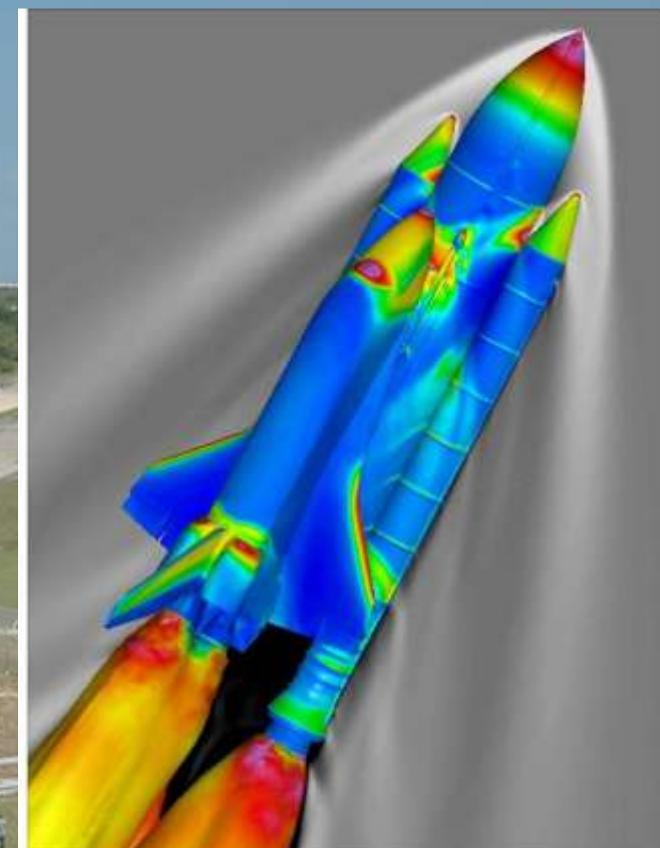
Aerodynamics and Debris Transport for the Space Shuttle Launch Vehicle



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The accomplishments described herein is the work of many talented people, including:

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NASA JSC Engineers:
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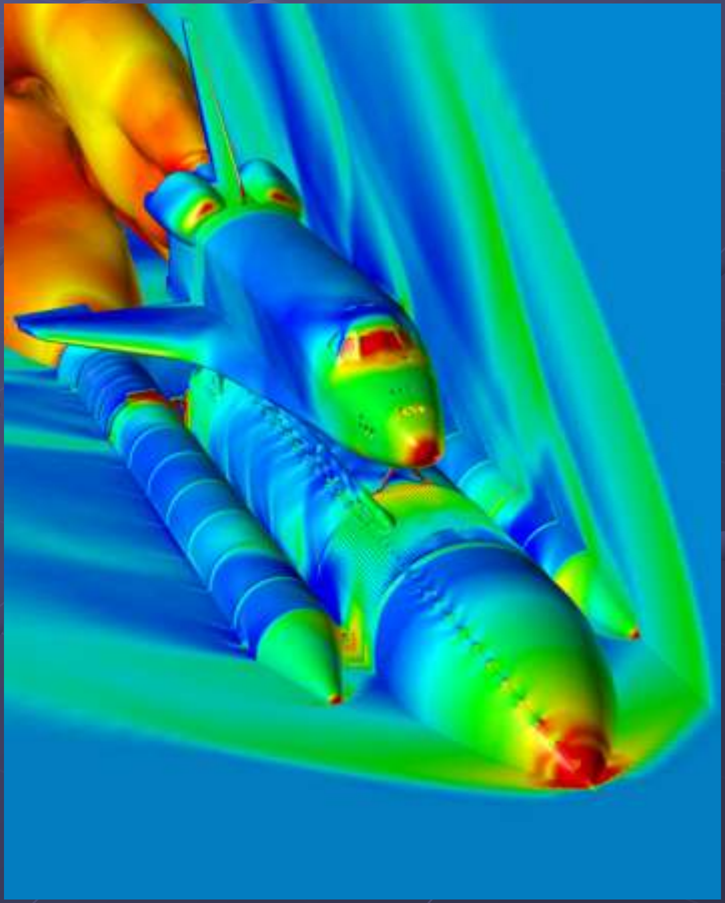
Darby Vicker
Phil Stuart
Jim Greathouse

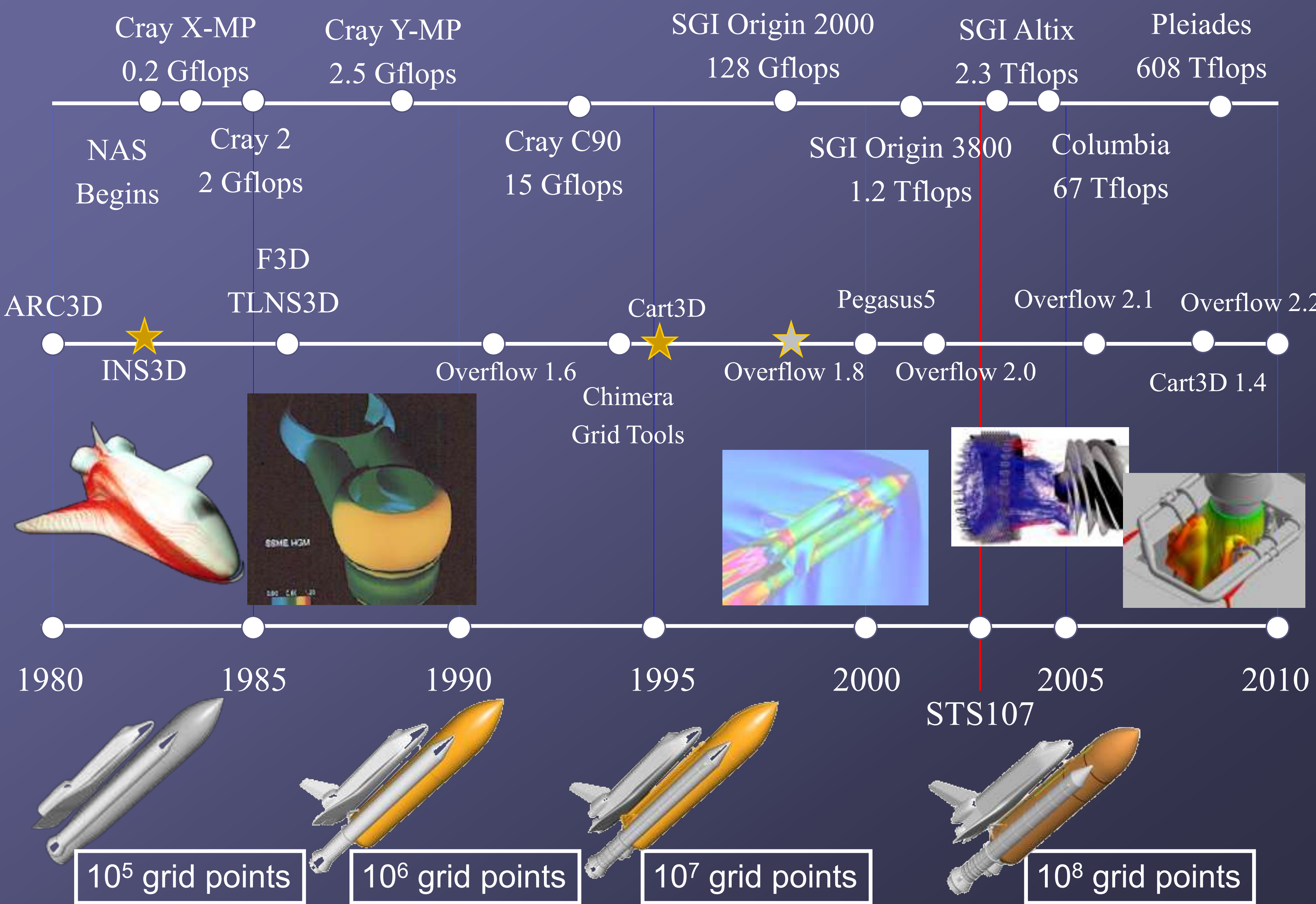
NAS Supercomputing Facility
Ames wind-tunnels and ballistic range



NASA Advanced Supercomputer Facility

- Provides massive computing power to all of NASA
- Pleiades: 112,896 cores
  - 7th biggest computer in the world (Nov 2011)
- Columbia: 4608 cores
  - Formerly 2nd biggest computer in the world
- Over 1.3 Tflops total compute capability

Timeline of NAS, Ames CFD, and Space Shuttle Applications



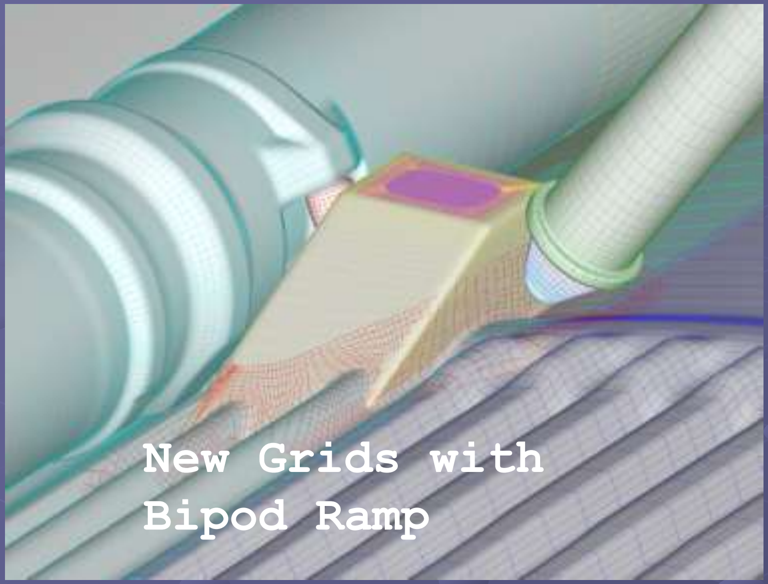
STS-107: Loss of Columbia

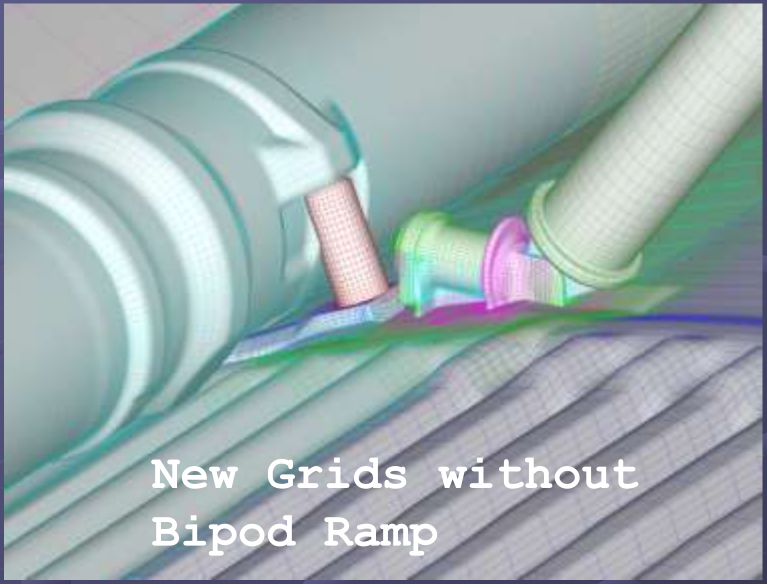
- Columbia and crew were lost on Feb 1st, 2003
- CAIB testing showed how a 1.7 lbm piece of foam traveling over 770 ft/sec could damage RCC wing leading edge
- Simulations performed at Ames were integral to the accident investigation and subsequent return-to-flight efforts

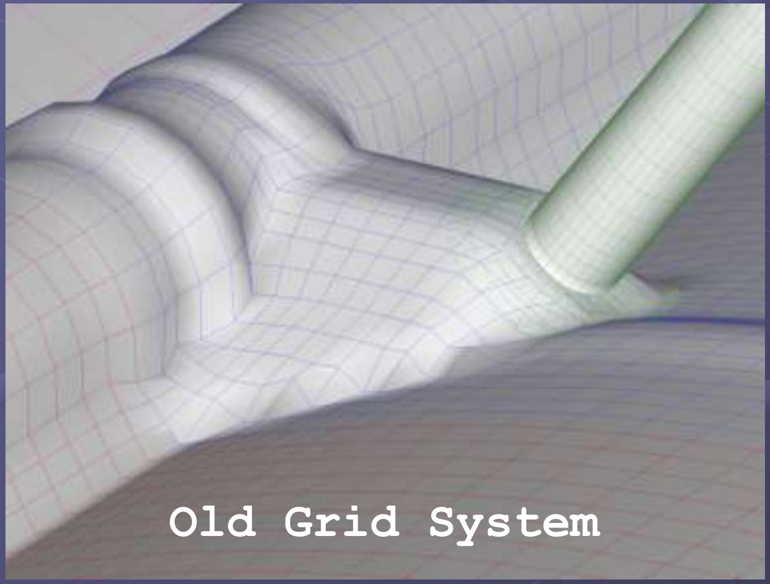
Support for STS-107 Accident Investigation

- Significant improvements to fidelity of Overflow CFD model of SSLV
- Steady-state simulations of many points along trajectory of STS-107
  - "The aerodynamic loads on the bipod ramps as calculated by the CFD results were well within the design certification limits, and were a small fraction of the design limits at the debris-release conditions at MET=81.7 seconds"
- Time-accurate 6-DOF simulations of SSLV and bipod-ramp foam debris using Cart3D

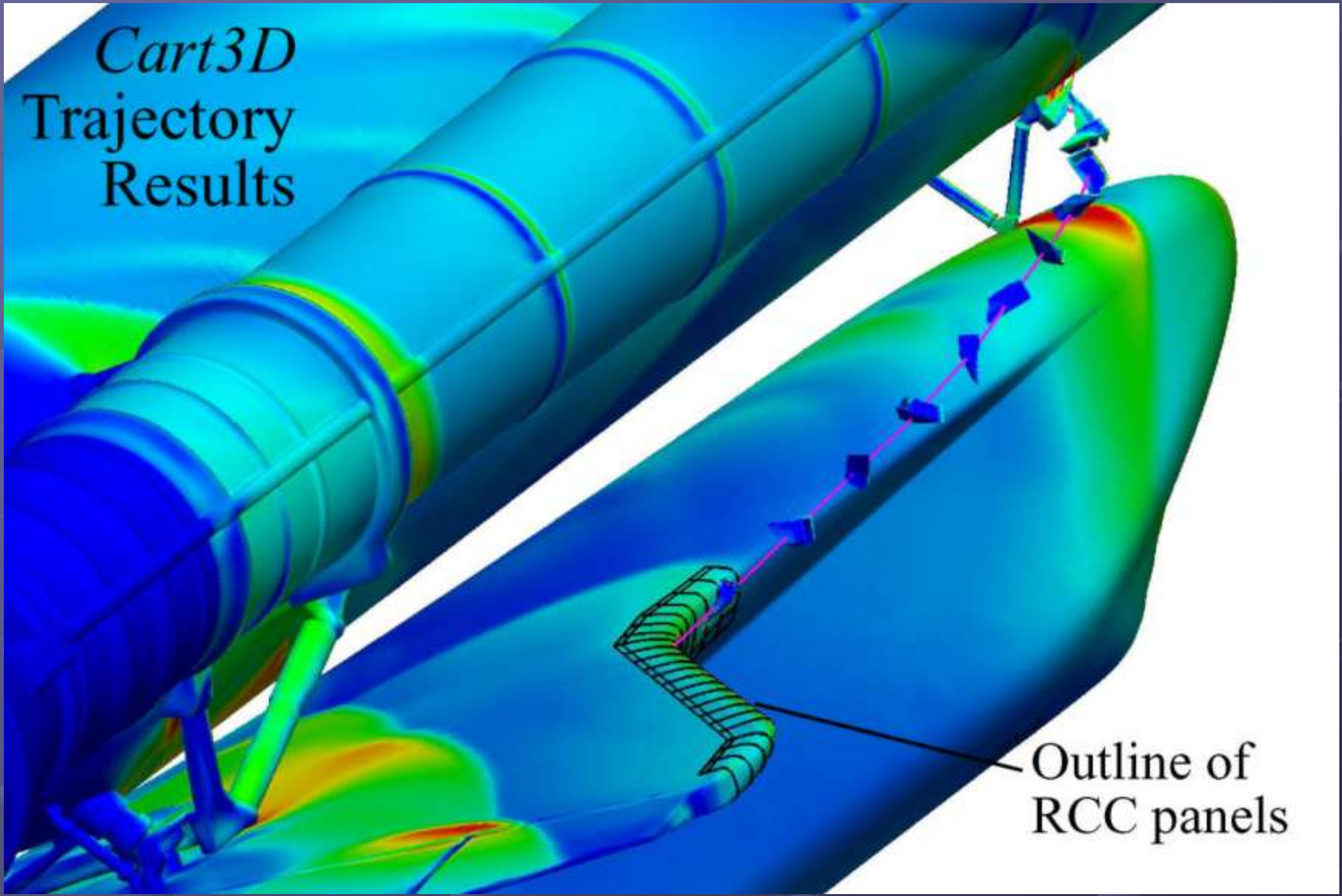
Geometry Details







Cart3D 6-DOF Simulations, Mach=2.46



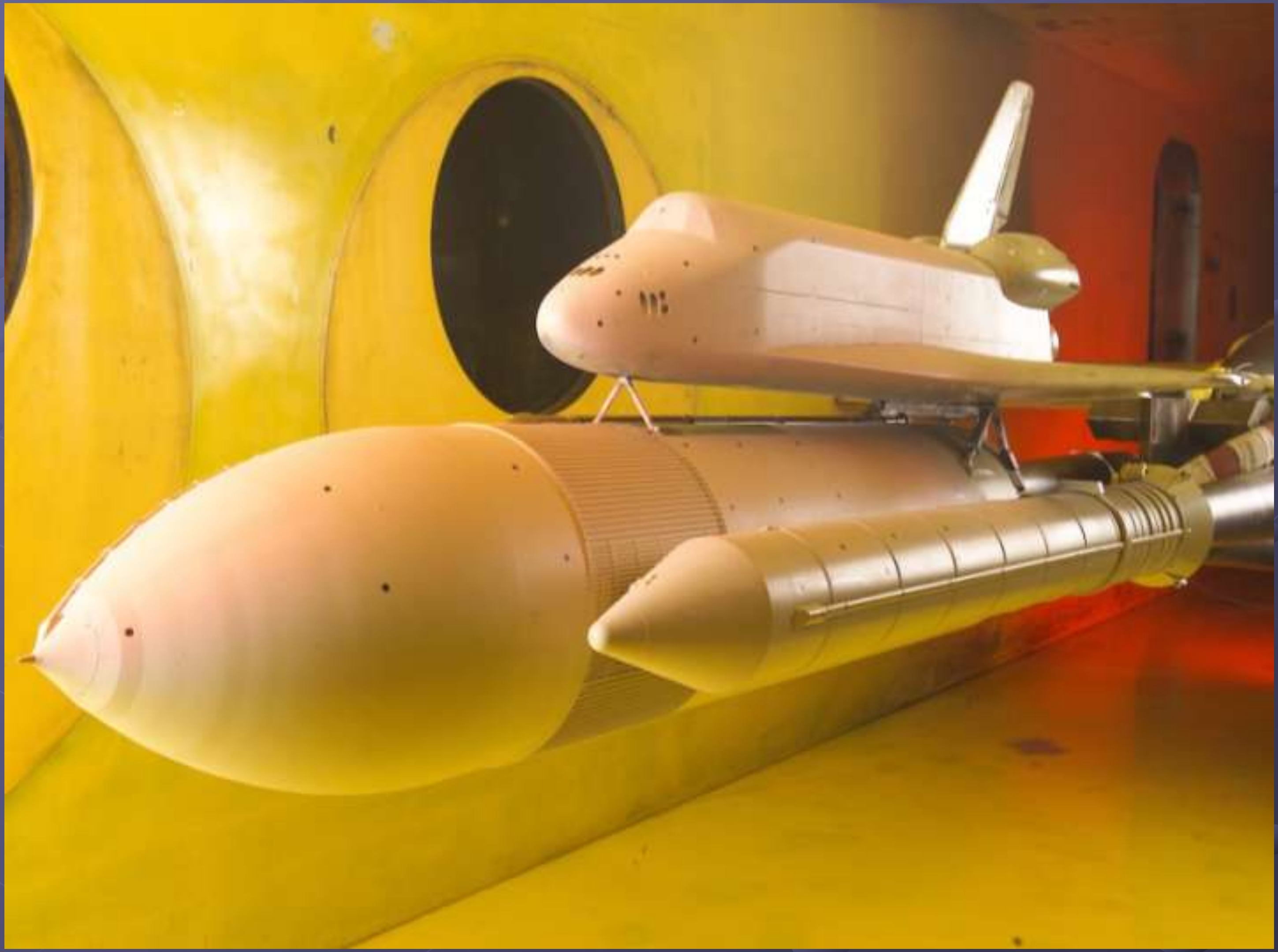
Return To Flight

- Overflow solutions of ascent
  - Analyze aero loads on External Tank design changes
  - Provide CFD flow-fields for debris analysis
  - Correlation of 3% Wind-Tunnel tests
- Debris Transport Analysis
  - Develop next generation of debris analysis software
  - Develop aerodynamic models for debris

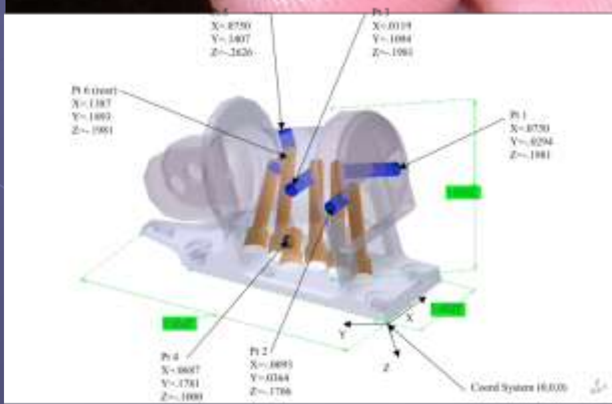
CFD Analysis of SSLV Ascent

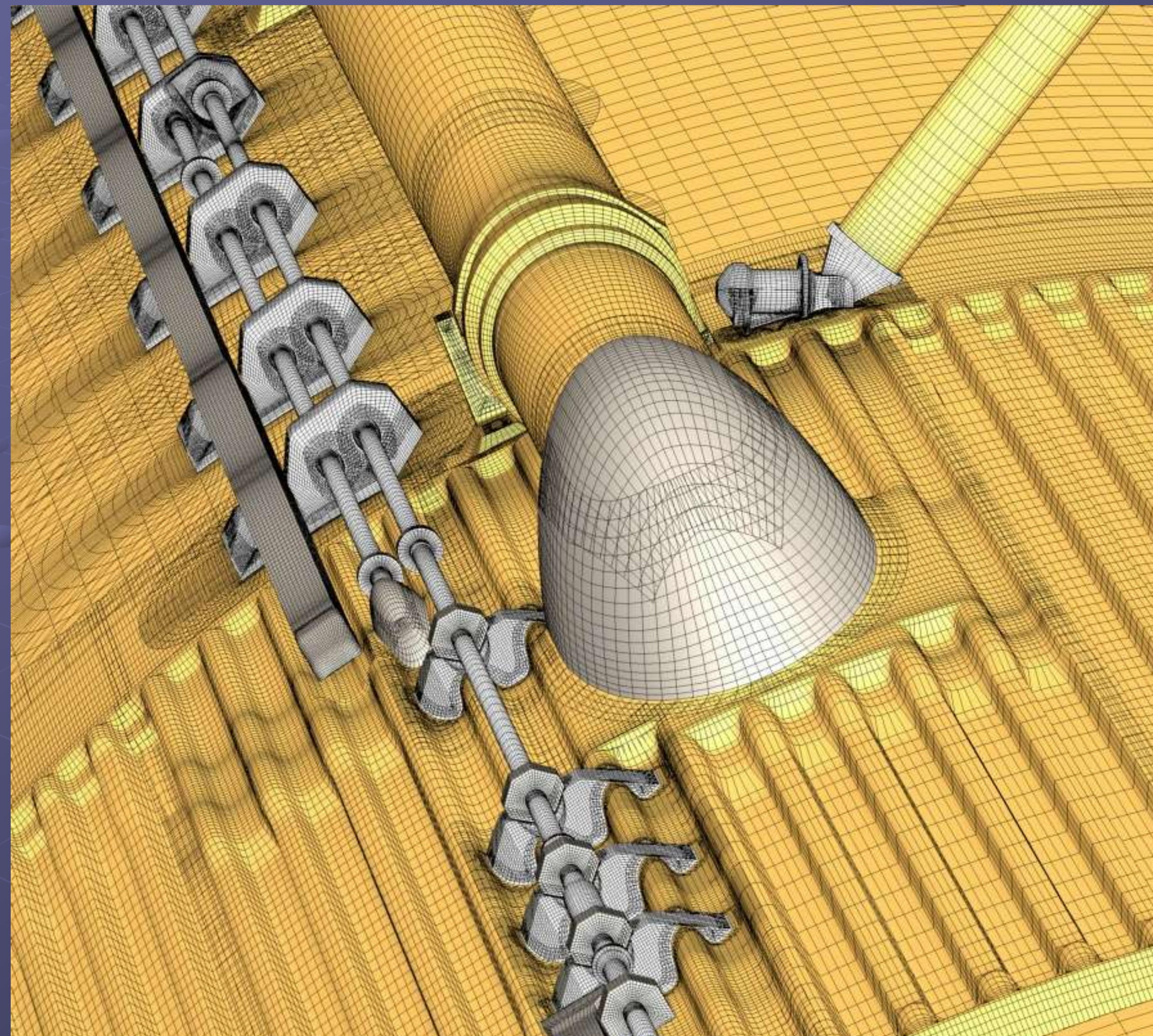
- Over 400 Overflow solutions run for Return-to-Flight
- New grids generated for each ascent condition
  - 2 hours on 32 Itanium-2 CPUs
  - 30 to 50 million grid points each
- Average of ~1000 Itanium-2 CPU hrs / solution
  - ~20 hours of wallclock time running on 64 Itanium-2 CPUs
  - Never converges to a steady-state: aft end of ET, attachment hardware, plumes, etc
  - Typically run for ~10,000 iterations

IA-700 Wind Tunnel Tests
ARC 9x7 Unitary, AEDC 16T

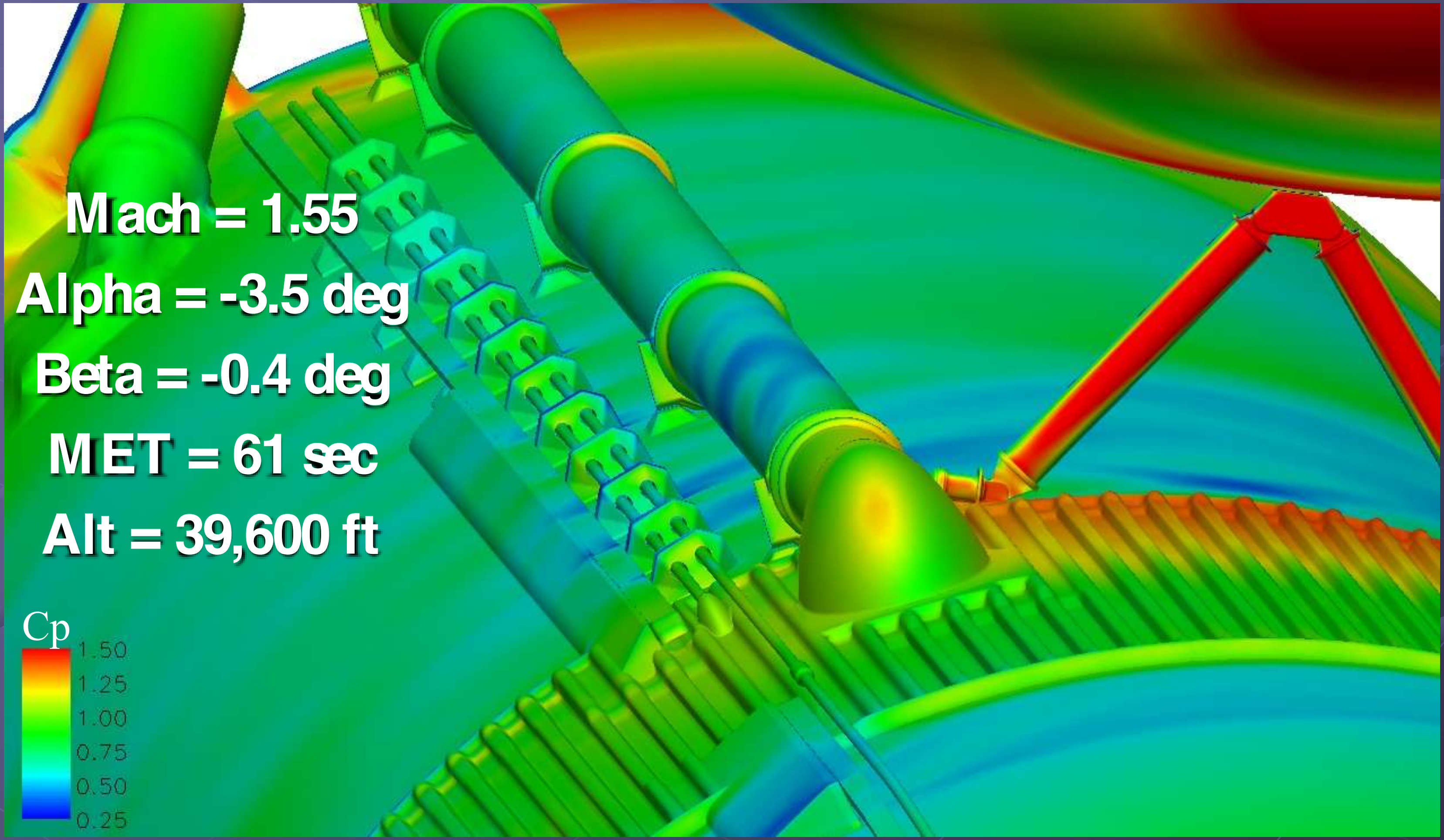


Bi-pod Ramp Removal





RTF Solutions
Addition of Ice/Frost Ramps



Wind Tunnel Test Comparisons - External Tank - Phi = 203.75°

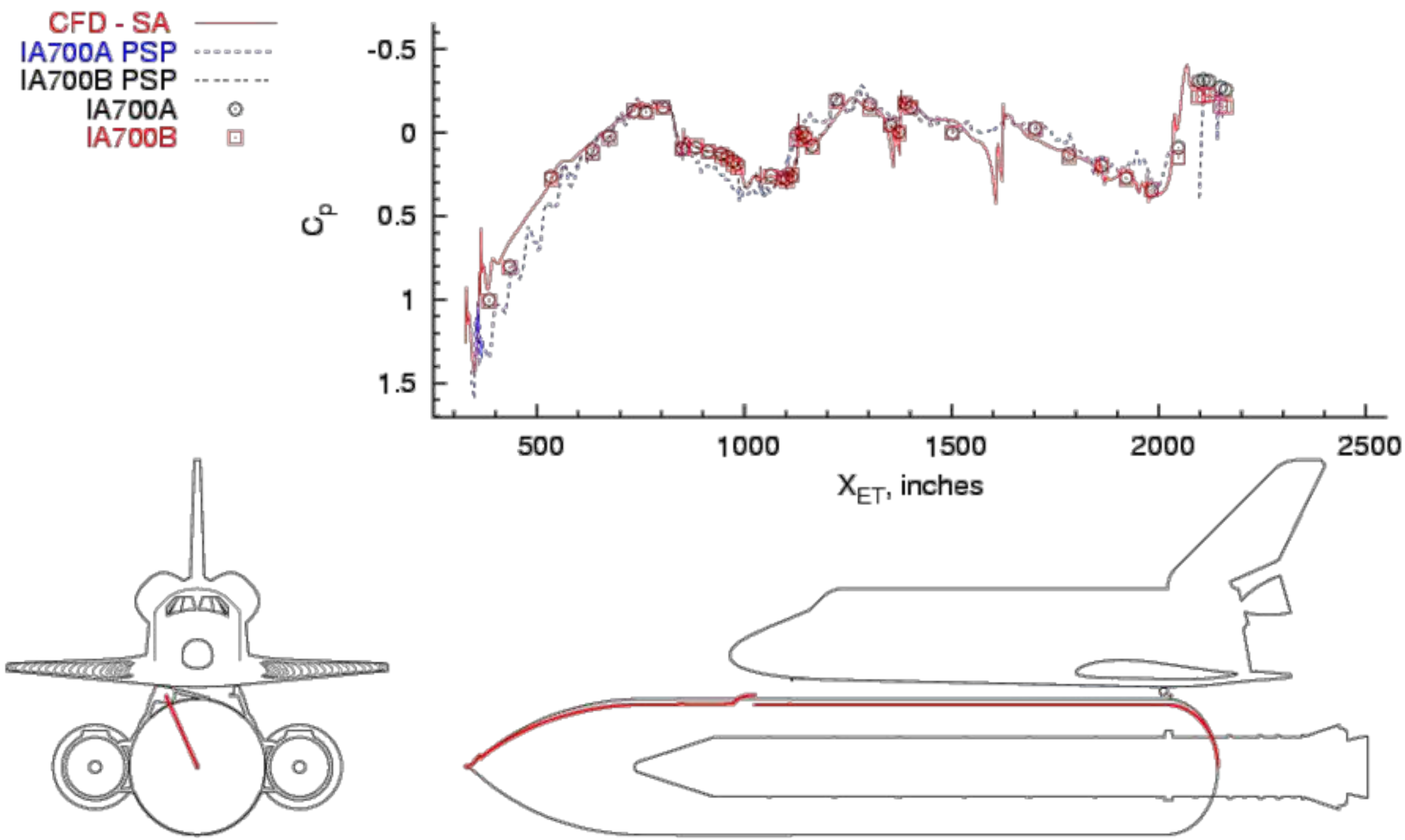
CFD - SA conditions: M_∞ = 1.550, α = 0.00°, β = 0.00°, Reynolds # = 2.50 x10[6]/ft, IB elevon = 10.00°, OB elevon = -2.00°

IA700A PSP conditions: M_∞ = 1.550, α = 0.00°, β = 0.00°, Reynolds # = 2.50 x10[6]/ft, IB elevon = 10.00°, OB elevon = -2.00°

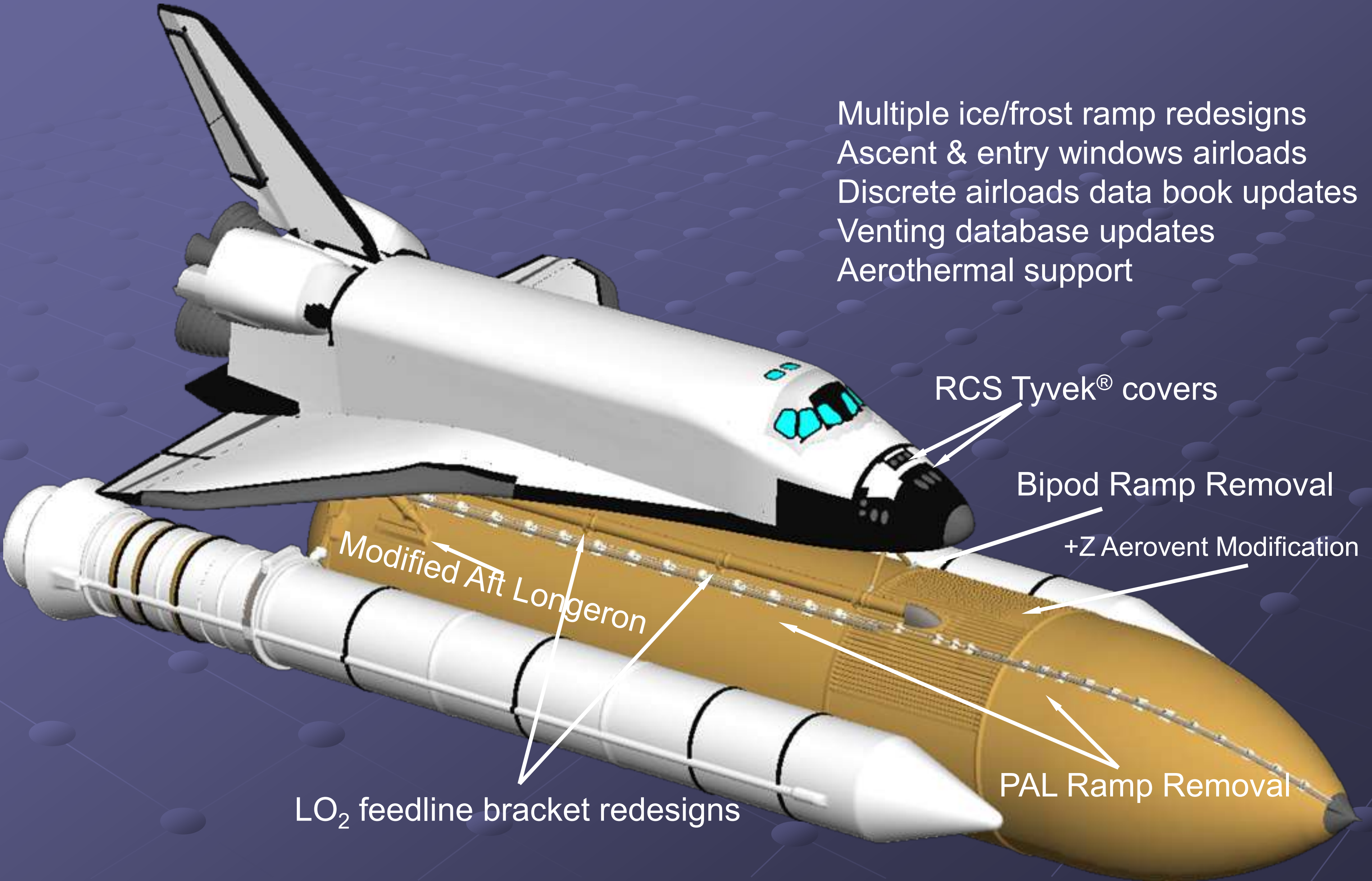
IA700B PSP conditions: M_∞ = 1.550, α = 0.00°, β = 0.00°, Reynolds # = 2.50 x10[6]/ft, IB elevon = 10.00°, OB elevon = -2.00°

IA700A conditions: M_∞ = 1.550, α = 0.03°, β = 0.00°, Reynolds # = 2.50 x10[6]/ft, IB elevon = 10.00°, OB elevon = -2.00°, Run = 890, Point = 6, LOX Roll = 15°

IA700B conditions: M_∞ = 1.550, α = -0.33°, β = -0.27°, Reynolds # = 2.50 x10[6]/ft, IB elevon = 10.00°, OB elevon = -2.00°, Run = 212, Point = 4, LOX Roll = 0°

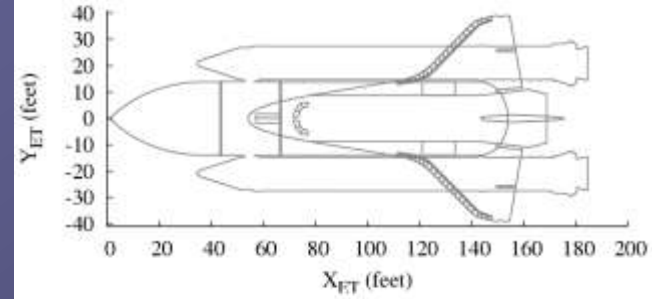


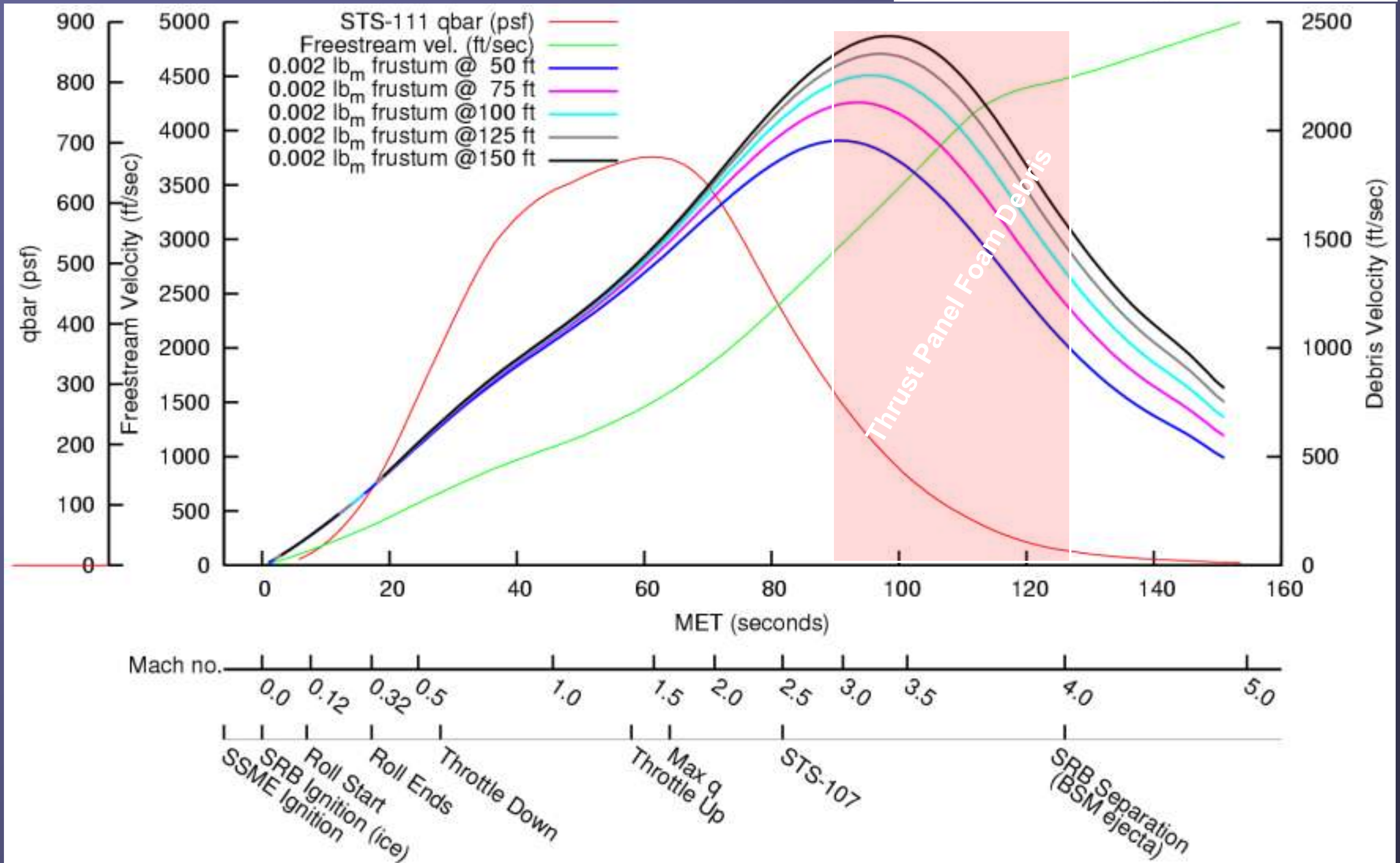
External Tank Redesign Assessments



Space Shuttle Ascent Debris Analysis

Ascent Profile and Debris Velocities





Debris Transport Process Overview

Debris Sources
- Material properties
- Installed geometry
- Likely debris shapes
- Failure mechanism, initial conditions

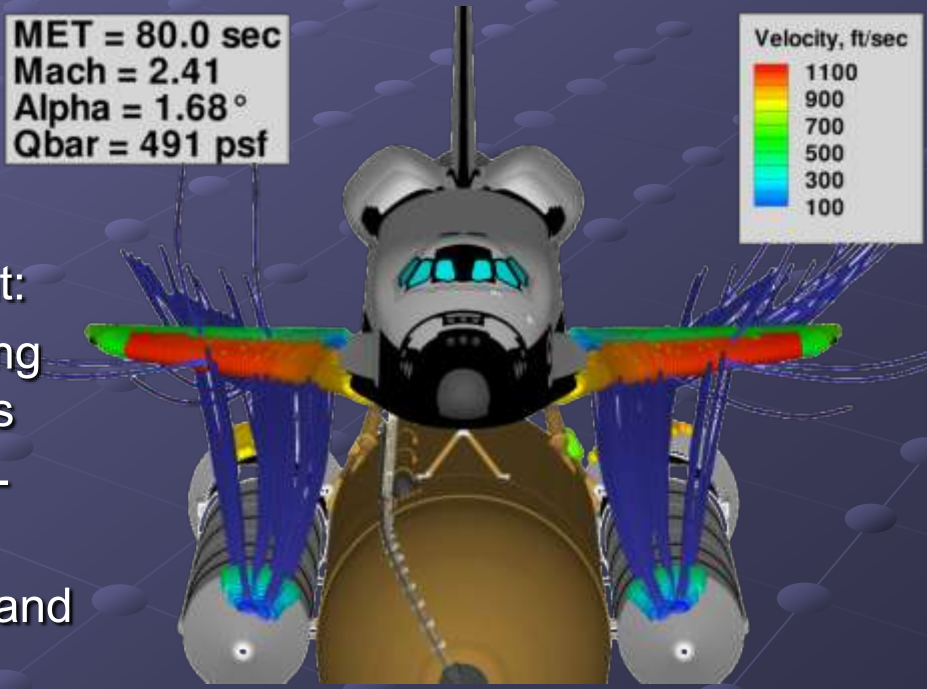
DTA Inputs
- Freestream conditions
- CFD-based flowfield
- Debris aerodynamic models
- Vehicle Geometry

DTA Environment
- Impact location, mass, velocity, incidence angle

Element Impact Capability
- Material properties
- Installed geometry
- Impact tolerance
- Damage tolerance

Debris Transport

- Ballistic debris integration:
  - Steady-state CFD flowfield
  - Integrate motion of point-mass subject to drag force due to relative local wind vector at current location in the flowfield
  - Neglects effect of cross-range dispersions due to lift
- Debris Transport software development:
  - Developed debris-drag models using Cart3D 6DOF unsteady simulations
  - Significant improvements to debris-trajectory computations
  - Wrote software for debris collision and proximity detection
  - Wrote general purpose sorting and filtering of impact data
- Millions of debris trajectories have been computed and analyzed



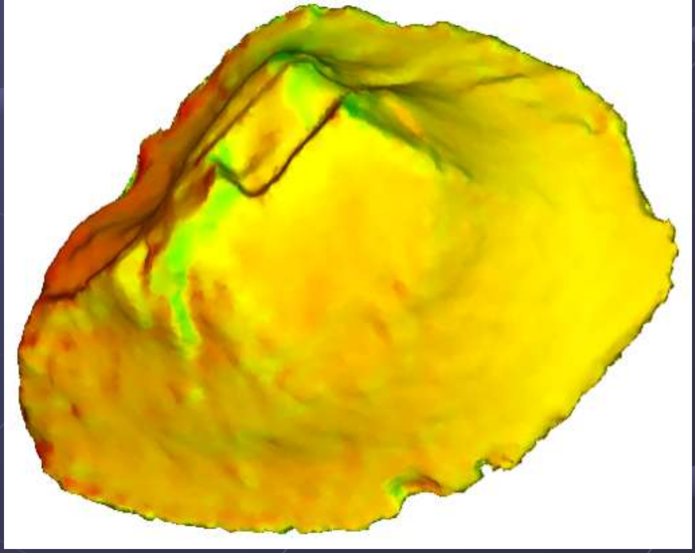
Debris Aerodynamics Modeling

- Debris Transport currently requires
  - **Drag model :** determines impact velocity
  - **Cross-range model** : determines impact locations

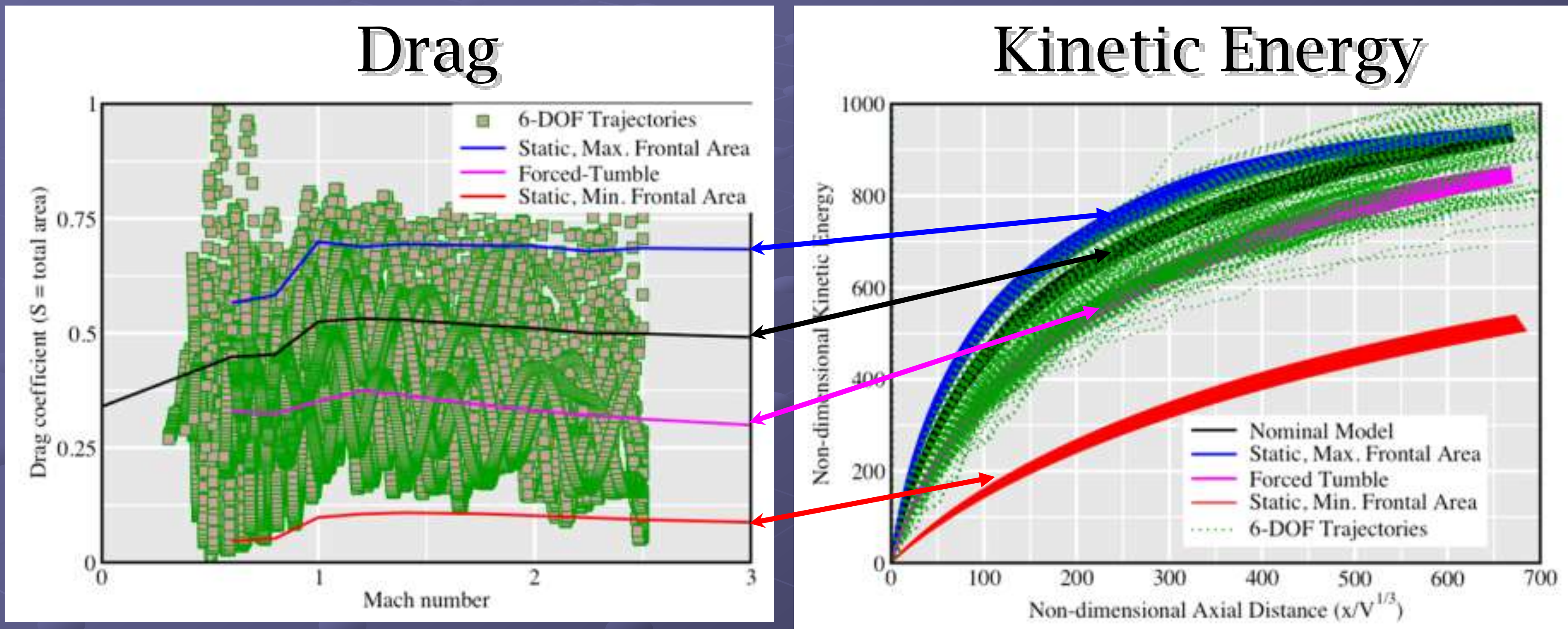
- Use Cart3D CFD methods to simulate debris released in a supersonic freestream

- Compute hundreds of 6-DOF trajectories using a Monte-Carlo approach, varying:
  - Shape
  - Material properties
  - Initial orientation
  - Initial rotation rates

- Have developed drag and cross range models for:
  - Foam divots
  - Ablator material
  - Hemisphere ice balls
  - Bellows ice
  - Umbilical ice
  - Gap fillers

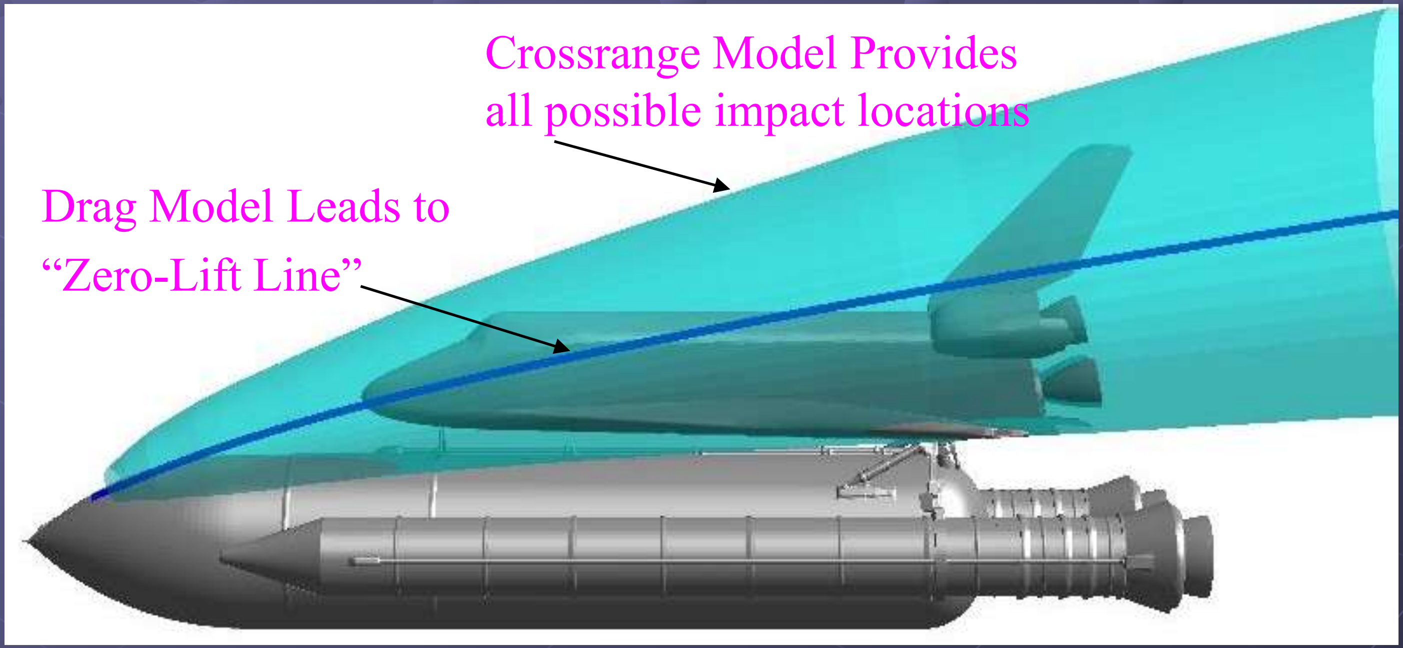


Foam Drag Modeling



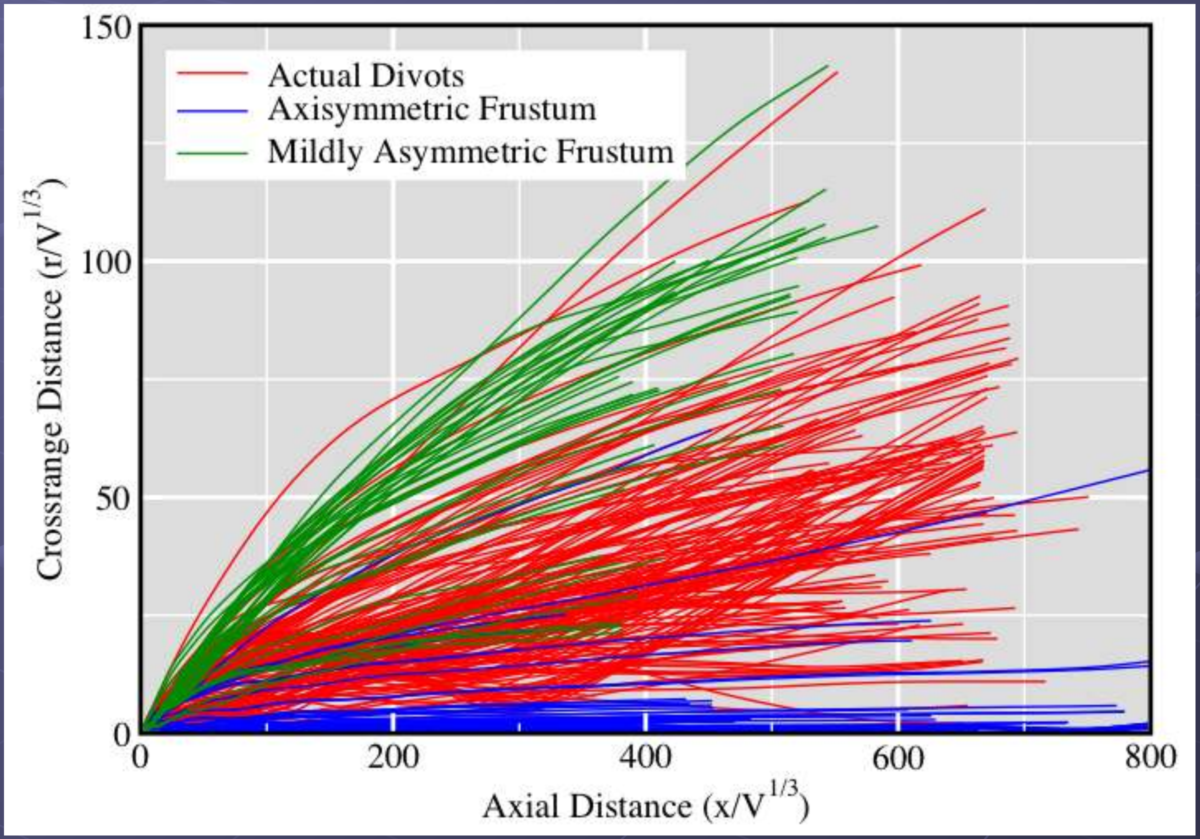
Foam Cross-Range Model

- Debris can generate aerodynamic "lift" in arbitrary direction during trajectory (referred to as crossrange).
- This effect is modeled in a post-processing step.
- Crossrange cone applied to zero-lift debris trajectories from ballistic code to determine possible impact points.



Foam Cross-Range Data

- Data from Monte-Carlo CFD 6-DOF trajectories used to develop crossrange cone
- Several shapes used to develop crossrange behavior
- Results can be scaled to arbitrary-sized debris
- A probability can be assigned to any location within crossrange cone

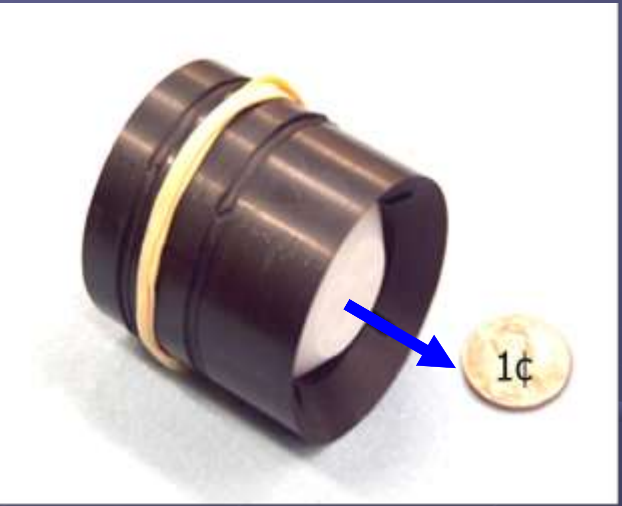


Validation With Gun Development Facility (GDF) Data

- There are two aspects to the validation effort:
  - Validate the ability of the Cart3D code to simulate a 6-DOF foam trajectory by direct comparison against range data. (validation of CFD method)
  - Validate the foam drag and cross-range models using the range data. (validation of models)

Ames Gun Development Facility

1.75" Powder Gun and Dump Tank



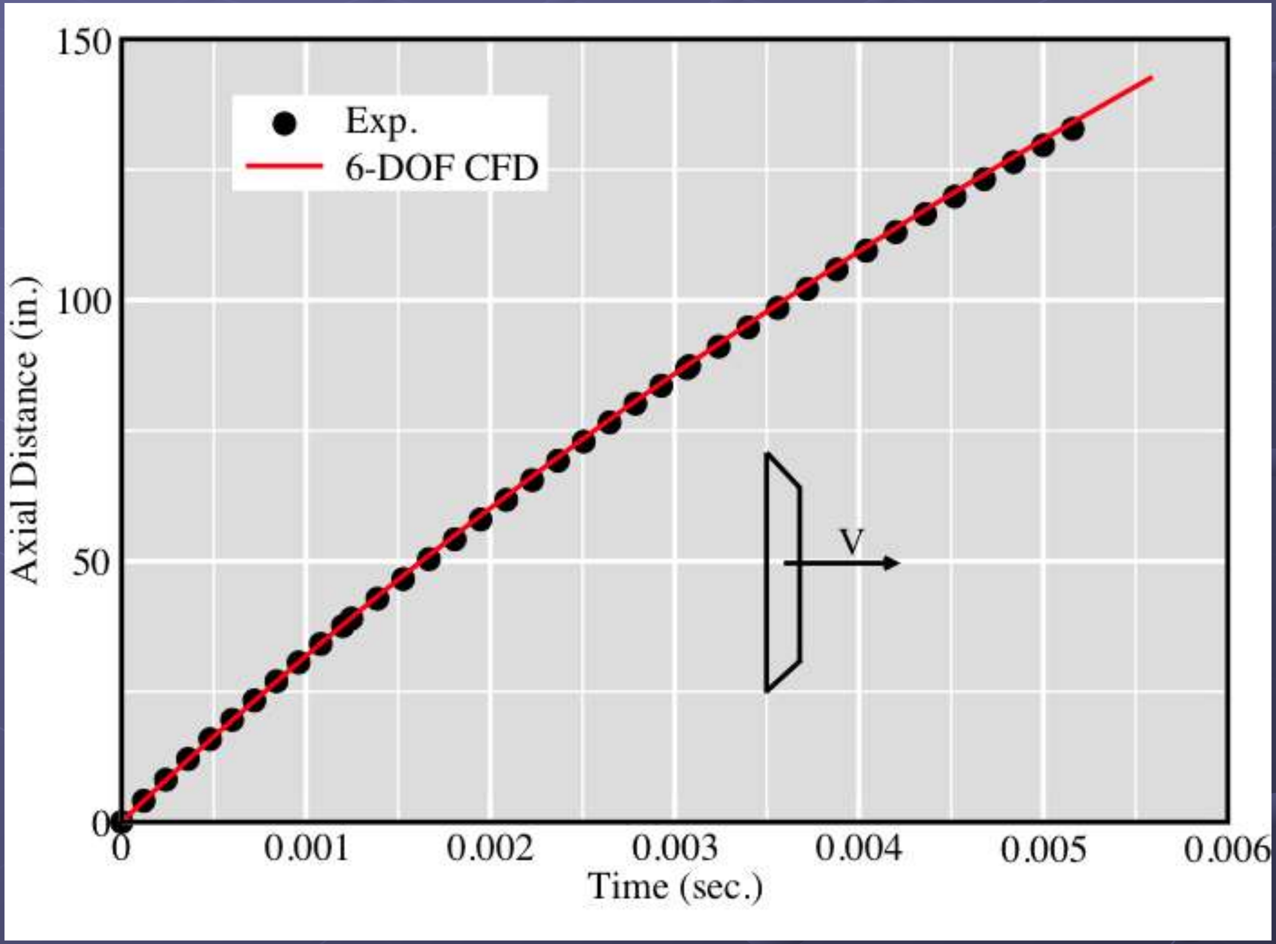
Sabot and Projectile

Side-View Cameras and Controllers

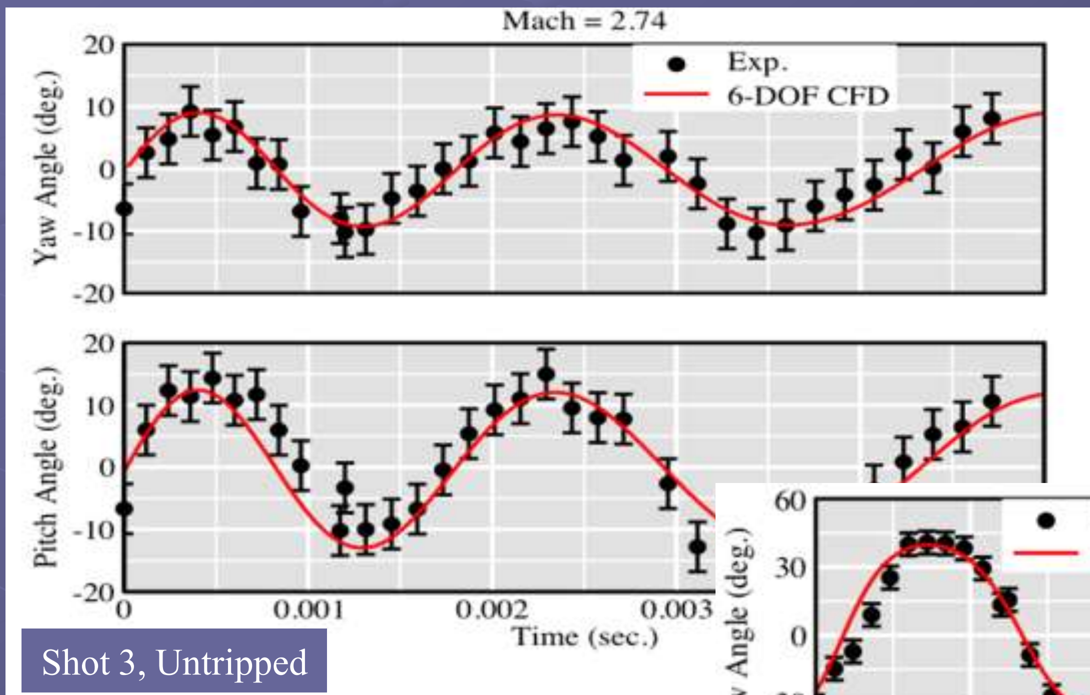
Test Section - Diaphragm, Lights, Light Screens, and Calibration Grids

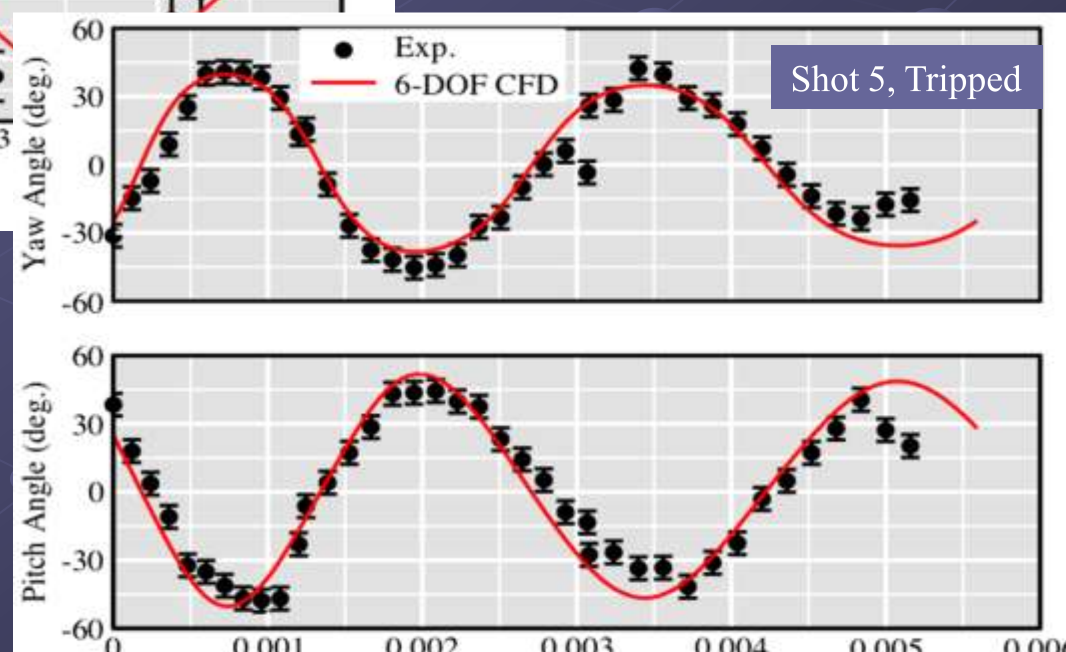
6-DOF Method Validation
Ames GDF ballistic data Distance vs Time

- Mach 2.51, 6000 g's deceleration



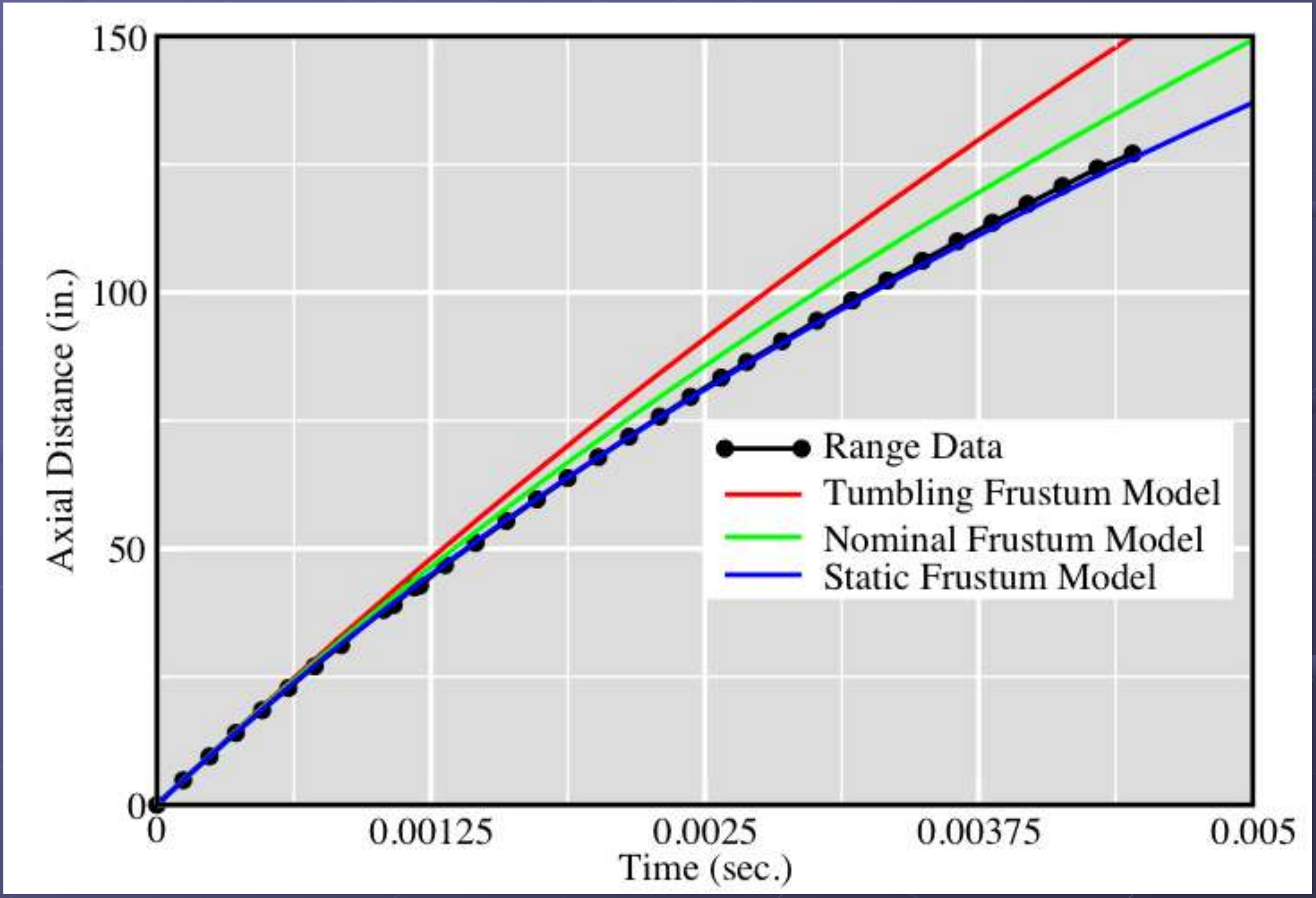
6-DOF Method Validation
Ames GDF ballistic data Pitch/Yaw vs Time





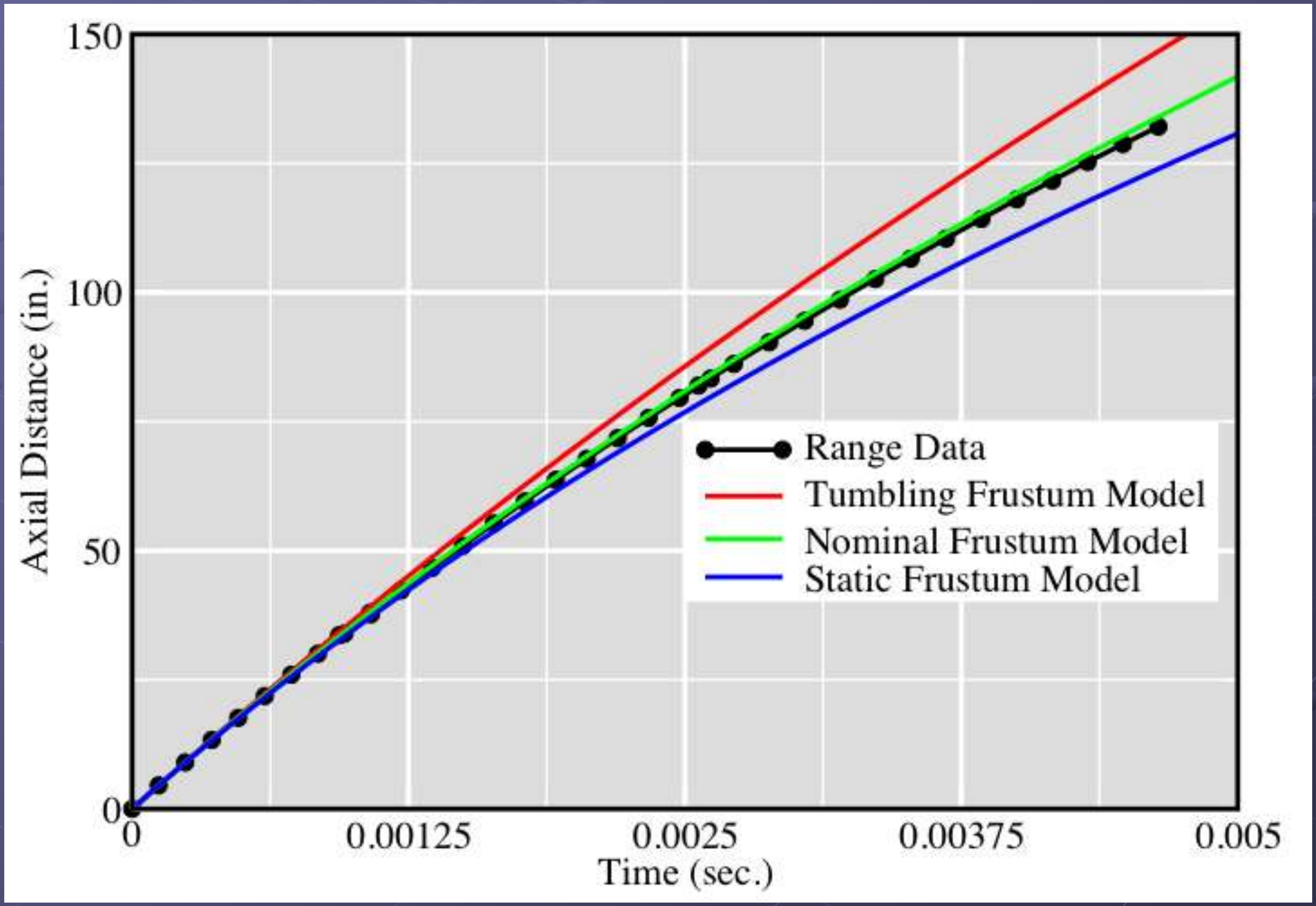
Drag Model Validation

- Low oscillation trajectory - shot 2, Mach = 3.00



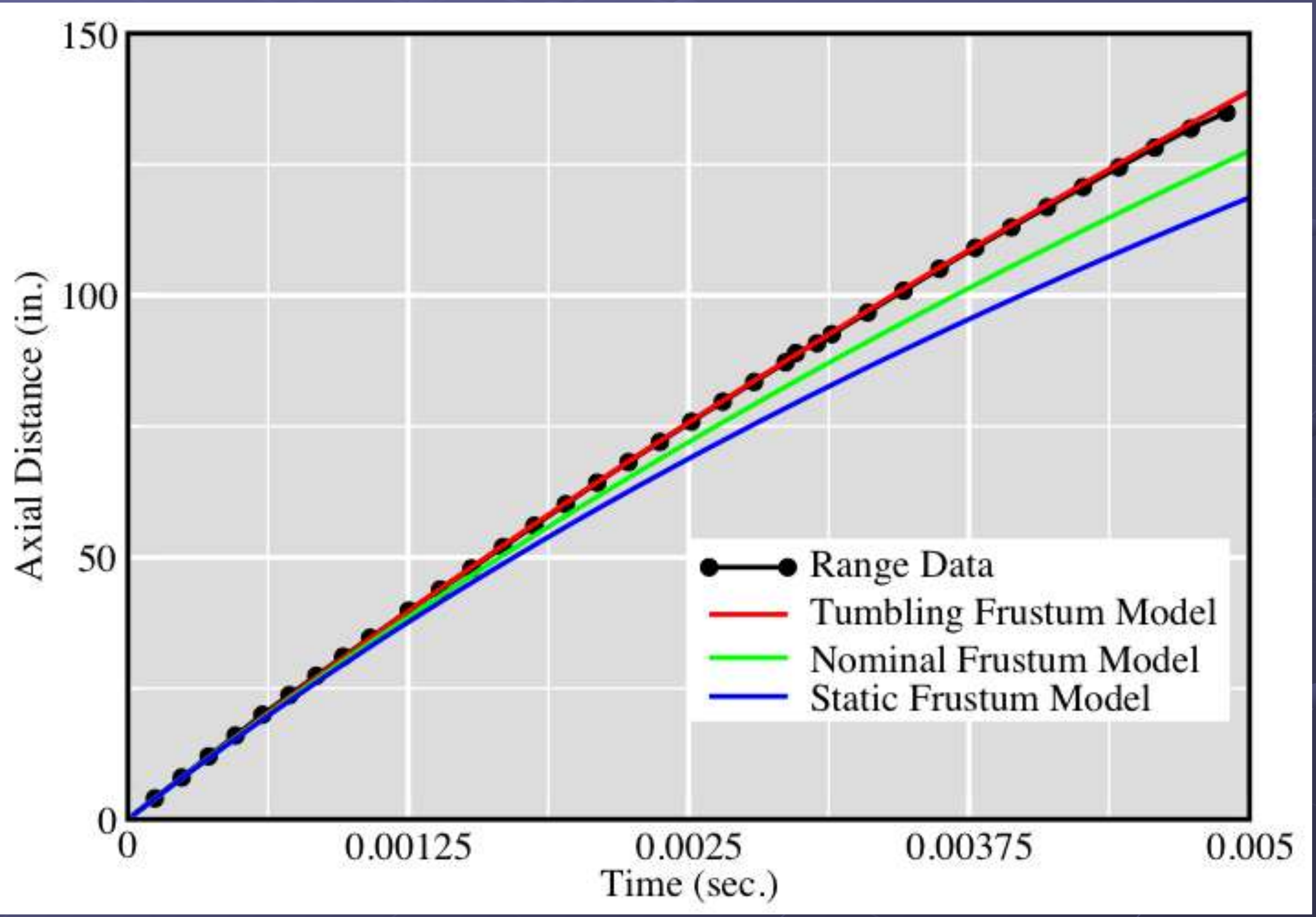
Drag Model Validation

- Medium oscillation trajectory - shot 7, Mach = 2.81



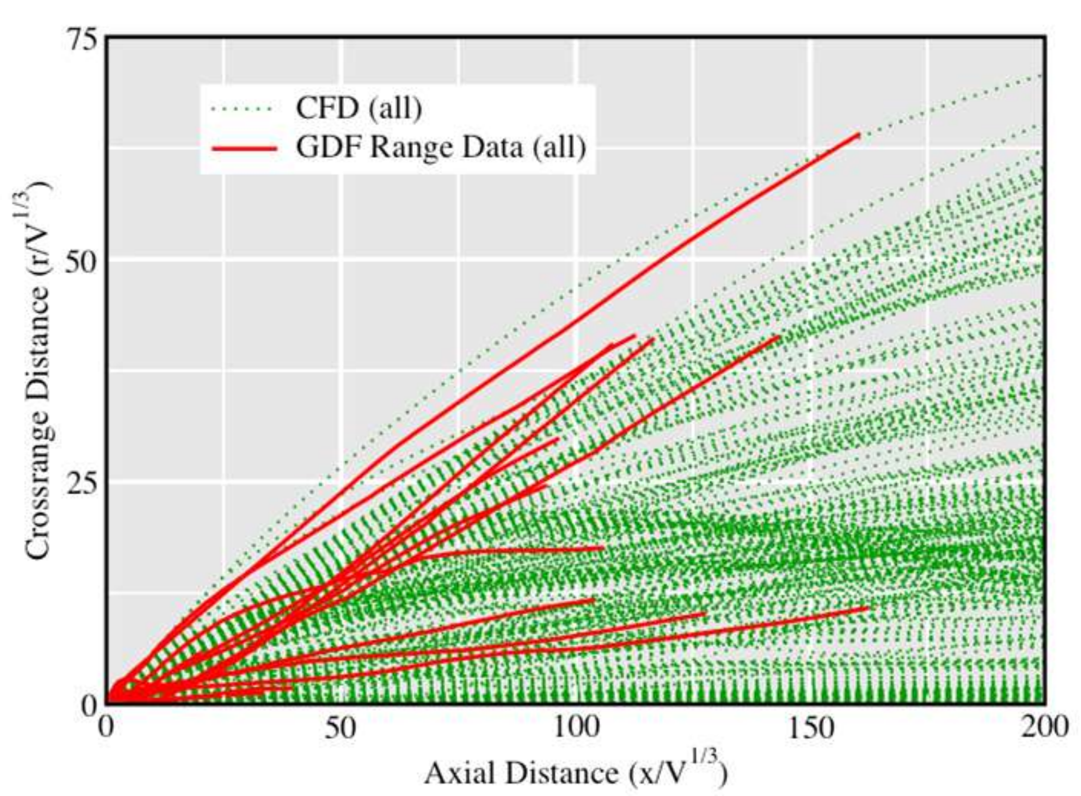
Drag Model Validation

- High oscillation trajectory - shot 6, Mach = 2.46



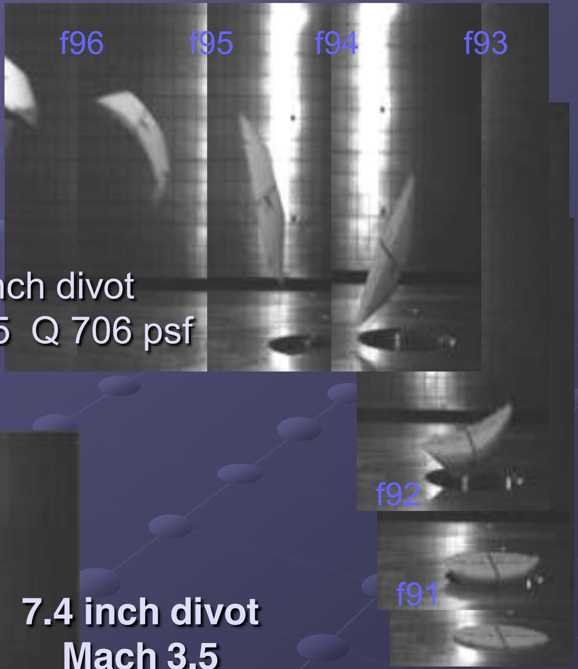
Cross-Range Model Validation

- Cart3D 6-dof predictions bound ballistic data
  - CFD (all) represents several hundred CFD trajectories generated from offset C.G. and asymmetric models
- Even mild asymmetry generates strong crossrange

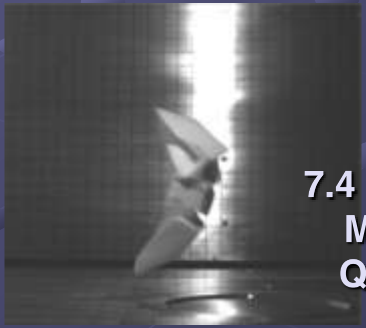


Additional Foam Testing

- CUBRC supersonic wind-tunnel foam ejection tests
- DFRC F15 flight ejection tests: 38 divots
  - 31 supersonic divots trimmed in high-drag orientation
  - 5 subsonic divots oscillated or tumbled
  - 2 divots re-contacted and broke apart
  - Deceleration matches nominal foam drag model



5.1 inch divot
Mach 3.5 Q 706 psf



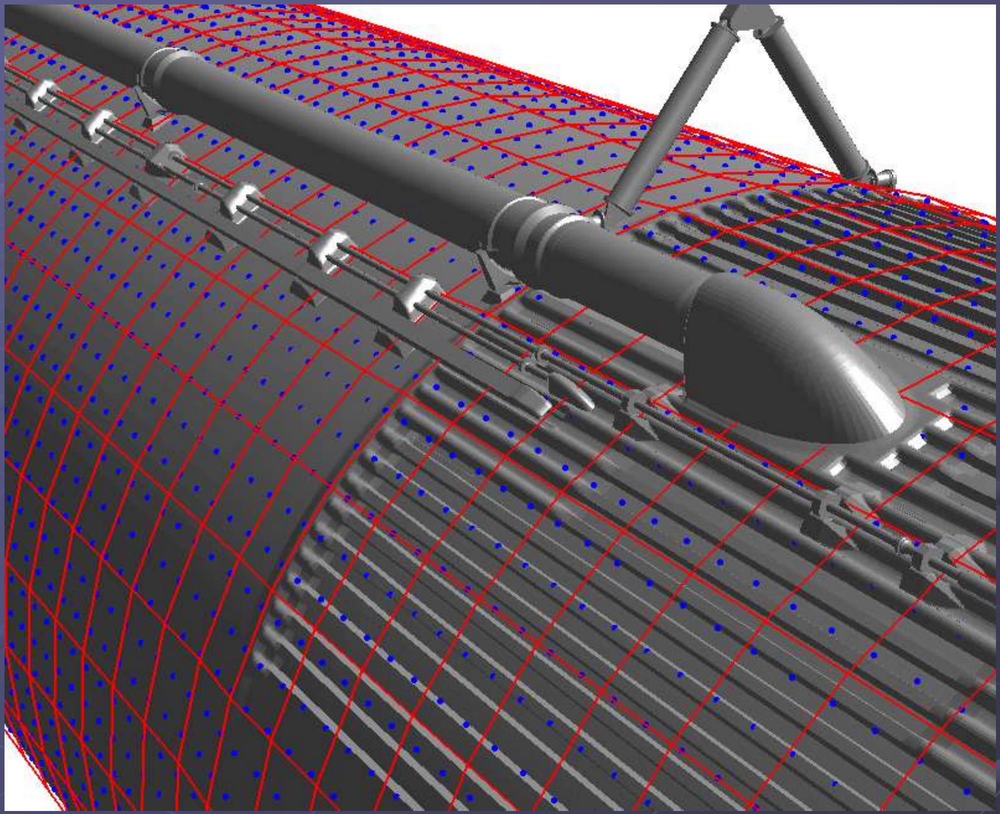
7.4 inch divot
Mach 3.5
Q 729 psf

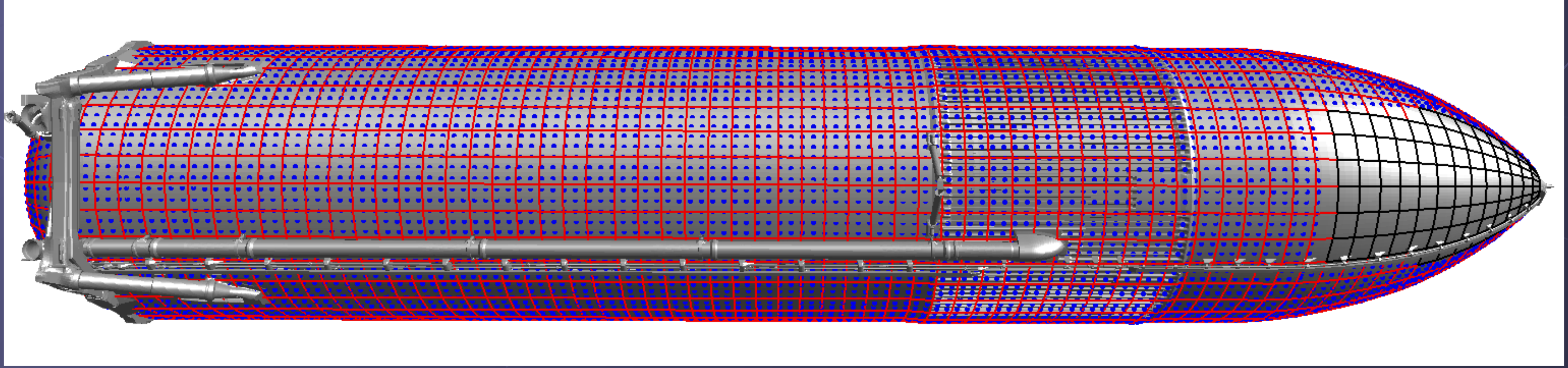
Updated Launch Commit Criteria

Determine allowable ice-ball size on the External Tank

Debris-Transport Analysis Procedure

- Compute all possible ice-debris trajectories
  - Release from 7600 locations (blue dots)
  - 35 different masses
- Compute impact conditions
  - RCC impact kinetic energy
  - Tile damage depths
- Map all impact data back to 1562 different source zones (red-grid cells)
- In each source zone, determine largest mass which does not exceed component capability





DTA By the Numbers

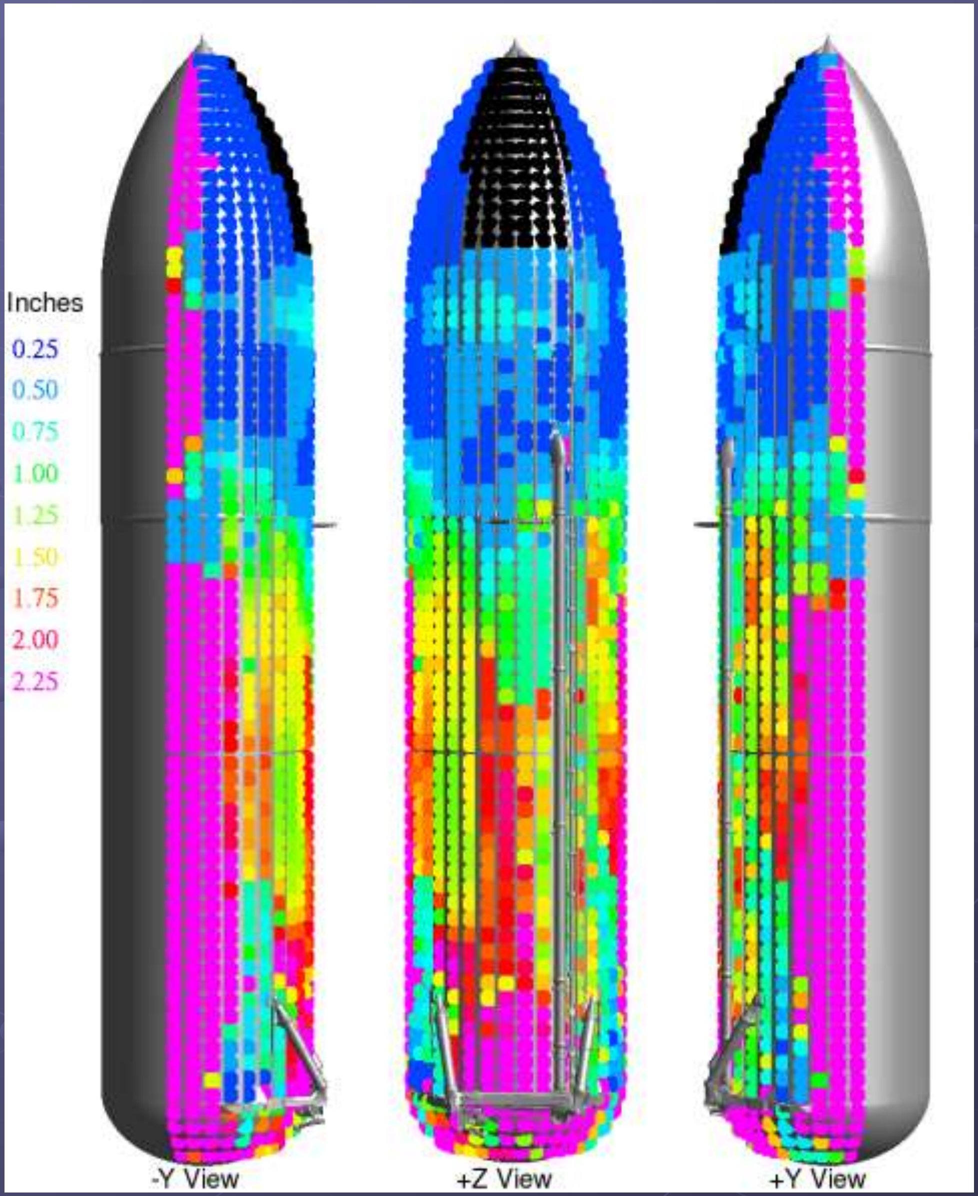
- 33 million ice-ball trajectories computed
  - 7600 release locations
  - 35 masses
  - 31 flight conditions
  - 2 ice-ball densities
  - 2 release velocities

- 10 million executions of the dprox code
  - 1562 subset zones
  - 35 masses
  - 31 flight conditions
  - 2 ice-ball densities
  - 3 impactor targets (tile, wing LE RCC, nosecap)

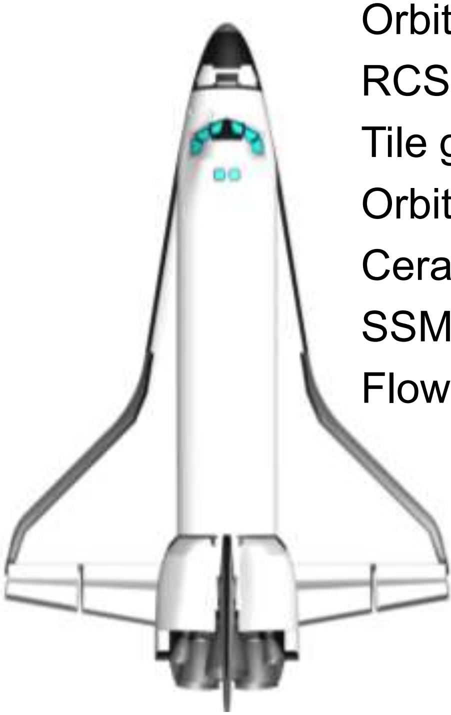
- 5 billion impacts evaluated

- 12,000 CPU hours used

Maximum Allowable Ice-Ball Diameters



List of Debris Assessments



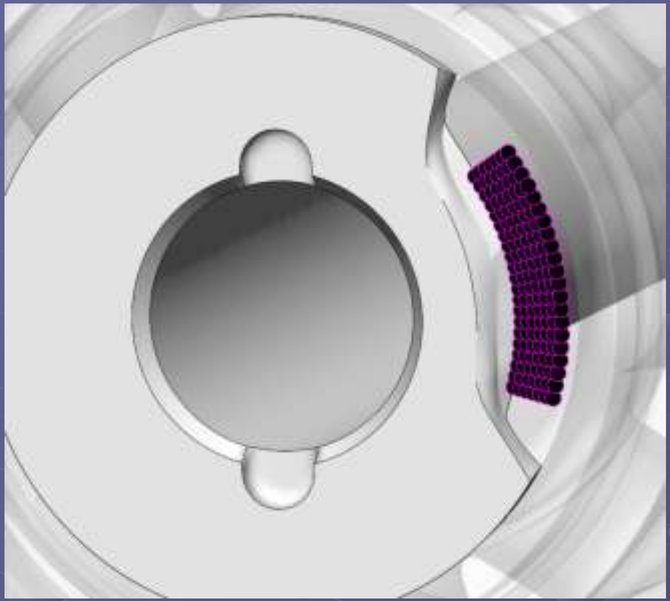
- T0 umbilical ice
- Orbiter/ET umbilical ice
- RCS Tyvek covers
- Tile gap-fillers
- Orbiter blankets
- Ceramic inserts
- SSME Ice
- Flow-control valves

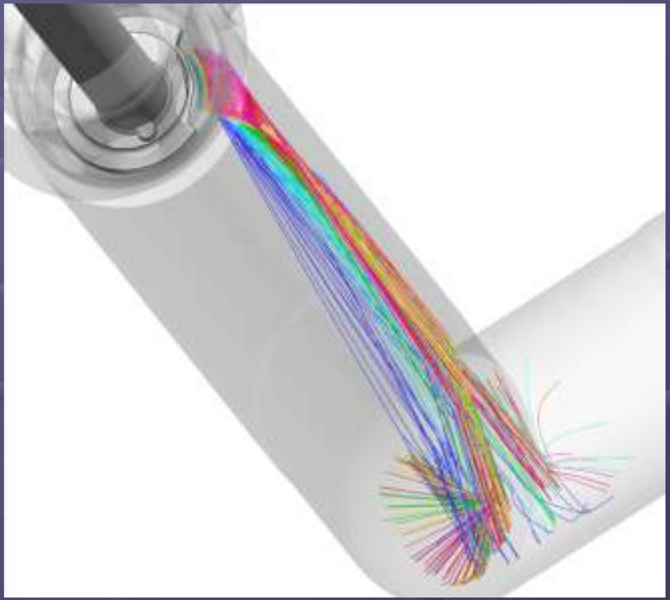
- ET PAL ramp foam
- ET Flange foam
- ET iceballs
- ET ice/froat ramps
- ET intertank foam
- ET feedline bellows ice
- ET feedline bracket ice

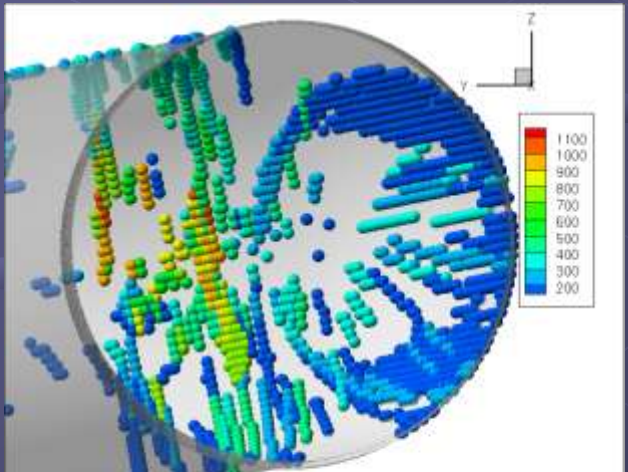
- SRB Weather-seal
- SRB phenolic glass
- SRB Ablator material
- SRB viton-coated nylon
- SRB BSM RTV

Example: Flow-Control Valve Debris

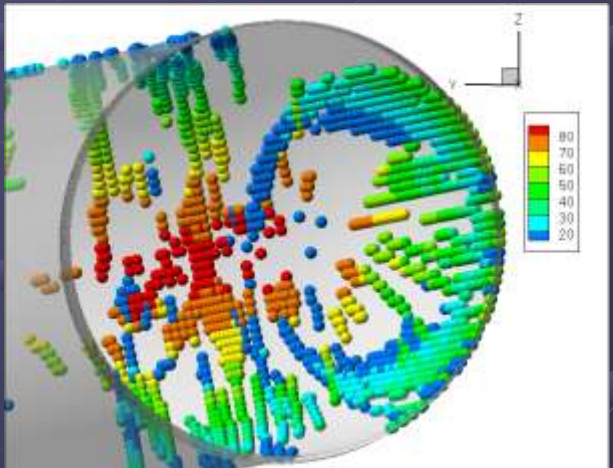
High Pressure GH2 Flow Regulator





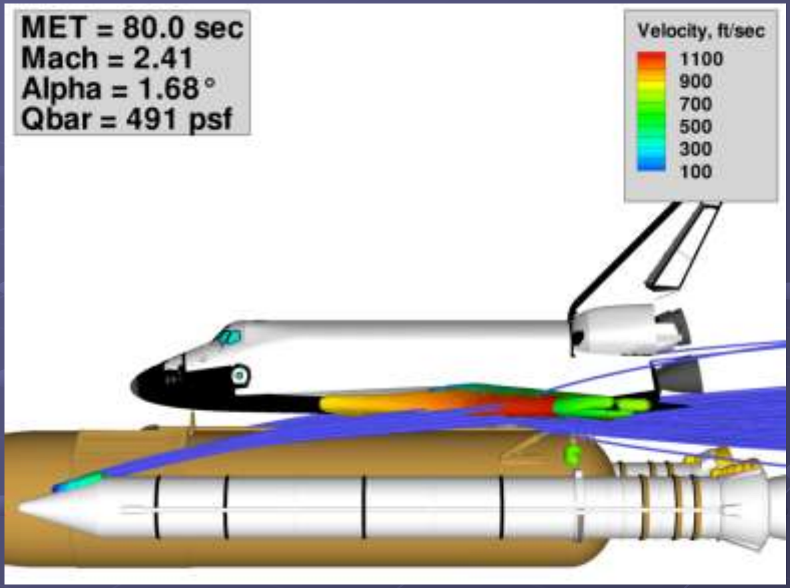


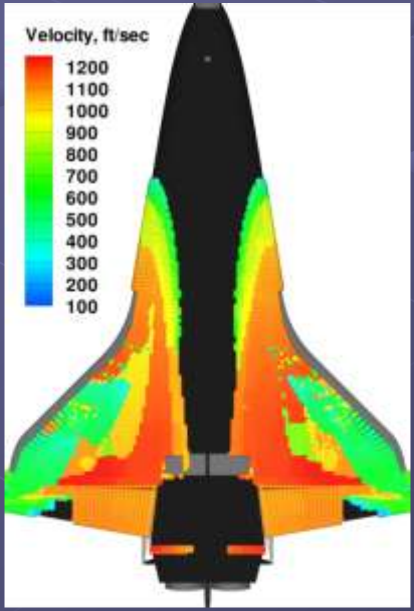
Impact Velocity, ft/sec

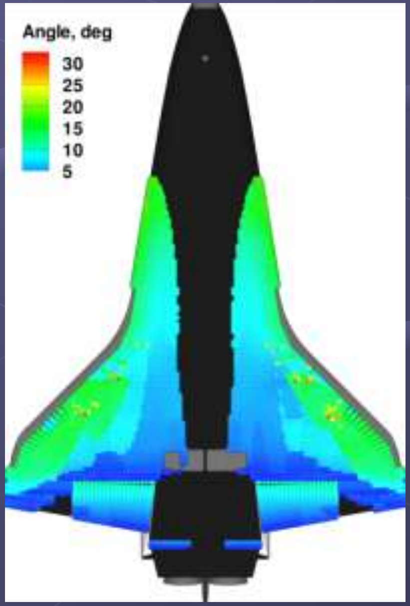


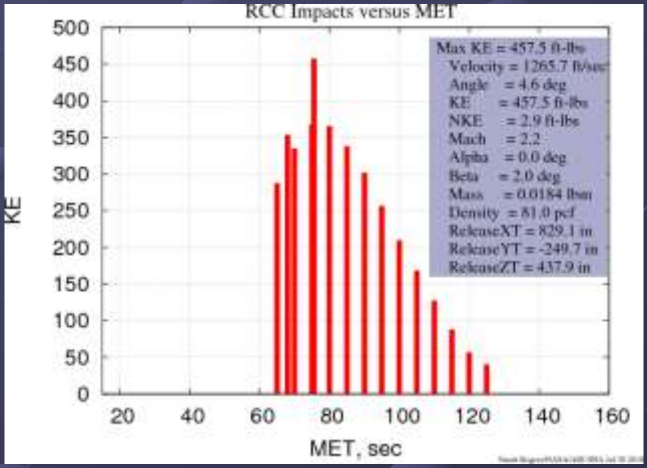
Impact Angle, deg

Example: SRB Booster Separation Motor RTV









Day of Launch Support

- Mission Control Center, Johnson Space Center, Houston
- Debris analysis team spends the hours before the launch making sure the vehicle is ready to fly
  - Final Inspection Team
  - Dozens of video cameras
  - Looking for ice, cracks in foam, and anything unusual
- My job includes being able to simulate potential debris and provide potential impact conditions
  - Execute debris analysis on NAS computers and produce data in less than an hour

Bat Debris

Space Bat

Concluding Remarks

- CFD simulations of SSLV ascent have become a valuable tool for the program
- Debris transport simulation has been used to quantify the debris environment during ascent
  - Helped the program focus on mitigation of the most dangerous debris sources
  - Make certain that the vehicle will only launch in a safe configuration

The End