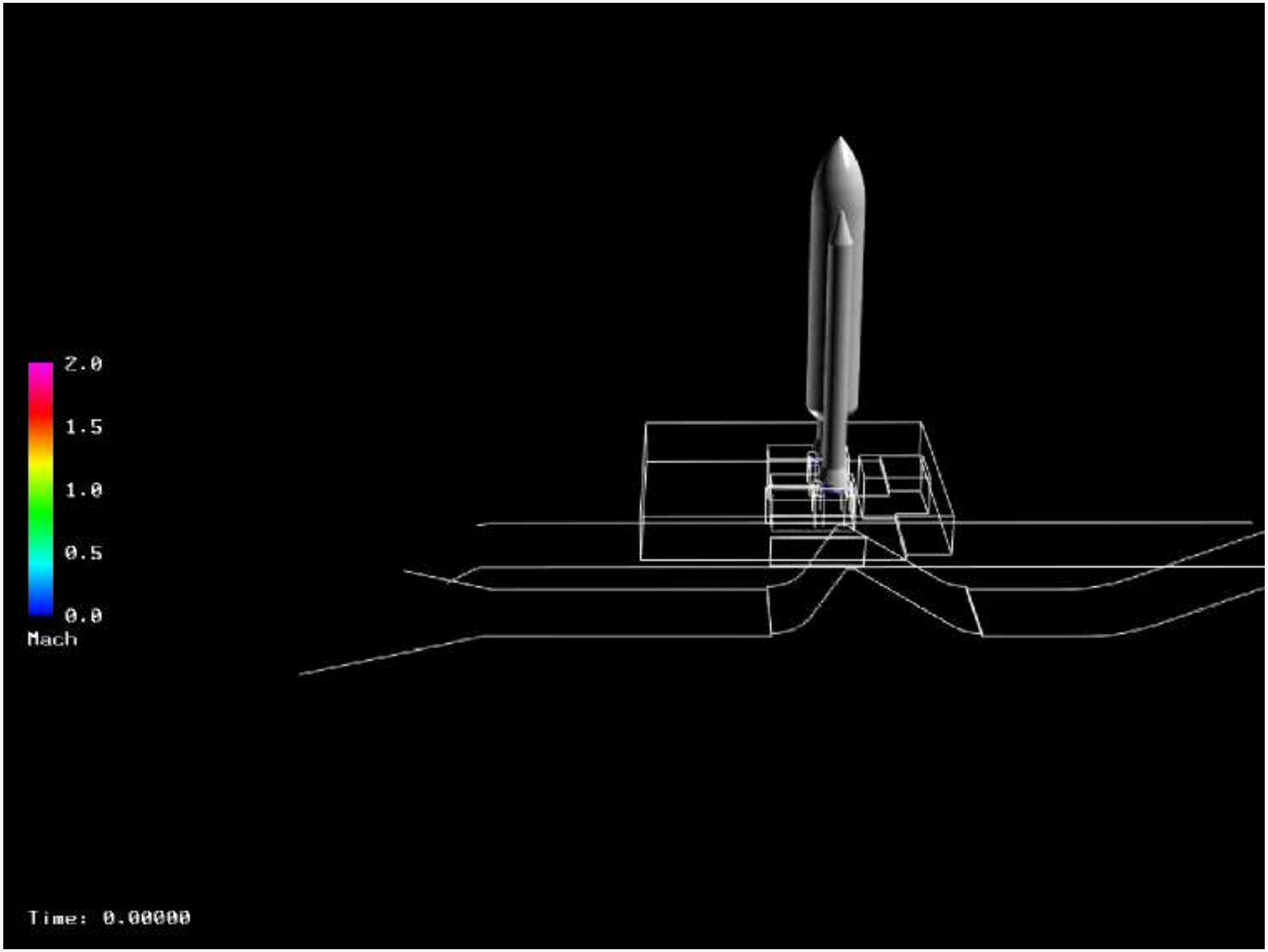




Computed Flame Trench Wall Pressure



Computed Flame Trench Flowfield



Summary and Discussions

Computational processes/issues for supporting mission tasks are discussed using an example from launch environment simulation

- Entire CFD process has been discussed using an existing code
- STS-124 conditions were revisited to support wall repair effort for STS-125 flight
- When water bags were not included, computed results indicate that IOP waves with the peak values have been reflected from SRB's own exhaust hole.
- ARES-1X simulations show that there is a shock wave going through the unused exhaust hole, however, plays a secondary role
- All three ARES-1X cases and STS-1 simulations showed very similar IOP magnitudes and patters on the vehicle. With the addition of water bags and water injection, it will further diminish the IOP effects.

For more complete flame trench simulation, need to include

- Water suppression system
- More complete nozzle (and plum) condition
- Multi-species (variable γ) effects

For more predictive launch environment analysis (supporting space exploration system development and operation in general), need

- Predictive unsteady flow simulation capability (algorithm + physical model)
  (This is a current CFD pacing item)