20+ Years of Chimera Grid Development for the Space Shuttle

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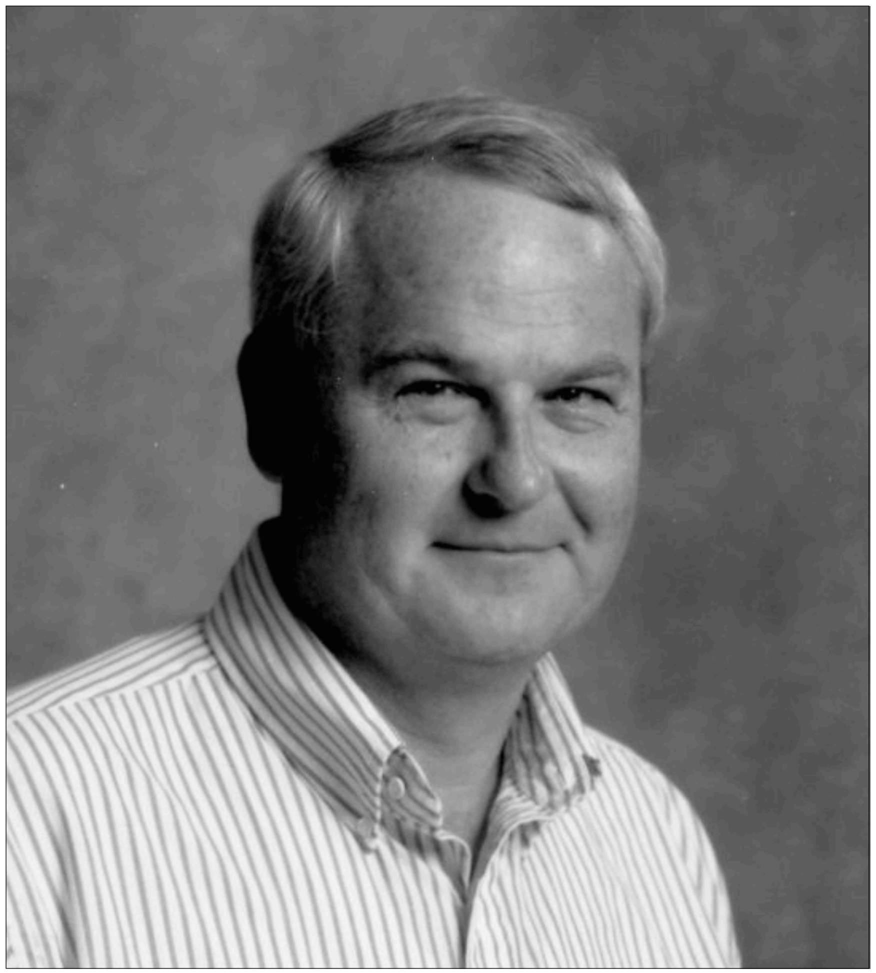
10th Symposium on Overset Composite Grid and Solution Technology

September 20-23, 2010, Moffett Field, CA

Dedication



Joe Steger

Kalpana Chawla

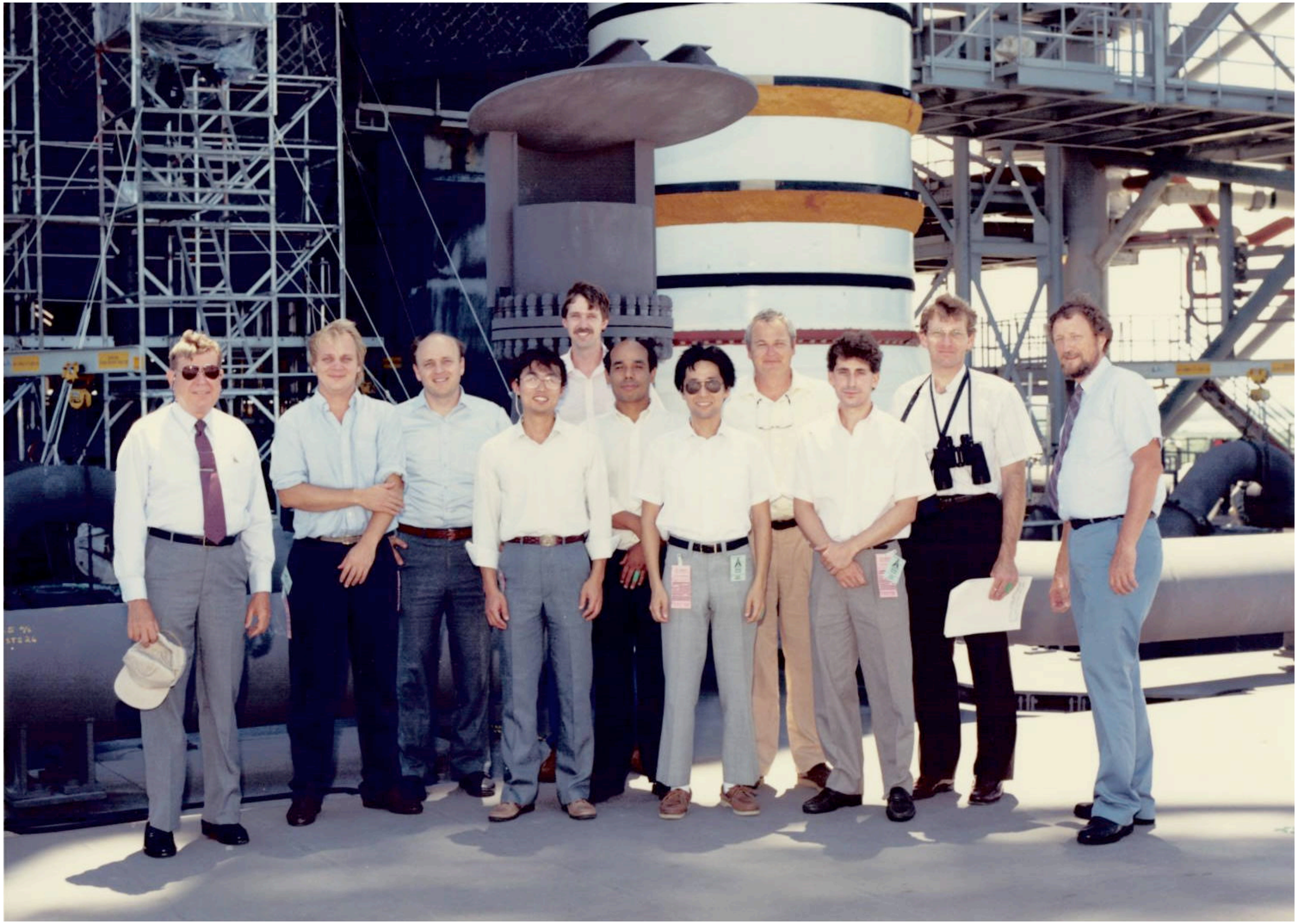
Outline – The Early Years (1987-1994)

- Introduction
- Shuttle problems
- Initial tools & grid system
- Collar grids & improved geometric fidelity
- Moving grid development
- State-of-the-art, ca. 1994

Introduction

- Post-Challenger time-frame
  - Re-examining many Shuttle issues
- JSC/Ames collaboration
  - Funded effort for technology development
- Rockwell Downey effort
  - Dan Dominik (group lead)
  - USA code from Rockwell Science Center
- Group members (1987-1994)
  - Ames: Joe Steger (group lead), Yehia Rizk, Bob Meakin, Pieter Buning, Ing-Tsau Chiu, Shigeru Obayashi, Maurice Yarrow, William Chan, Kevin Renze, Shmuel Ben-Shmuel (Rockwell)
  - JSC: Fred Martin (group lead), Steve Parks, Steve Labbe, Jeff Slotnick, Max Kandula, Dan Pearce, Ray Gomez, Ed Ma, Scott Stanley, Jay Le Beau, Thomas Wey

Shuttle Group Visit to KSC, 1988



(left to right)
Escort, Bill Riba, Bob Meakin, Ing-Tsau Chiu, Pieter Buning, Yehia Rizk, Shigeru Obayashi, Joe Steger, Jeff Slotnick, Fred Martin, Escort.

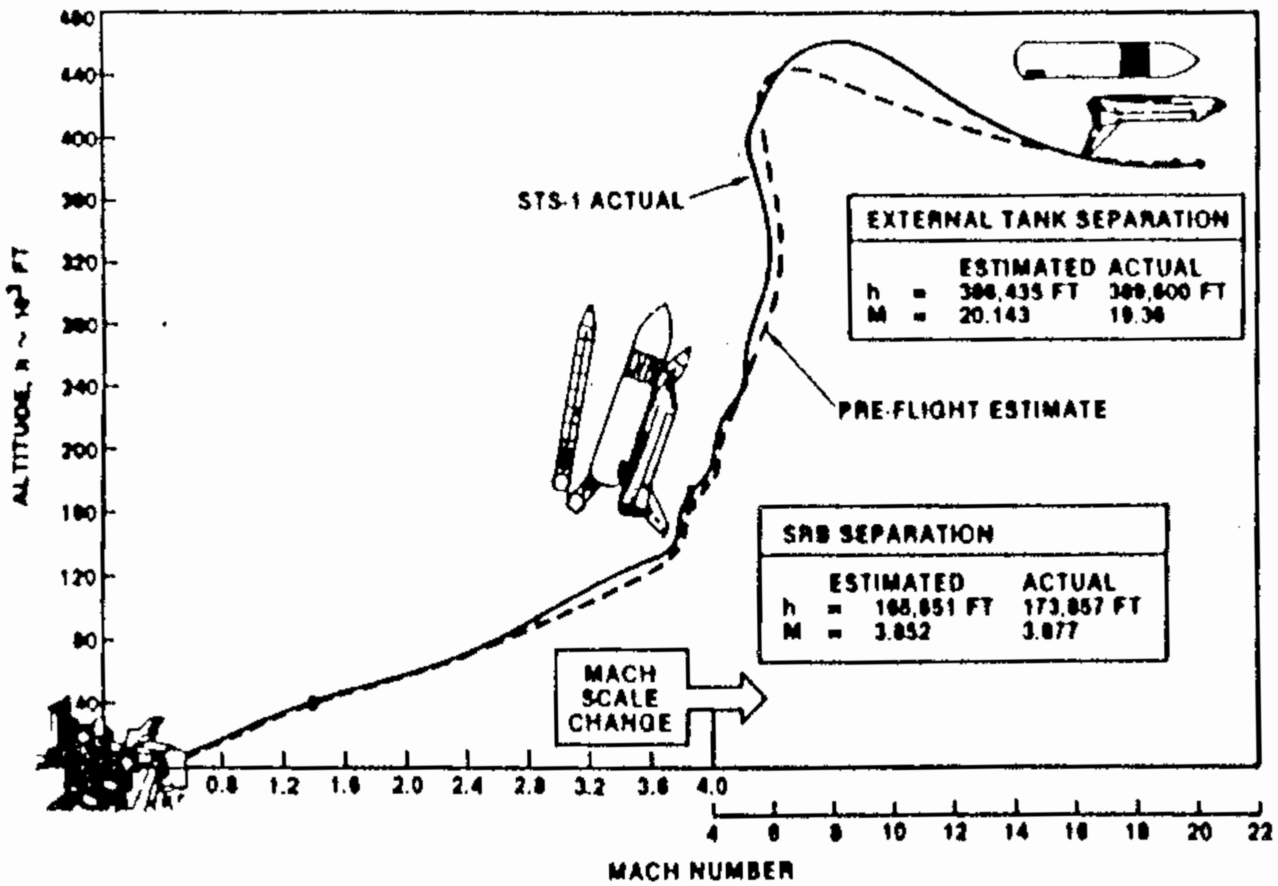
Shuttle Problems

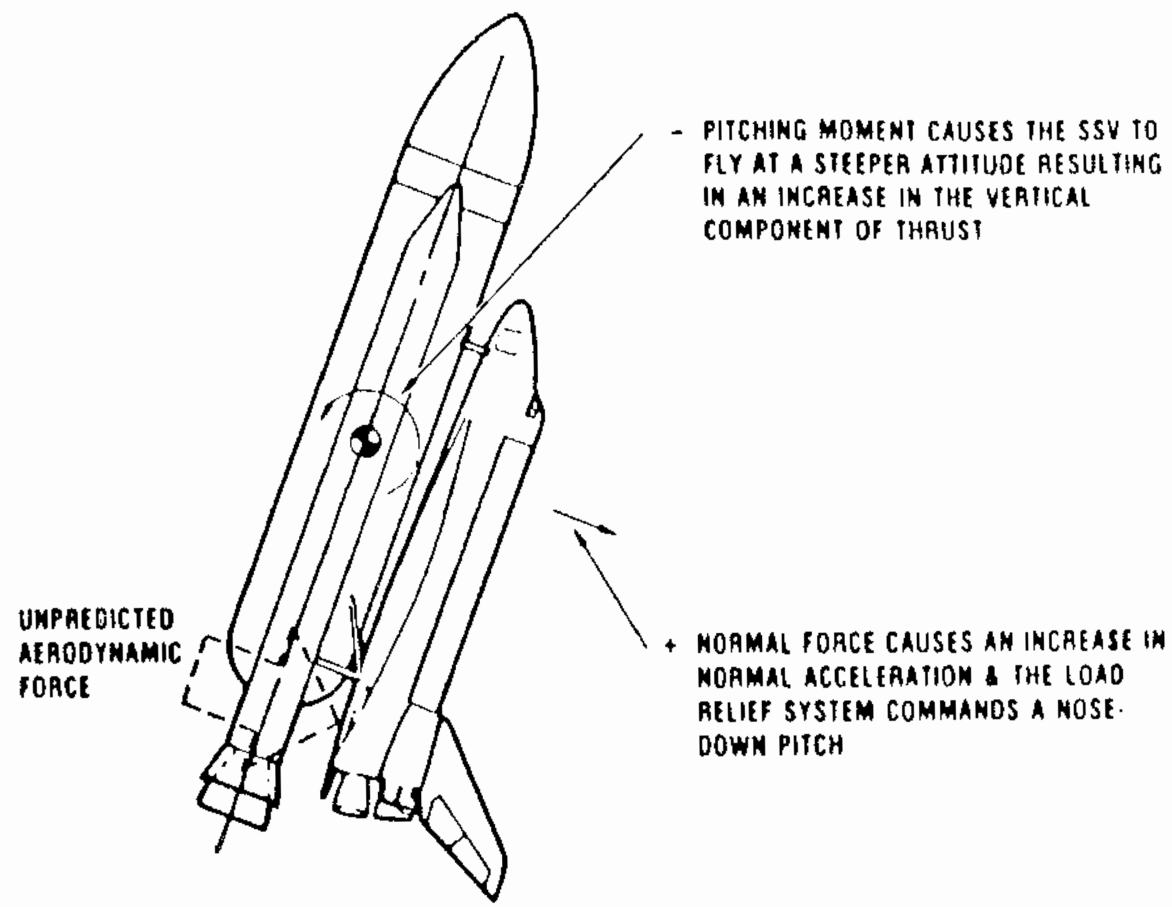
- Fast-sep abort
- STS-1 trajectory lofting
- Payload bay door loads
- and many more...

Reference: F.W. Martin, Jr., and J.P. Slotnick, “Flow Computations for the Space Shuttle in Ascent Mode Using Thin-Layer Navier-Stokes Equations,” **Applied Computational Aerodynamics**, P.A. Henne, ed., AIAA, 1990, pp. 863-886.

Historical Perspective

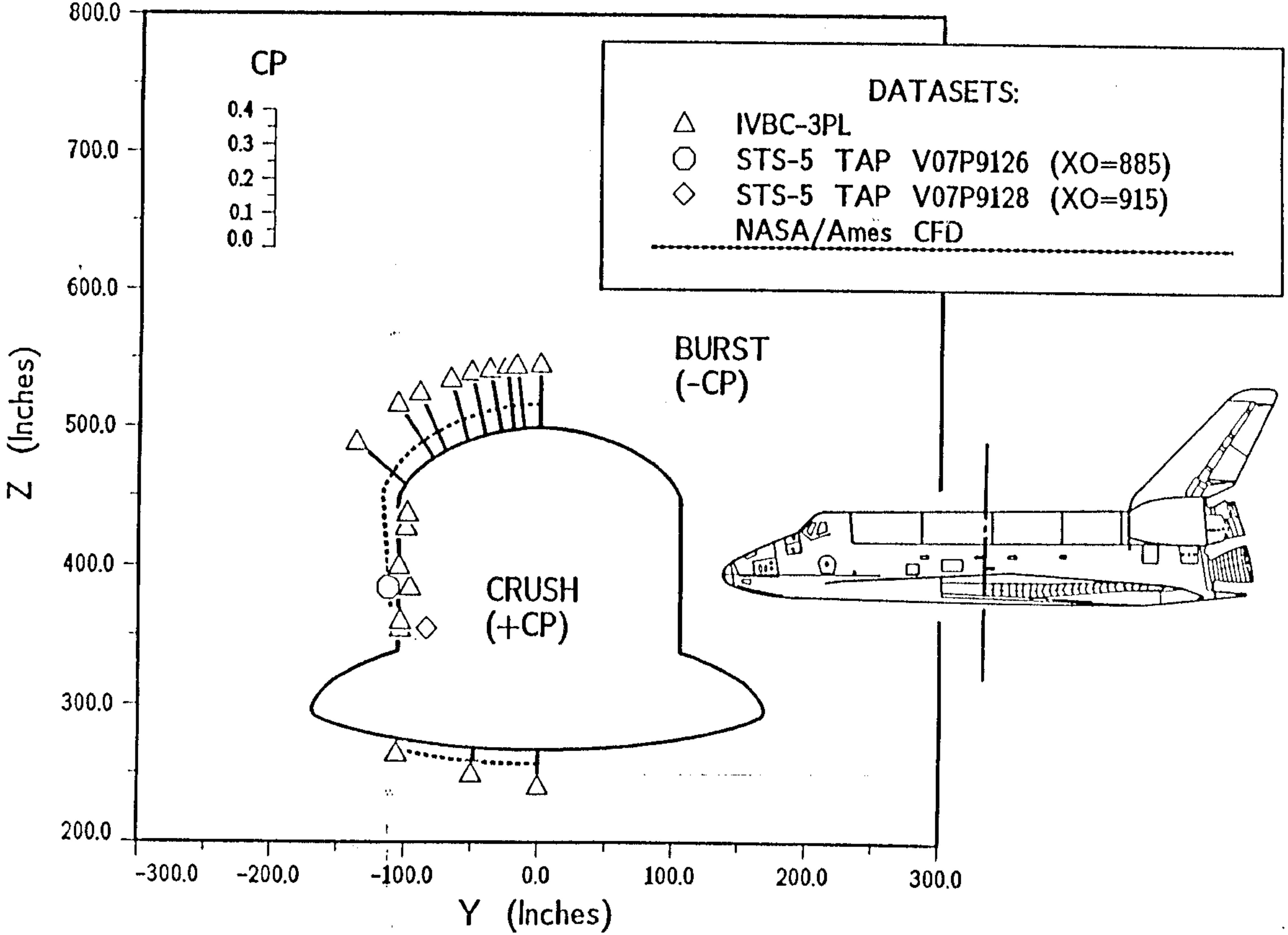
- Discrepancies exist between aerodynamic predictions and flight experience.





- Force and moment data was easily corrected with flight derived aerodynamic increments.
- Aerodynamic loads (pressure distribution) cannot be readily corrected because of *limited* flight pressure measurements.

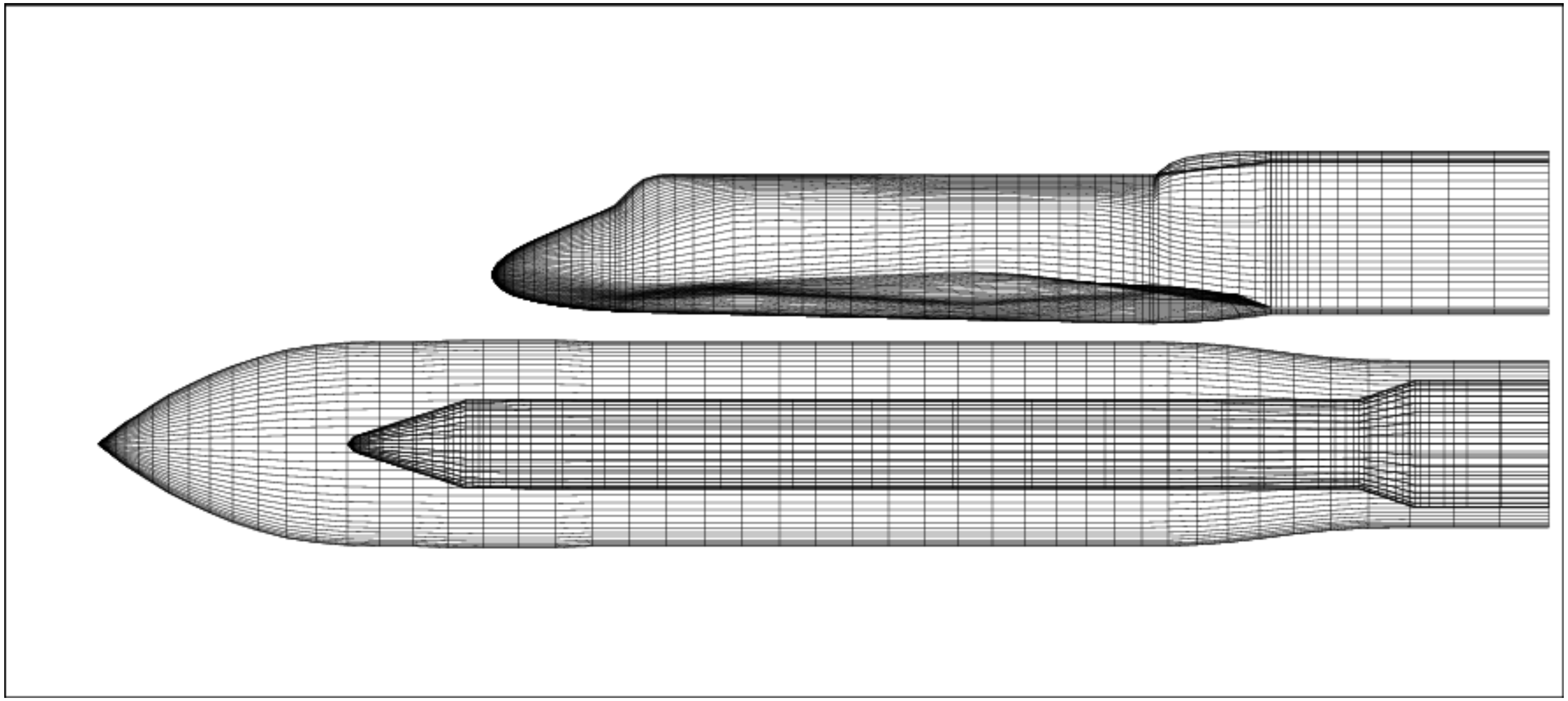
PAYLOAD BAY DOOR PRESSURE COMPARISONS
ORBITER X-STATION (X0) = 905 inches

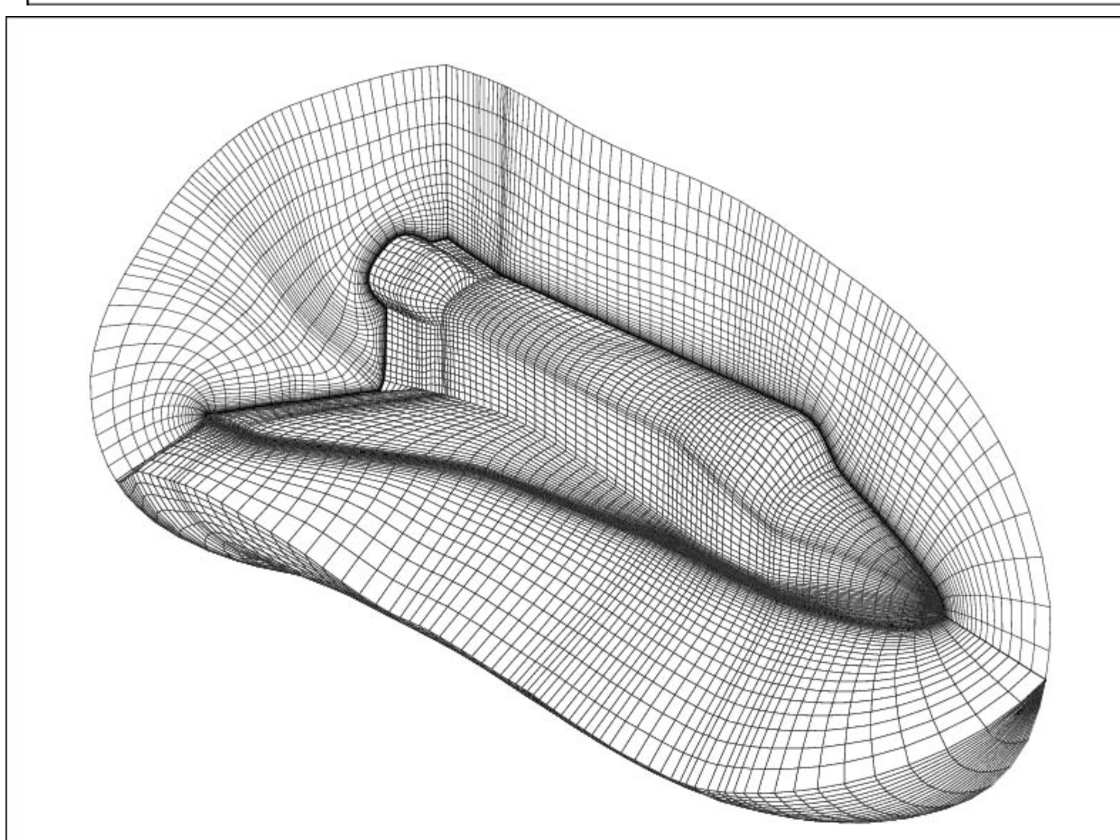


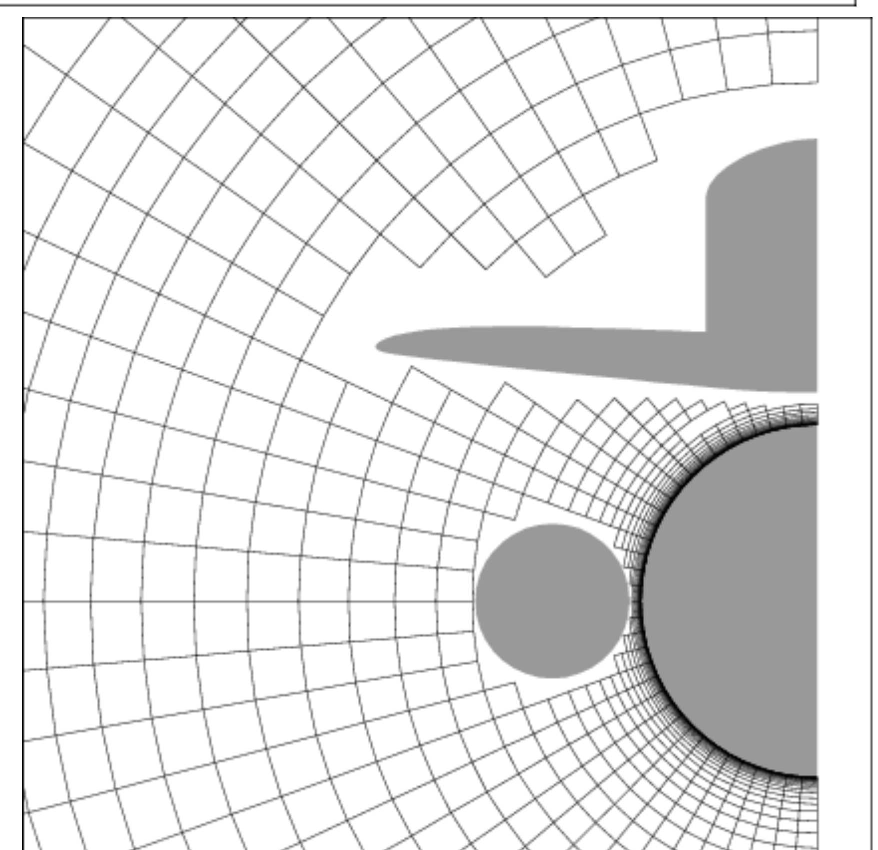
Initial Tools and Grid System

- Grid generation: HYGRIIID
  - Joe Steger, Yehia Rizk, NASA TM 86785 (1985)
  - Hyperbolic equations for marching out from surface
- Grid connectivity: PEGSUS
  - Jack Benek, Joe Steger, Carroll Dougherty, Pieter Buning, AEDC-TR-85-64
  - Grid hierarchy; grid surfaces form hole-cutting boundary
- Flow solver: F3D
  - Susan Ying, Joe Steger, AIAA-86-2179
  - Flux split in streamwise direction, central differencing in cross-flow directions
- Surface grids: Hand-coded

Initial Grid System: 3 grids, 250K points (AIAA-88-4359)





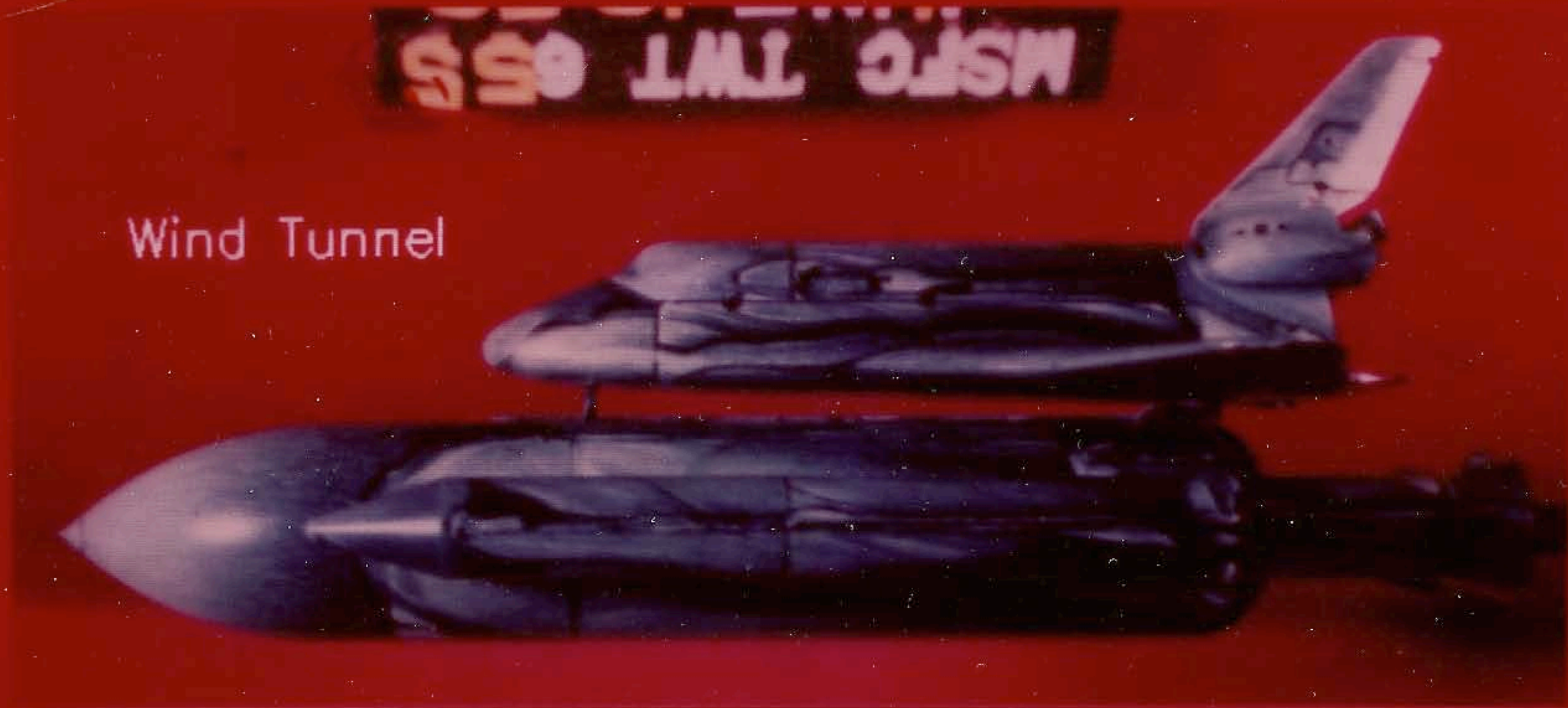


STS ASCENT CONFIGURATION
OIL FLOW COMPARISON

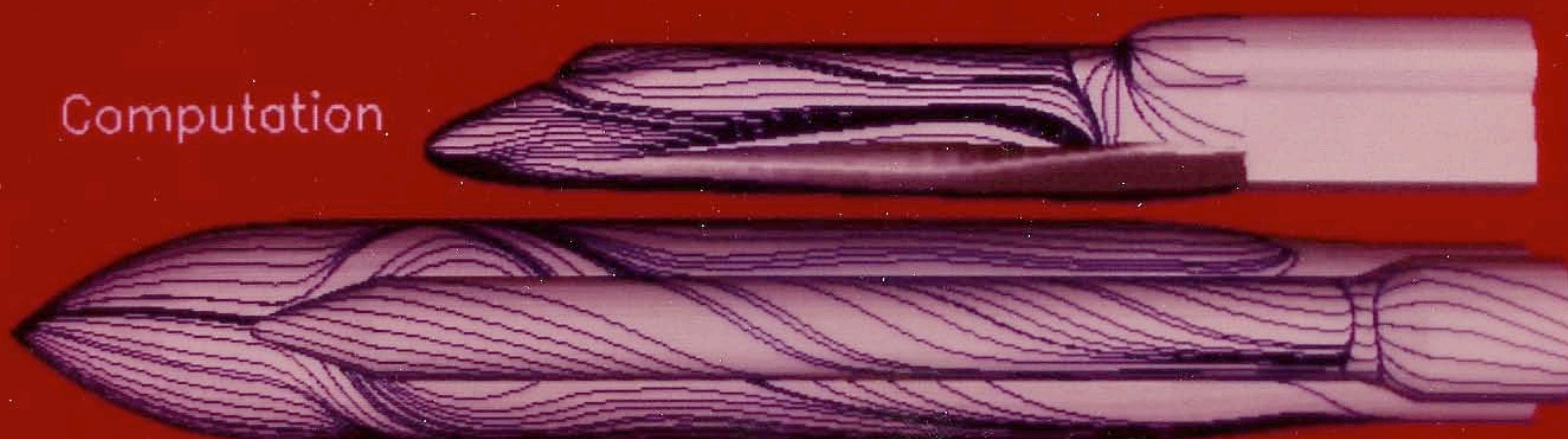
TWT 655 PA27 Wind Tunnel Test with F3D/Chimera Navier–Stokes Solver

Mach 2
Alpha –4 deg

Wind Tunnel



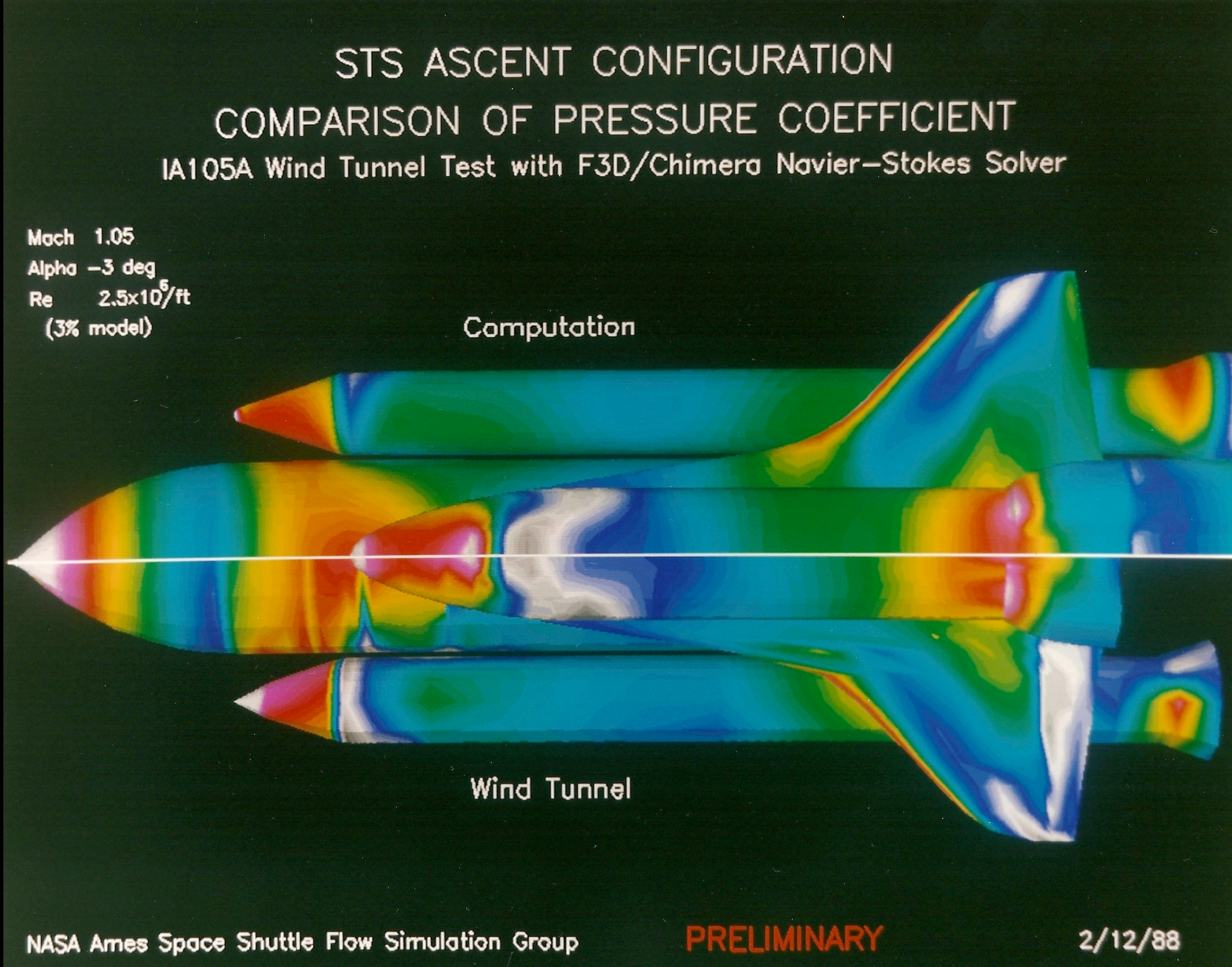
Computation

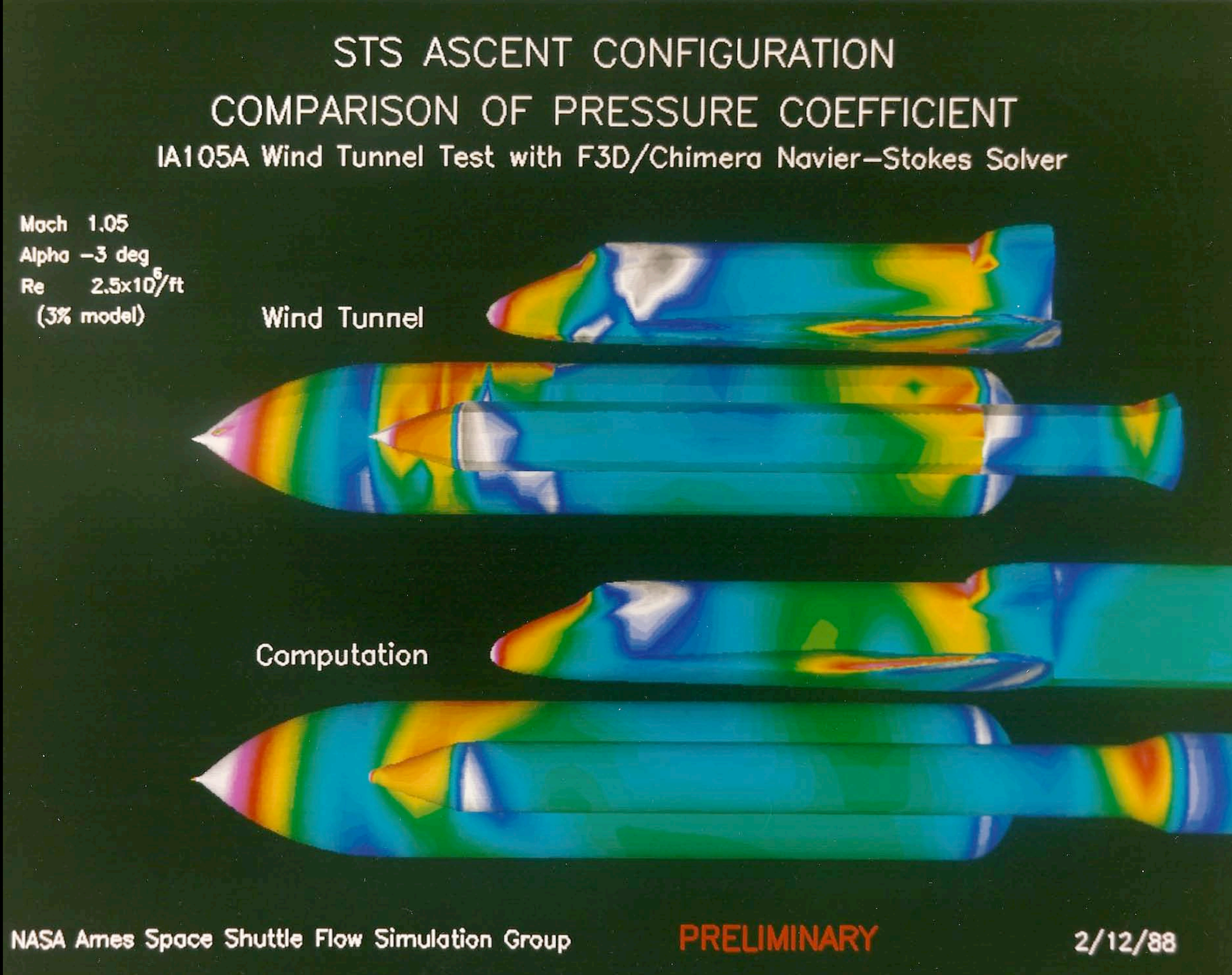


NASA Ames Space Shuttle Flowfield Group

PRELIMINARY

12/22/87


STS ASCENT CONFIGURATION
COMPARISON OF PRESSURE COEFFICIENT
IA105A Wind Tunnel Test with F3D/Chimera Navier-Stokes Solver
Mach 1.05
Alpha -3 deg
Re 2.5×10^6/ft
(3% model)
Computation
Wind Tunnel
NASA Ames Space Shuttle Flow Simulation Group
PRELIMINARY
2/12/88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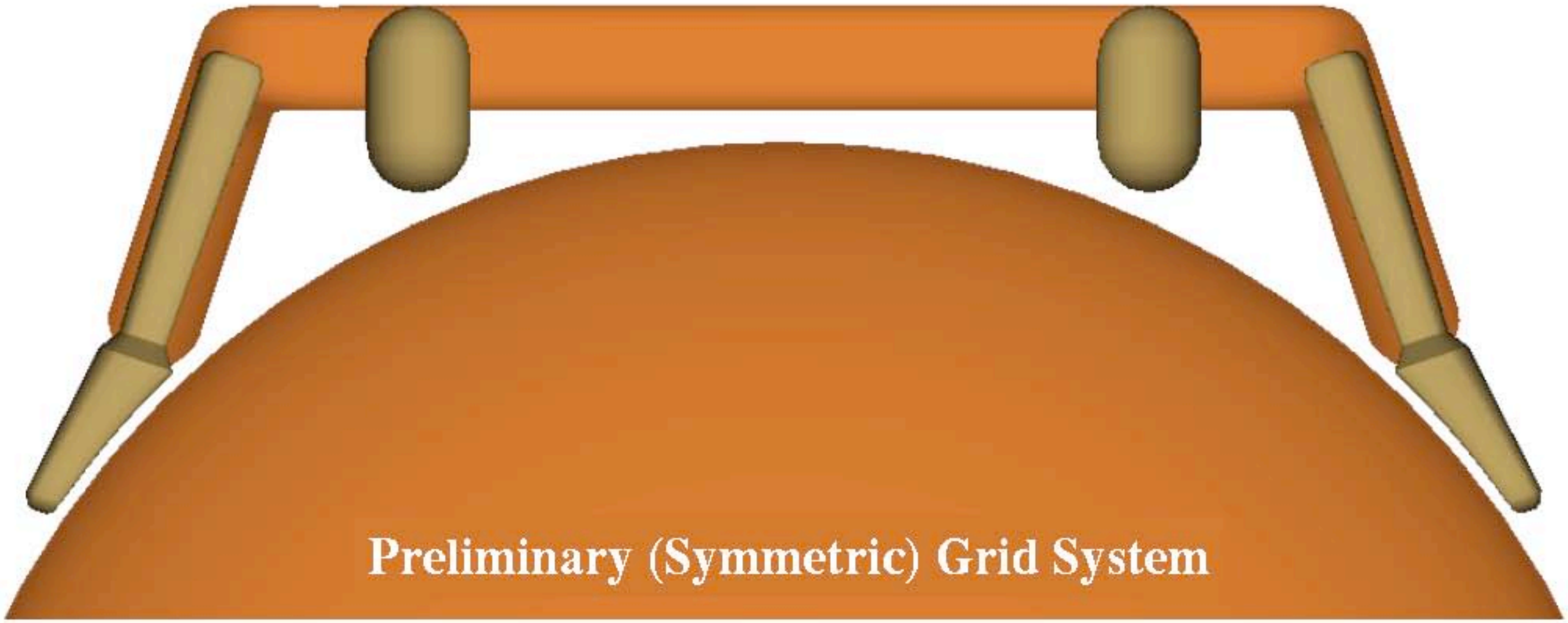
Computation
NASA Ames Space Shuttle Flow Simulation Group
PRELIMINARY
2/12/88

Added Components

- Elevon deflections (sheared grid)
- SRB attach ring and Integrated Electronics Assembly (IEA box)
- Forward and aft Orbiter/ET attach hardware

Previous ET/Orbiter Aft Attach Models

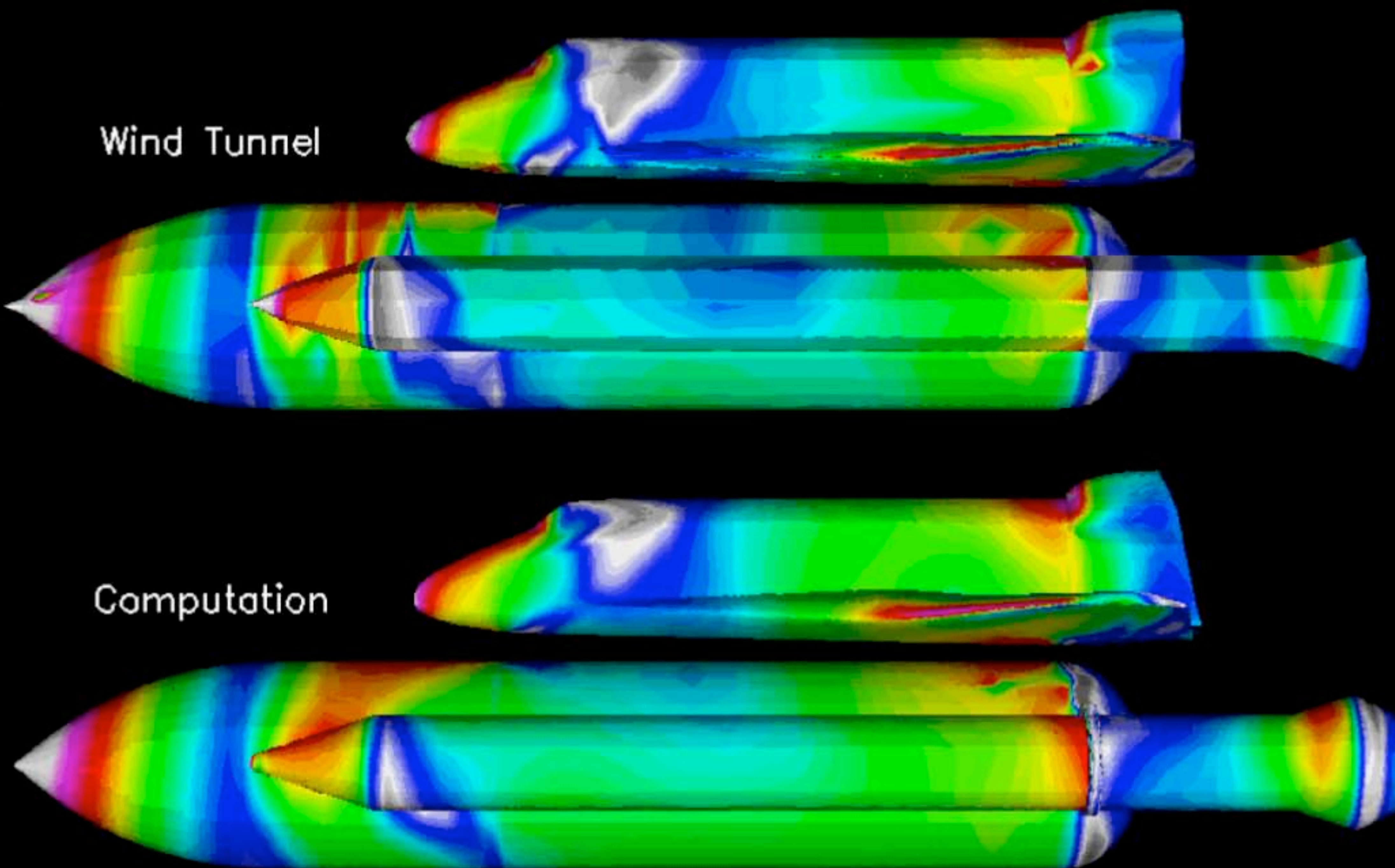


STS ASCENT CONFIGURATION

COMPARISON OF PRESSURE COEFFICIENT

IA105A Wind Tunnel Test with F3D/Chimera Navier–Stokes Solver

Mach 1.05
Alpha –3 deg
Re 2.5×10^{6}/ft
(3% model)



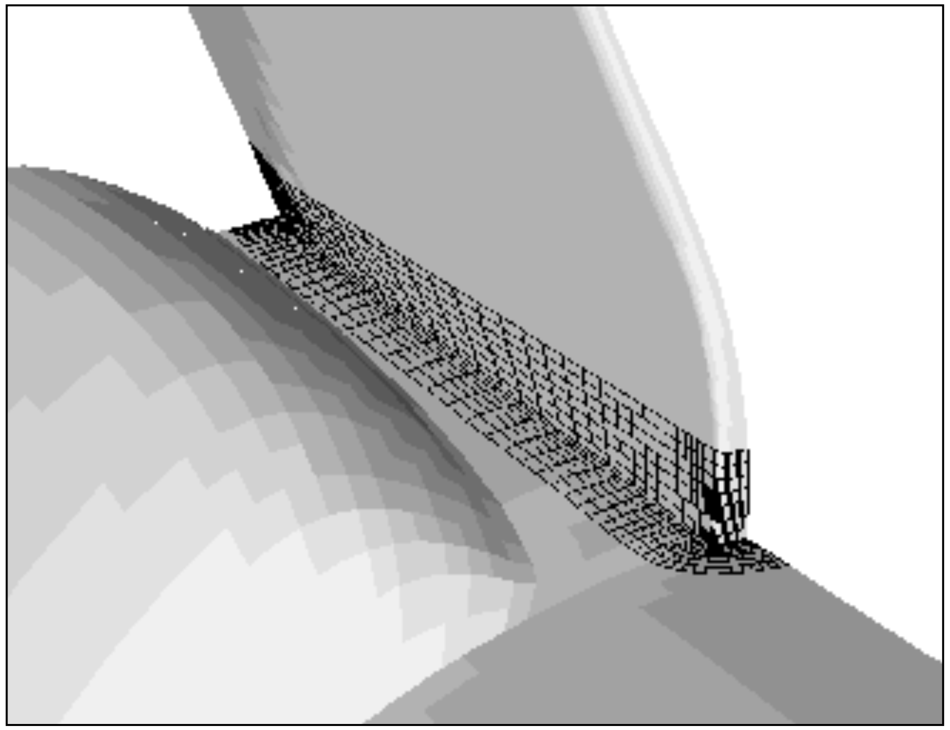
NASA JSC Space Shuttle Flow Simulation Group

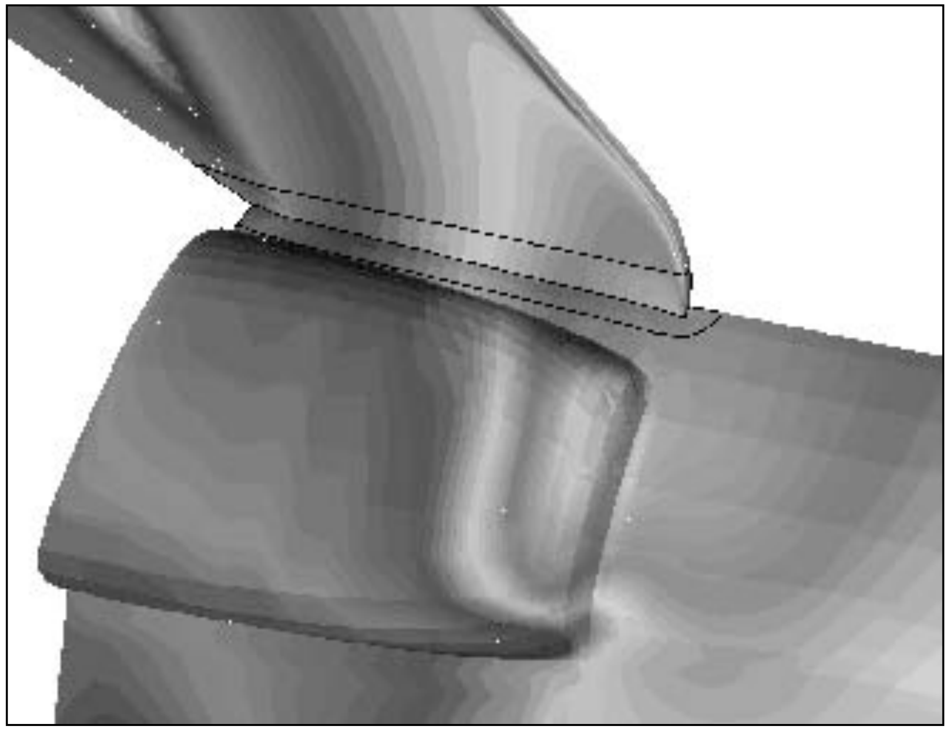
PRELIMINARY

3/3/90

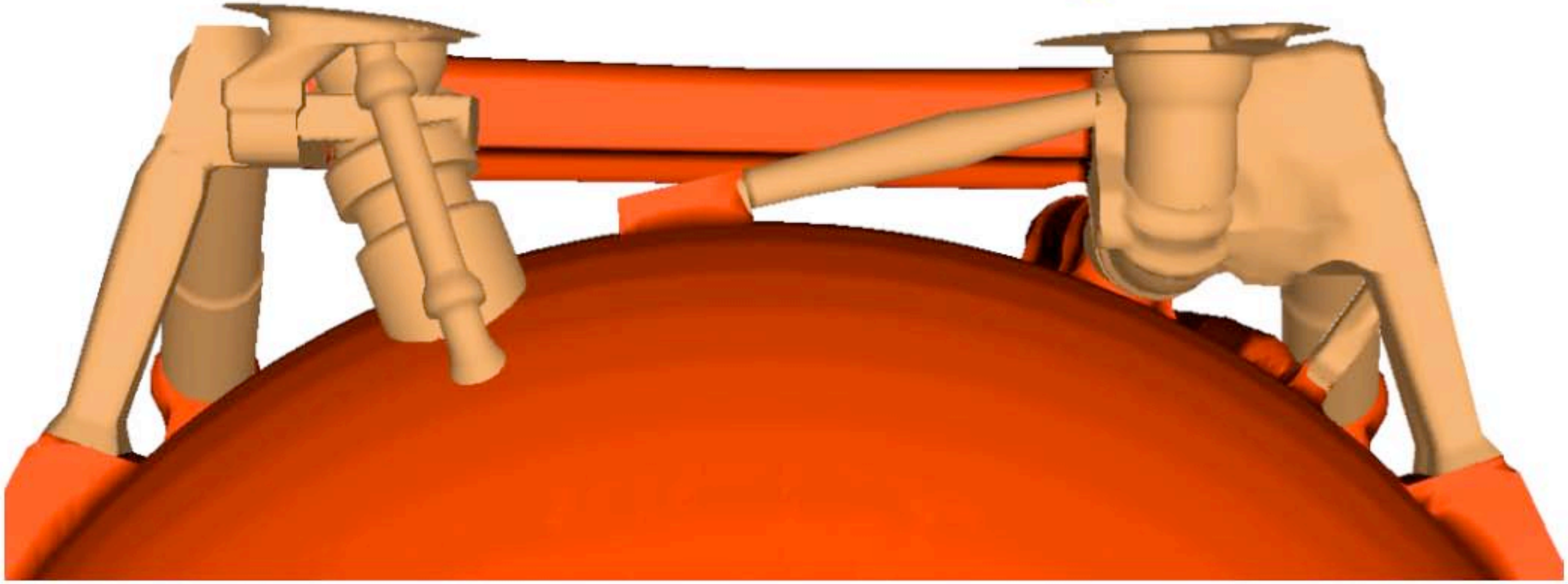
Collar Grids, Improved Geometric Fidelity

- Steve Parks, Collar Grid Tools (AIAA-91-1587)
  - Intersection lines, hyperbolic surface grid generation, surface projection
  - Orbiter vertical tail
  - Orbiter aft bulkhead (OMS pods, SSME’s)
  - Orbiter/ET attach hardware
  - ET/SRB attach hardware

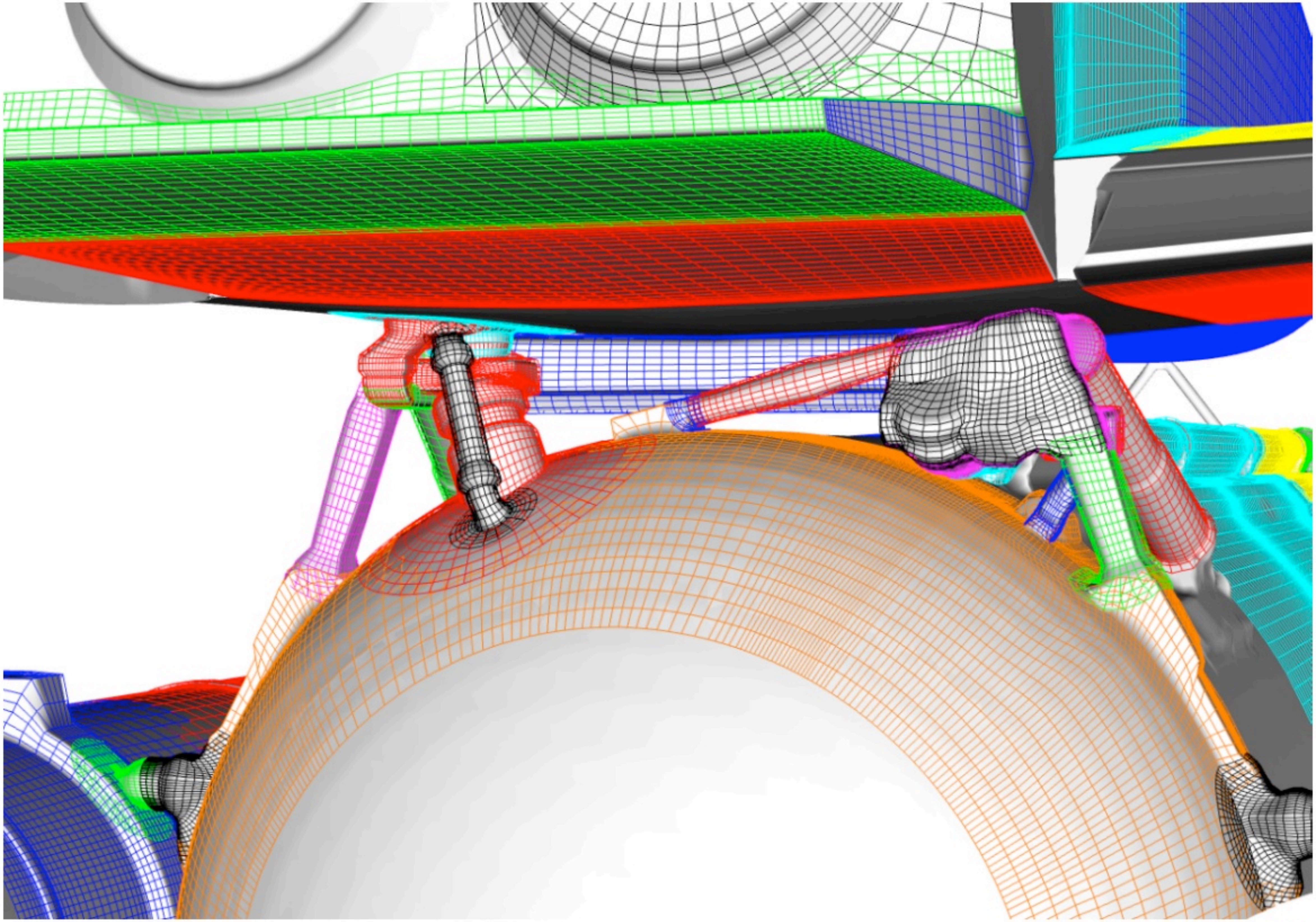




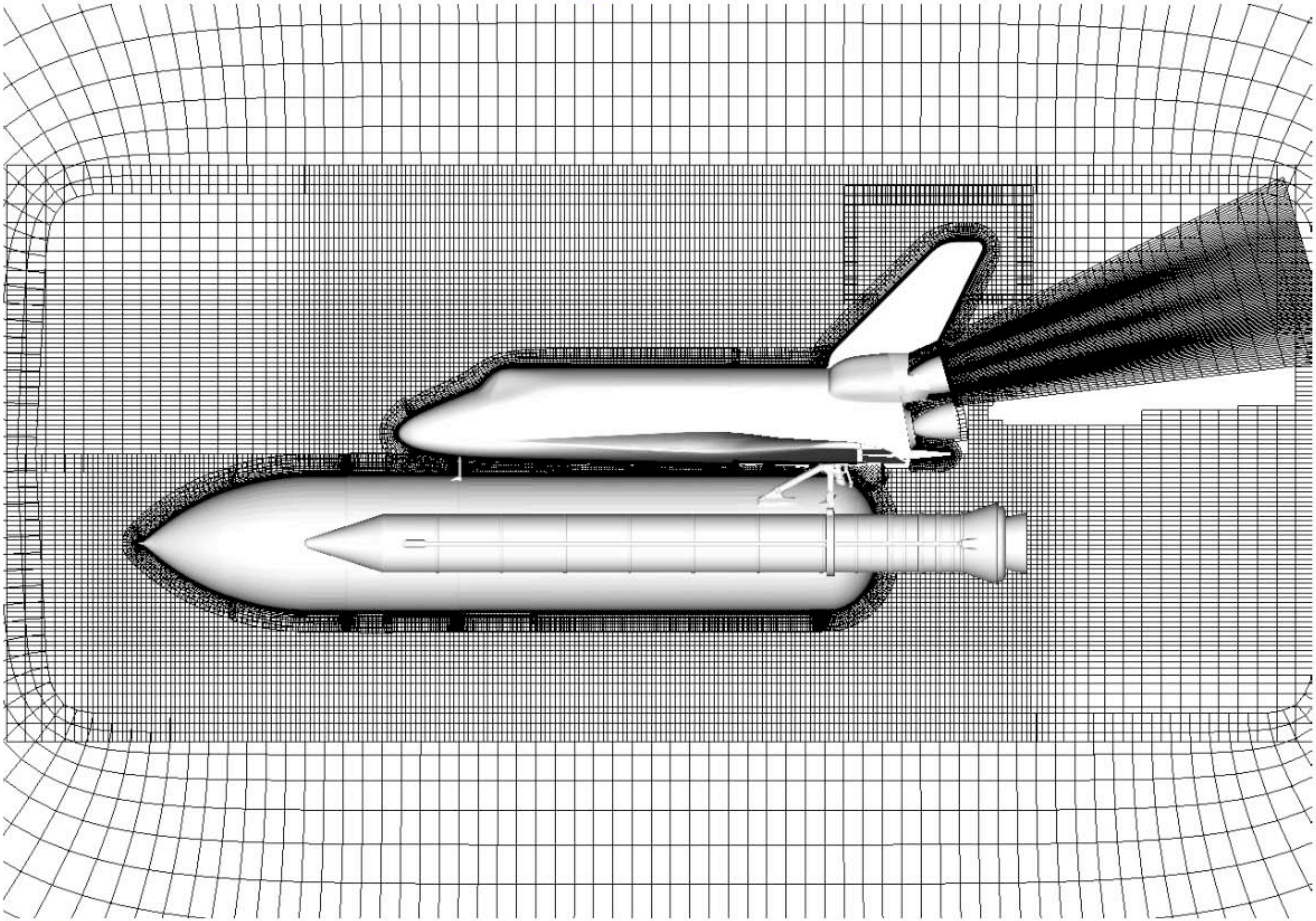
New Aft Attach Model vs Flight Hardware



Surface Grid Topology of Aft Attach Region



Domain Decomposition of Volume

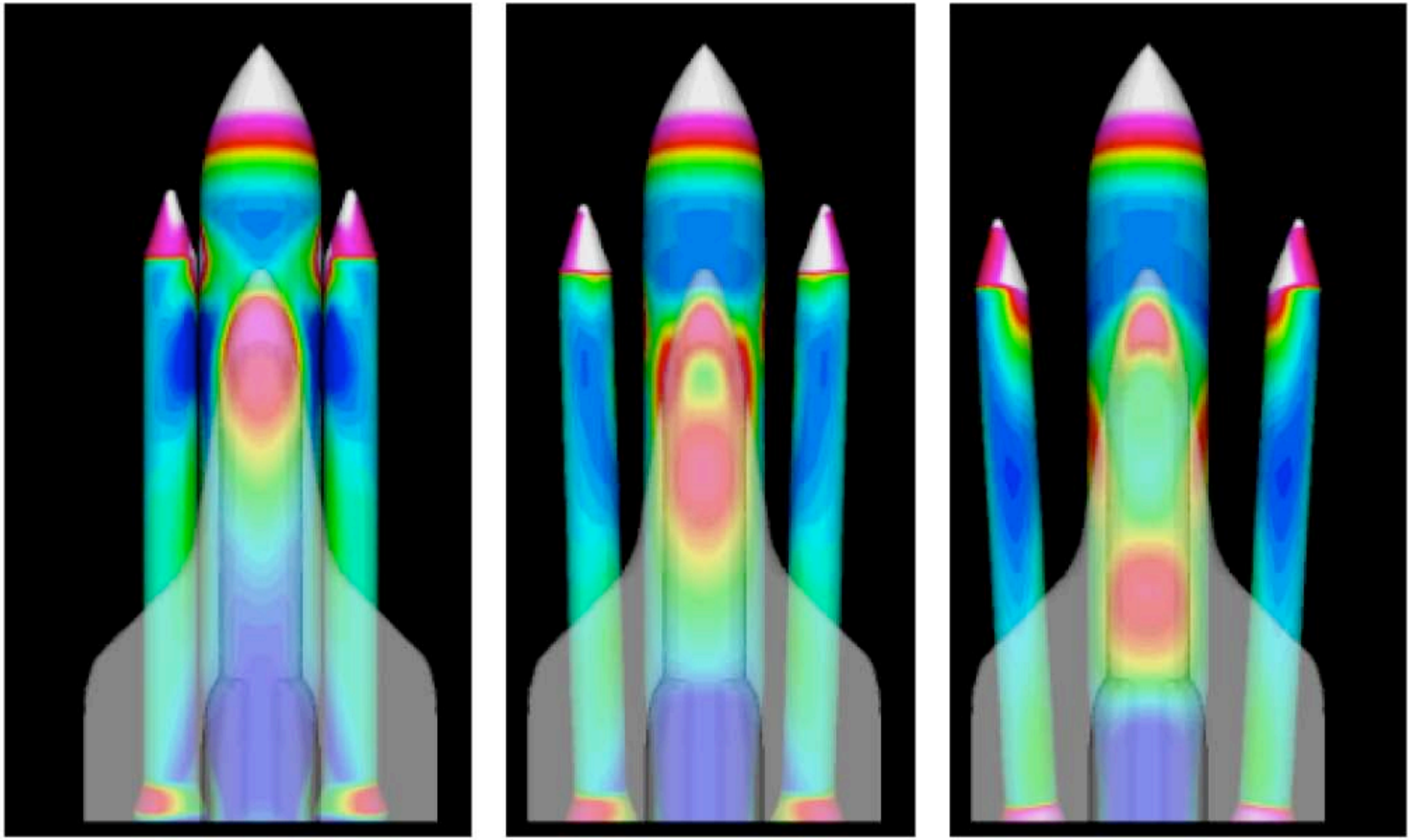


Moving Grid Development

- Original 2D store separation work
  - Carroll Dougherty, Jack Benek, Joe Steger, NASA TM 88193 (1985)
- Modification of PEGSUS for moving body problems
  - Bob Meakin and Norm Suhs (AEDC), AIAA-89-1996
- Development of DCF3D
  - Bob Meakin, Ing-Tsau Chiu, AIAA-91-1586, 95-0854
- Cartesian off-body grid generation and adaption
  - Bob Meakin, AIAA-95-1722
- Much further development including X-ray hole cutting and OVERFLOW-D
  - Bob Meakin et al., through the Army Rotorcraft CFD group

SRB Separation Sequence, Mach 4.5

3 grids, 350K points, 500 time-steps
(from Meakin and Suhs, AIAA-89-1996)



t = 0.0 sec   t = 0.34 sec   t = 0.68 sec

State-of-the-Art, ca. 1994

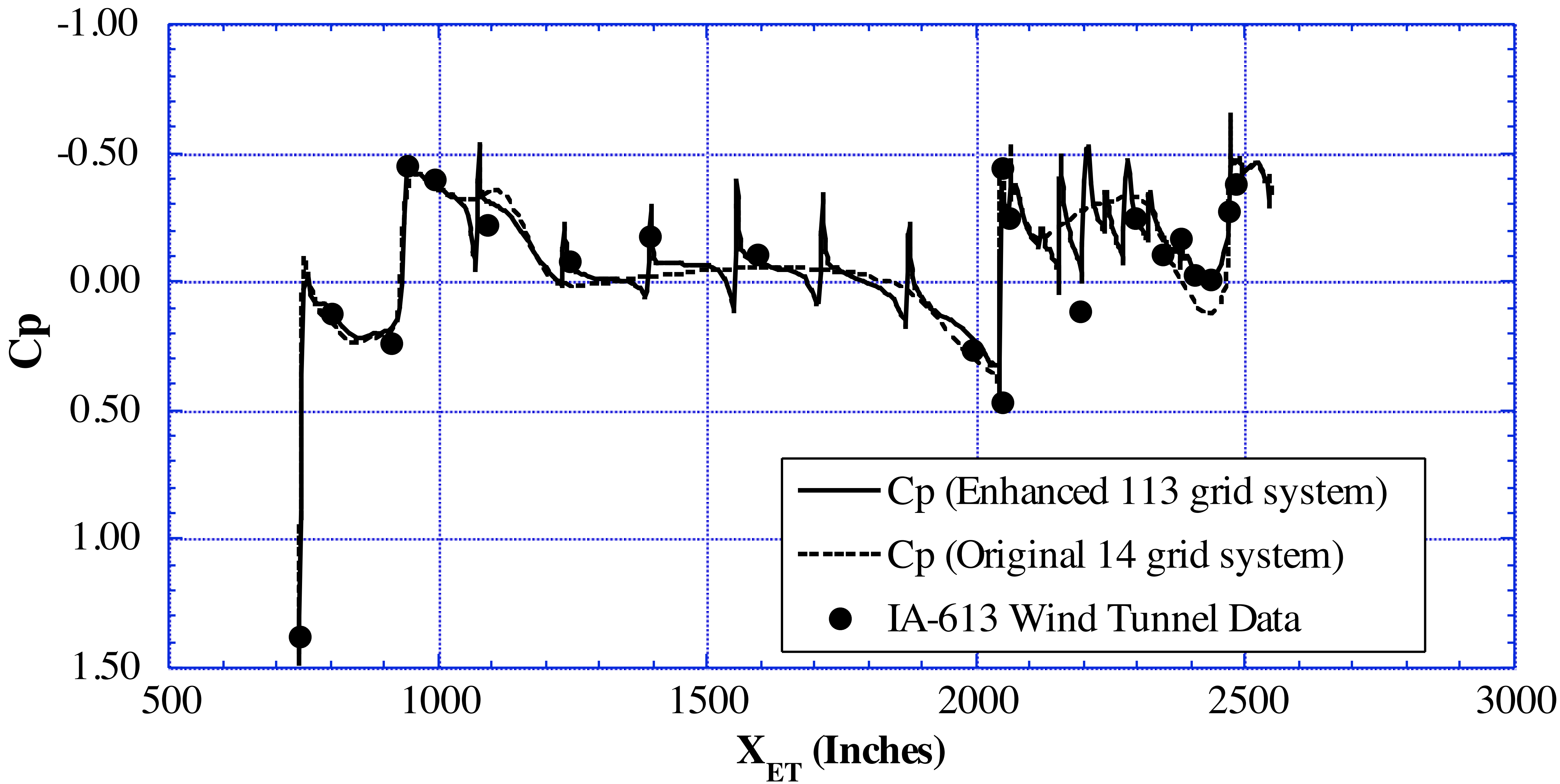
- Surface and volume grid generation
  - HYPGEN/HGUI William Chan, Joe Steger, Ing-Tsau Chiu, AIAA-91-1588
  - Collar Grid Tools Steve Parks, Buning, Chan, Steger, AIAA-91-1587
  - SURGRD William Chan, AIAA-94-2208
- Overset grid assembly
  - DCF3D Bob Meakin, Ing-Tsau Chiu, AIAA-91-1586, 95-0854
  - PEGSUS 4.0 Norm Suhs, Bob Tramel, AEDC-TR-91-8
  - PEGSUS 4.1 Ing-Tsau Chiu, Pieter Buning, 1991-2000
- Flow Solver
  - OVERFLOW Pieter Buning, Renze, Slotnick, Kandula et al., AIAA-92-0437, 93-0521, 94-2357
  - OVERFLOW-D Bob Meakin, Wissink, Potsdam, Chan, AIAA-2001-0593
- Post-processing
  - FOMOCO William Chan, AIAA-95-1681

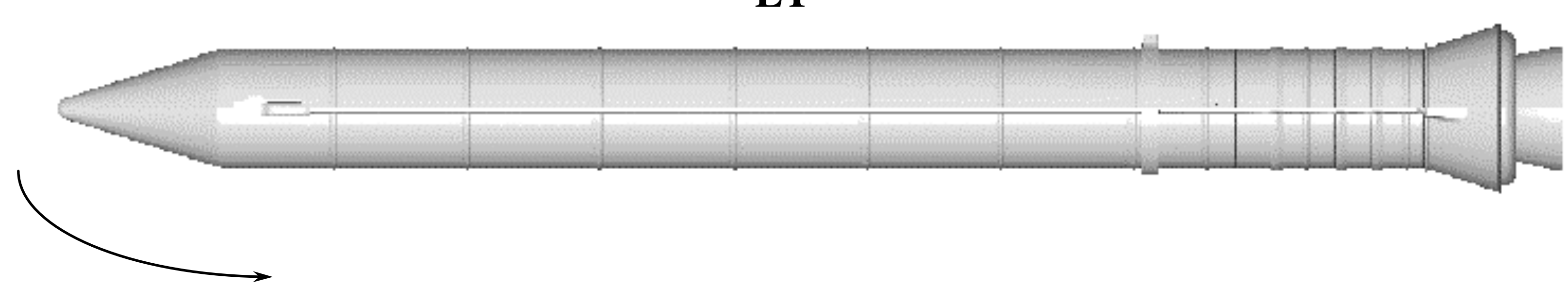
Flow Solver and Computer Time

Date	Code & computer improvements	Speed up	Date	Grid Size, number of steps	Increase
1987	F3D, Cray 2 (1 proc)	1	1987	¼ Mpts, 850 steps	1
1990	Cray Y-MP (1 proc)	2	1989	¾ Mpts	3
1991	OVERFLOW (Pulliam-Chaussee diag)	3	1991	1.6 Mpts	2
1992	Cray Y-MP (5/8 proc)	5	1993	3000 steps (flight Re, plumes)	3.5
1994	Cray C-90 (7/16 proc)	3.5			
1994	OVERFLOW time-step improvement	2	1994	16 Mpts	10
		200x			200x

Solid Rocket Booster Surface Pressures

Φ = 0°, Mach 1.25, WT Re((Gomez & Ma, AIAA-94-1859)

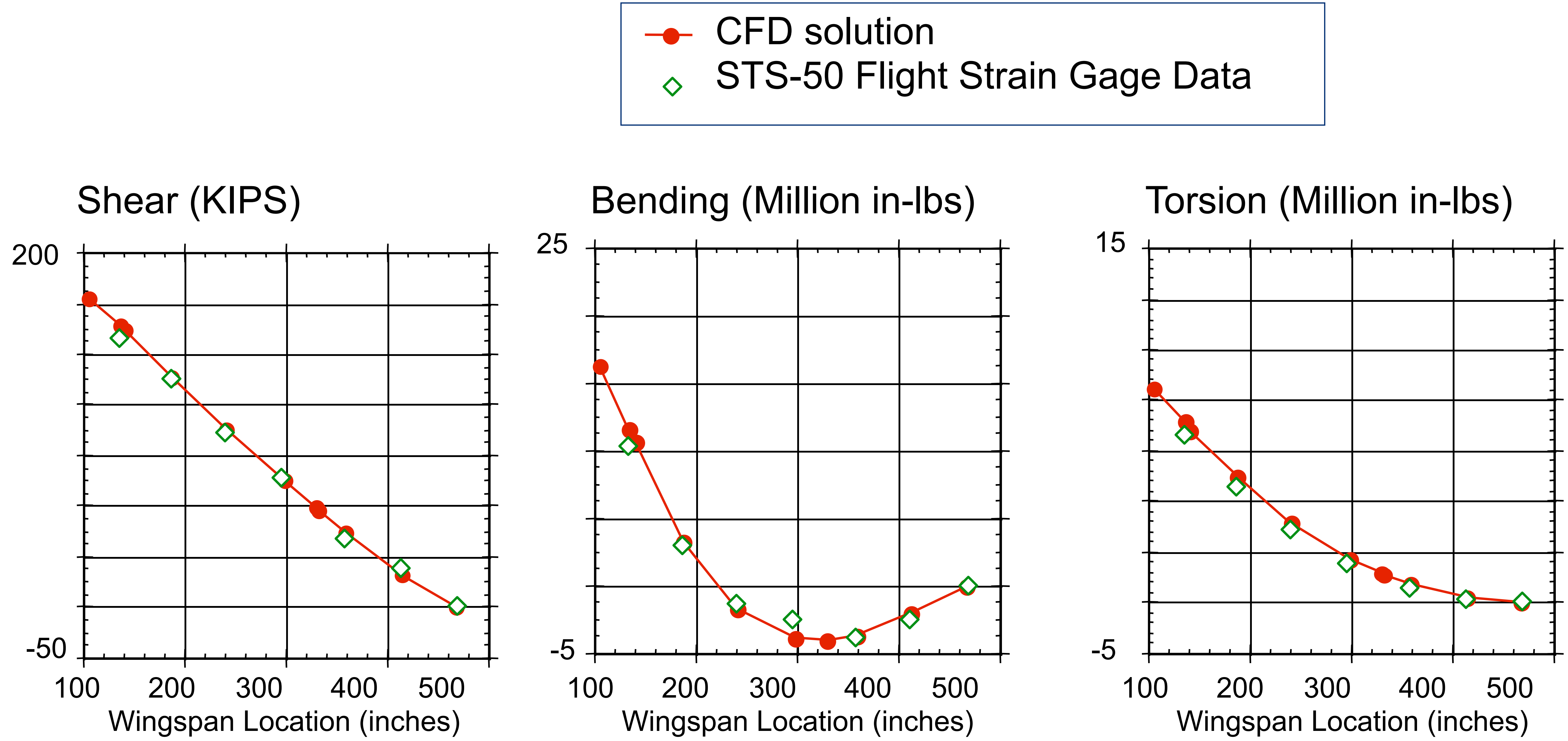


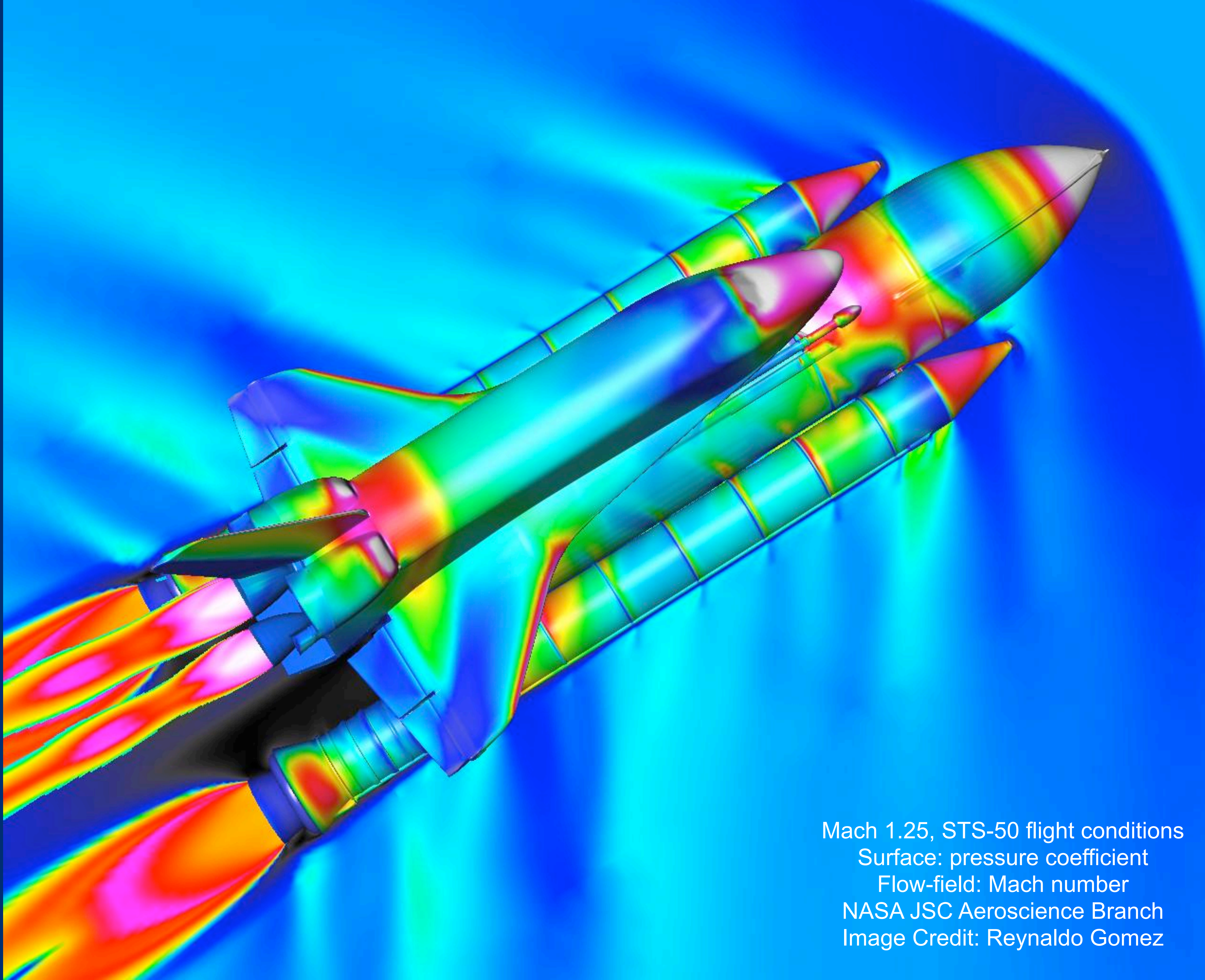


Flight Orbiter Wing Loads (Left Wing)

Mach 1.25, Flight Re

(Slotnick, Kandula, Buning, AIAA-94-1860)

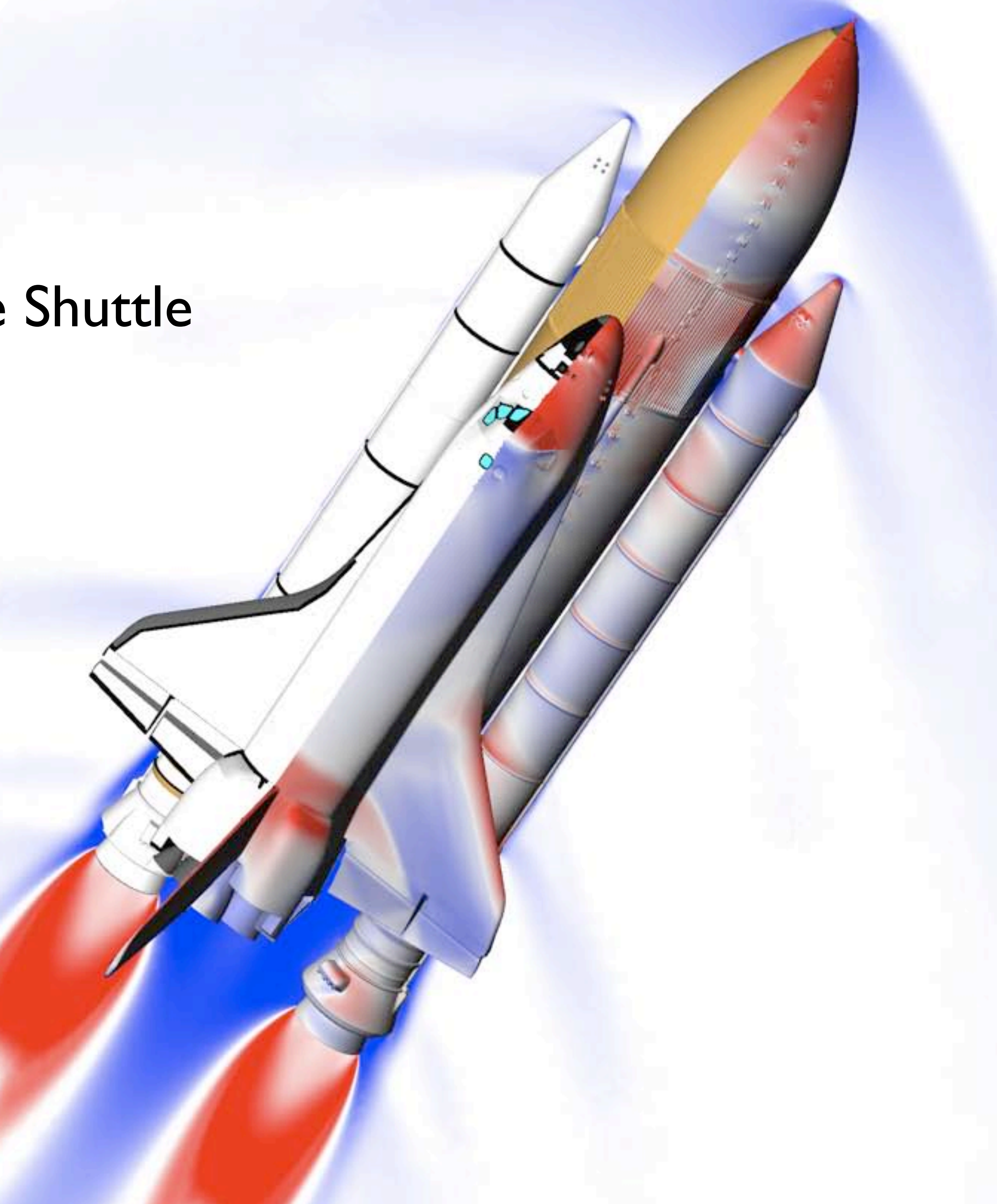




Mach 1.25, STS-50 flight conditions
Surface: pressure coefficient
Flow-field: Mach number
NASA JSC Aeroscience Branch
Image Credit: Reynaldo Gomez

20+ Years of Chimera Grid Development for the Space Shuttle

STS-107, Return To Flight, End of the Program



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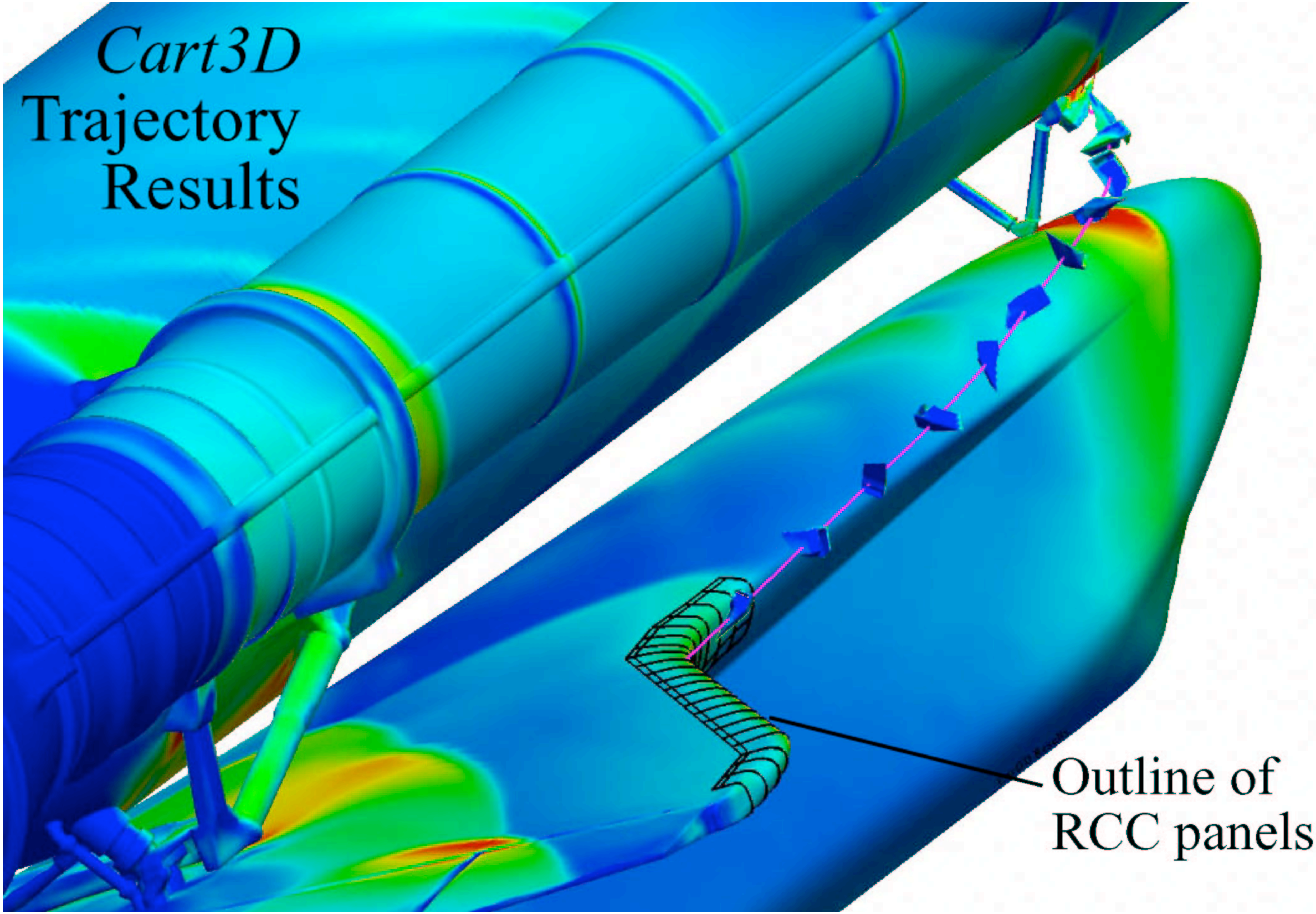
NASA Johnson Space Center
Houston, Texas
September 2010

STS-107 Debris AIAA 2005-1223



The loss of STS-107 initiated an unprecedented detailed review of all external environments.

Ascent **airloads**, acoustics, **heating**

Debris liberation, **transport** and capability assessments.

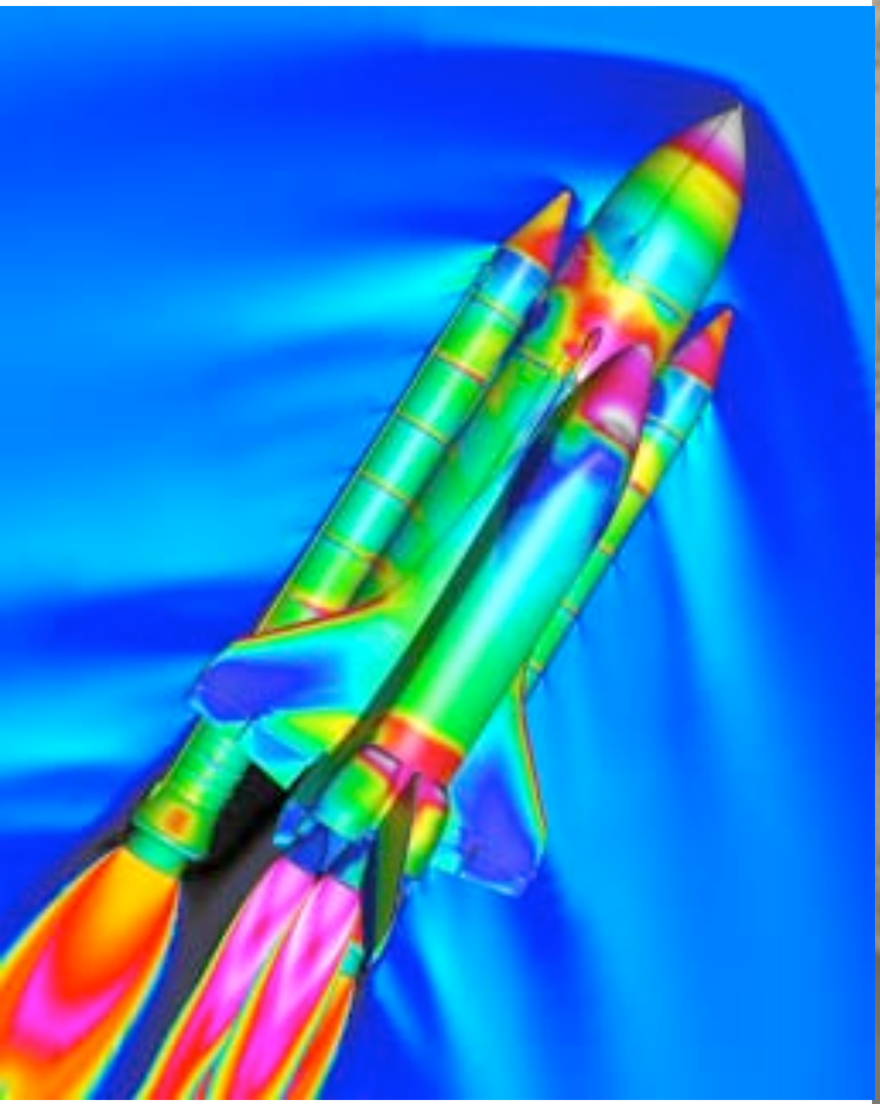
Bipod redesign assessments.

Greatly increased emphasis on verification & validation.

STS-114 and subsequent missions

- PAL ramp foam loss, additional redesign work.
- Prelaunch, inflight and postflight debris transport assessments.

Aerodynamic Tools

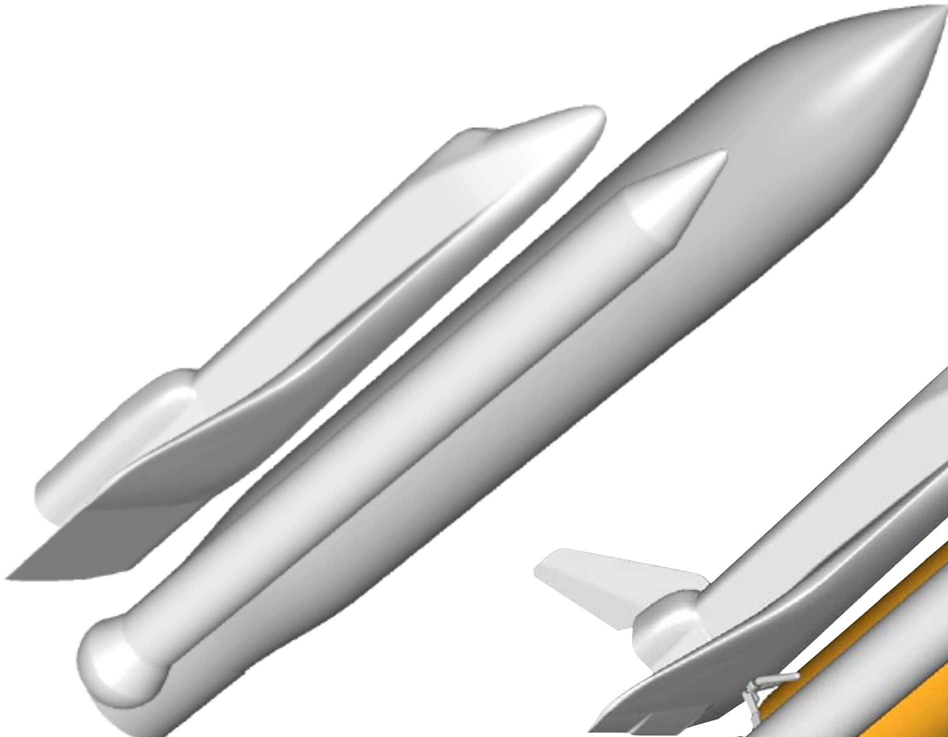


Modeling & Simulation

Ground Test

Flight Test

Space Shuttle Launch Vehicle (SSLV) Grid System Evolution

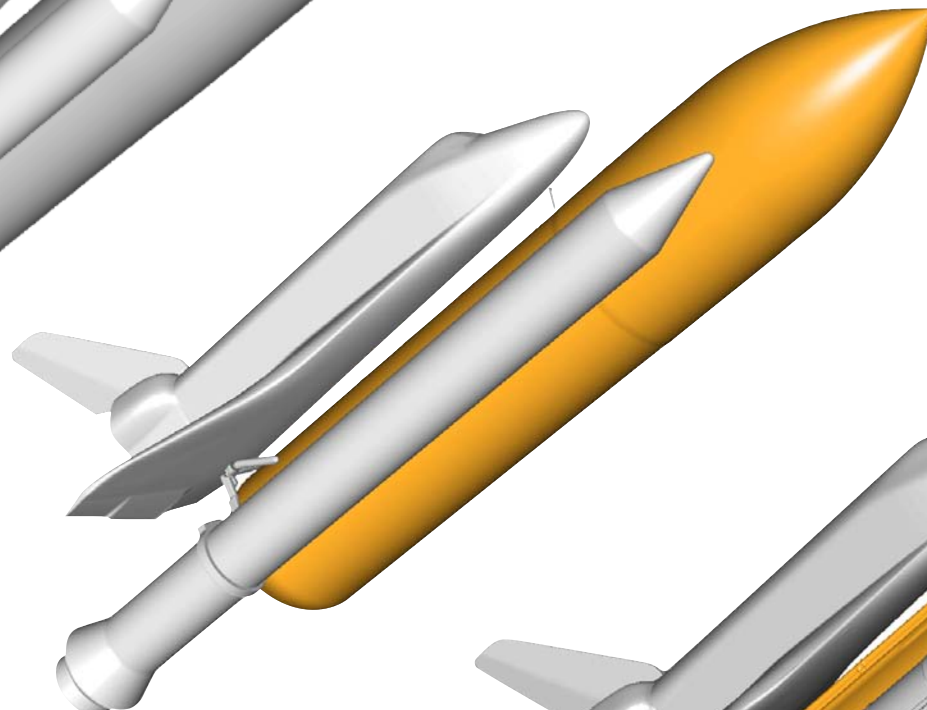


Early 80's grid system

3 Grids

10k surface points

0.3 million volume points

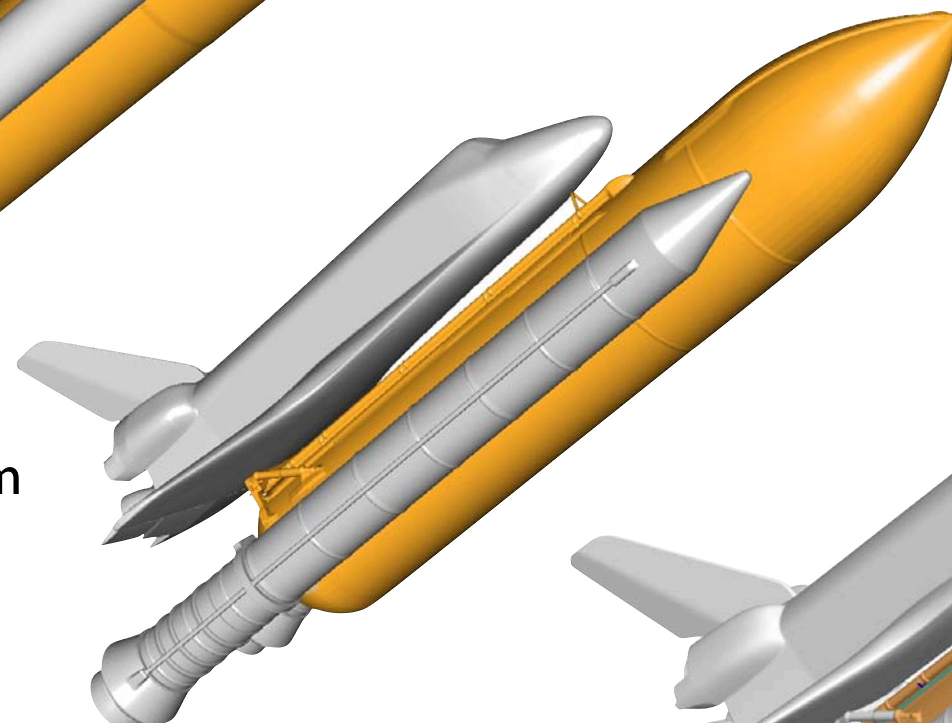


Late 80's grid system

14 Grids

35k surface points

1.6 million volume points

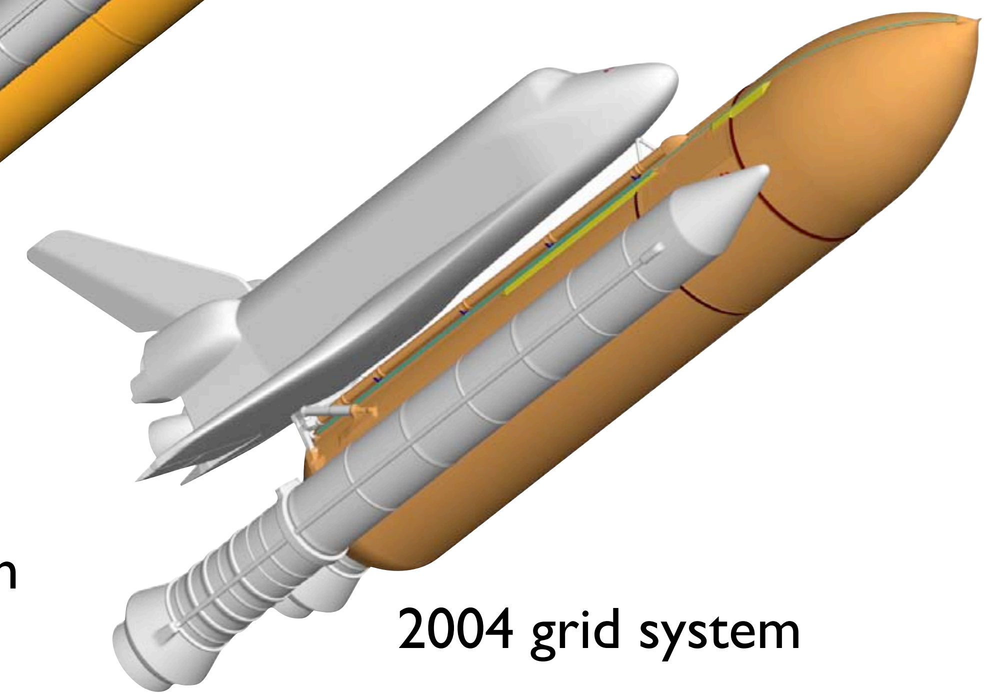


Early 90's grid system

113 Grids

268k surface points

16.4 million volume points



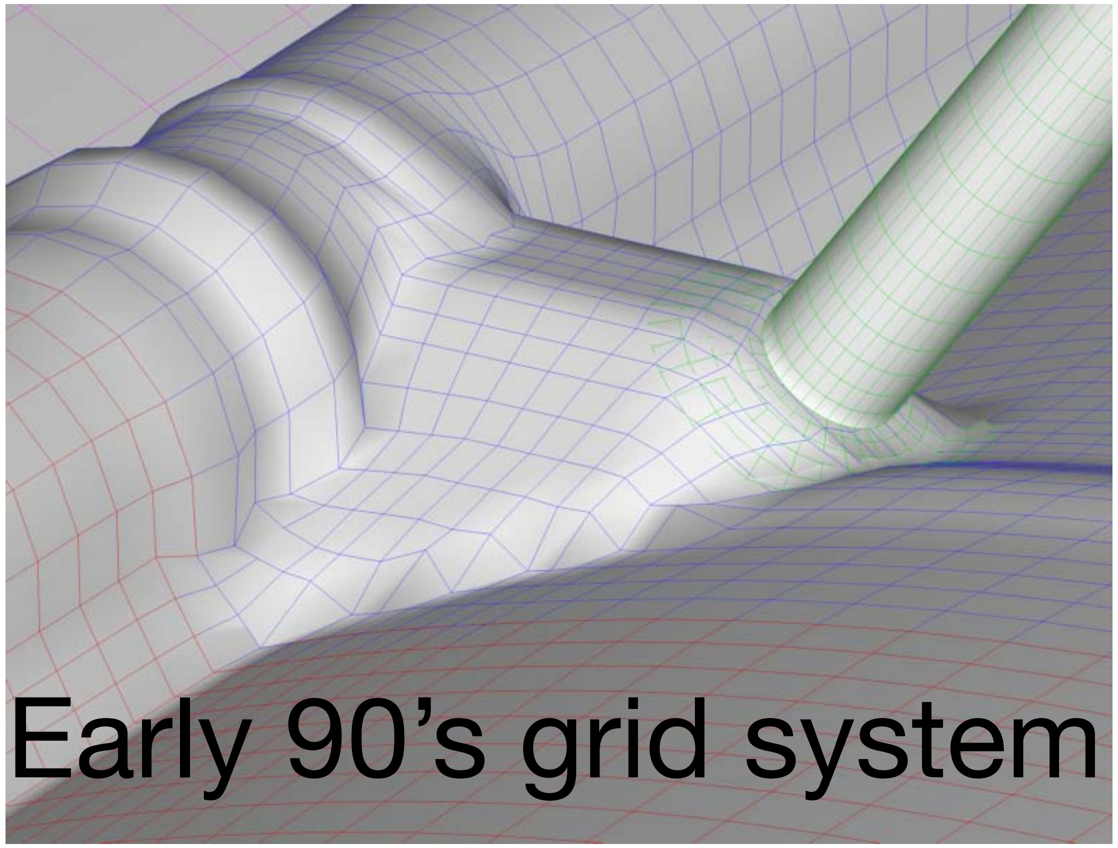
2004 grid system

267 Grids

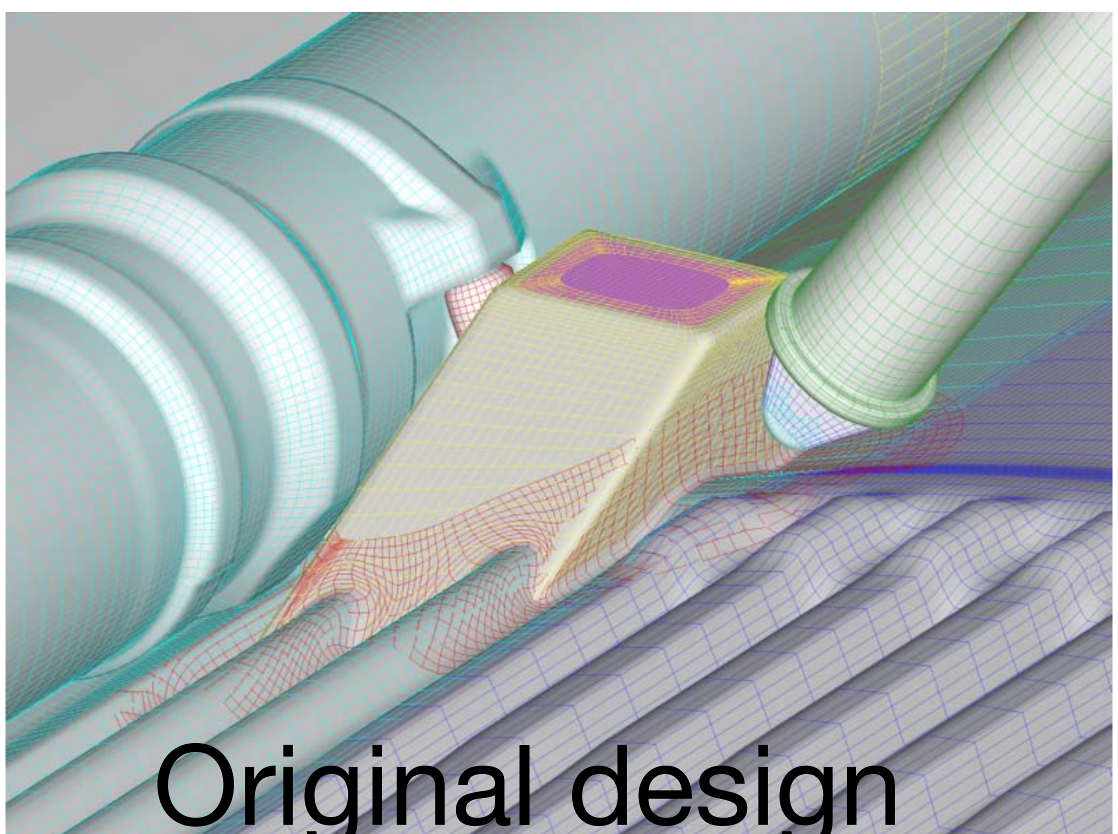
636k surface points

34.8 million volume points

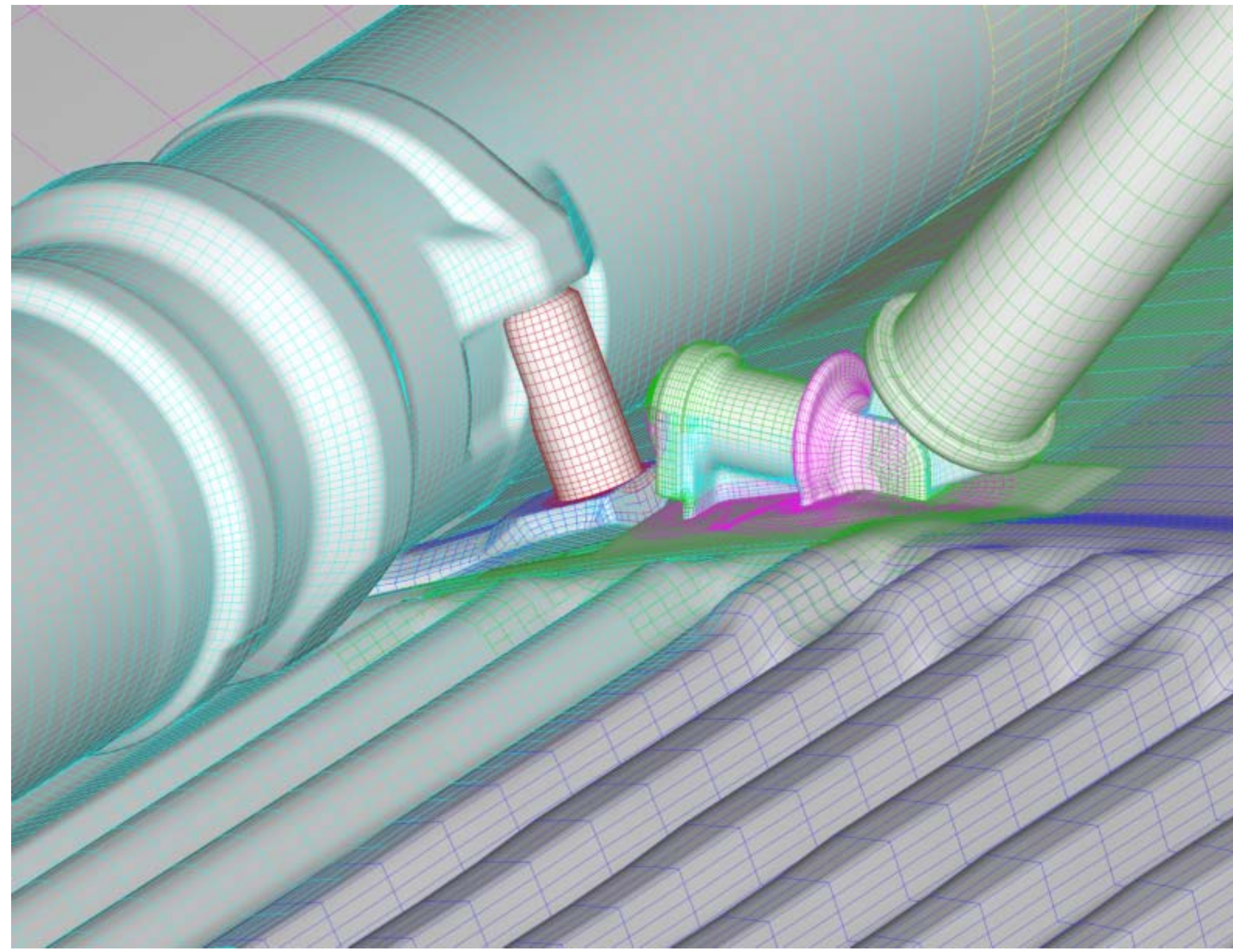
Bipod Ramp Redesign



Early 90’s grid system

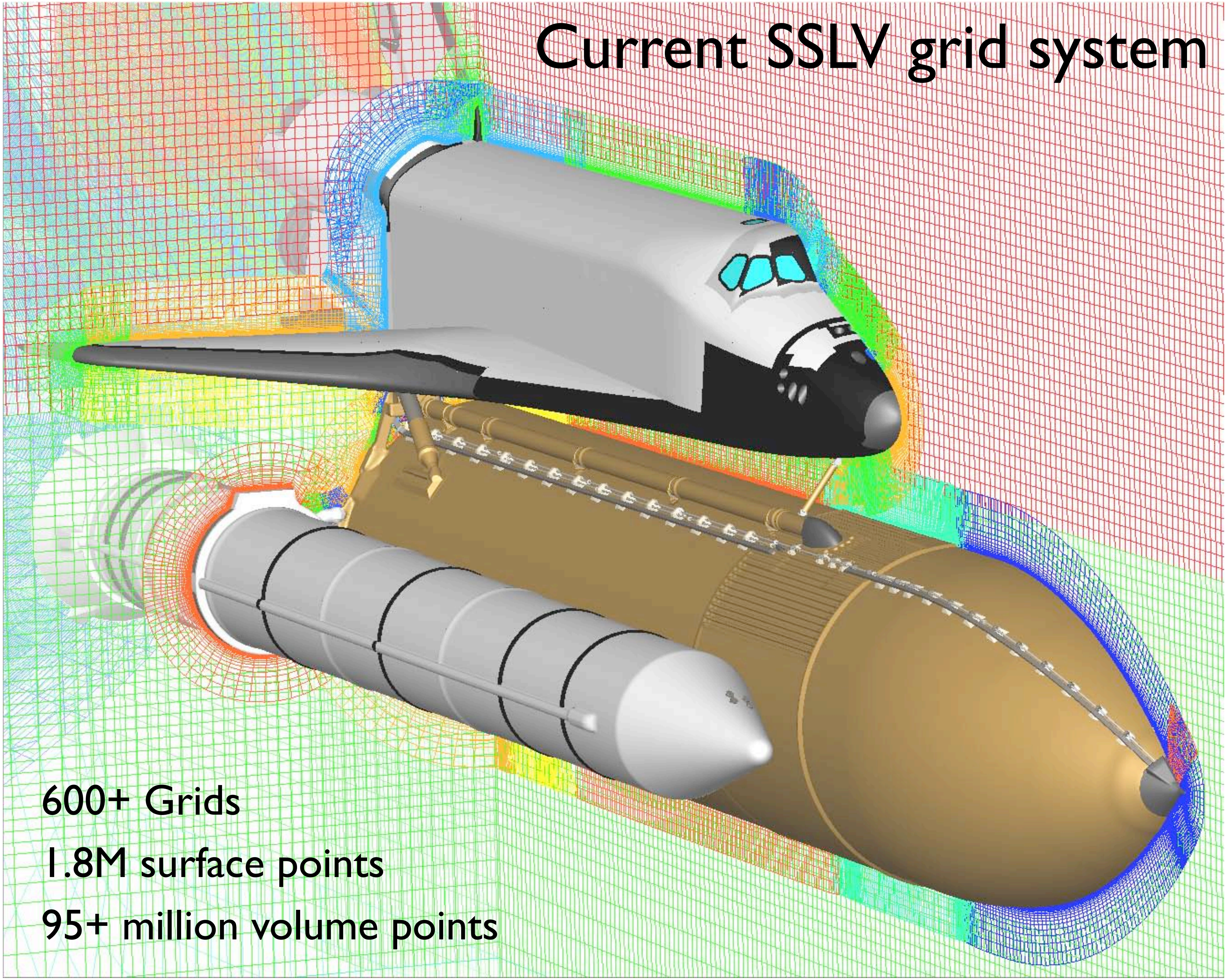


Original design



Current configuration

Current SSLV grid system

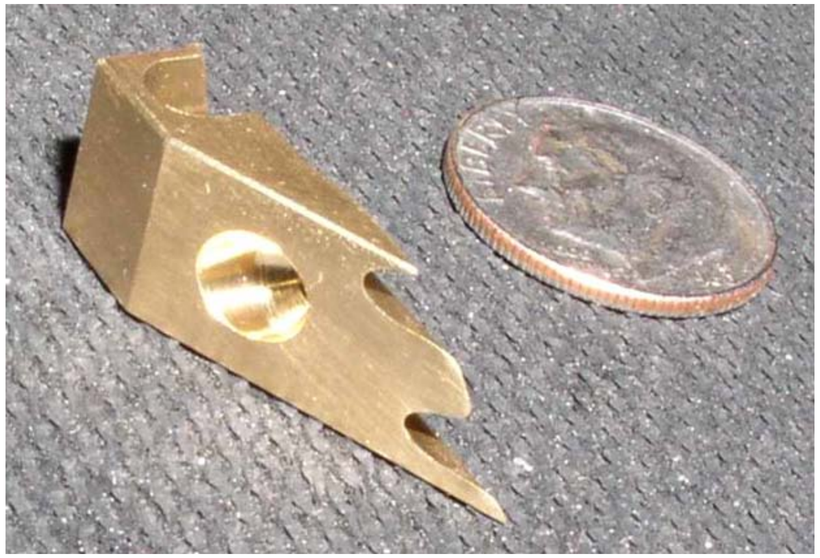


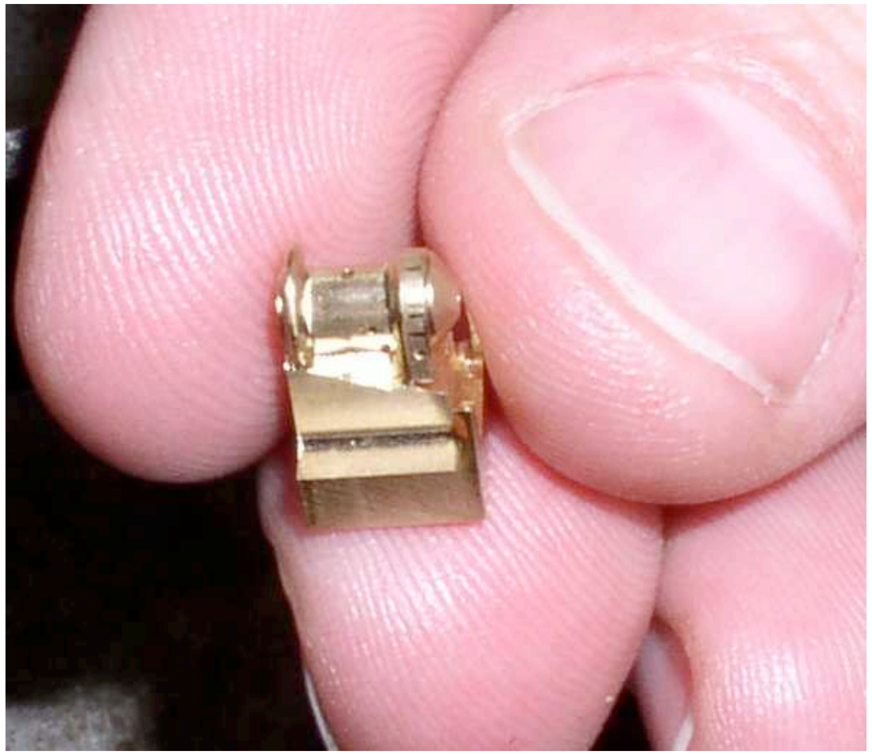
600+ Grids

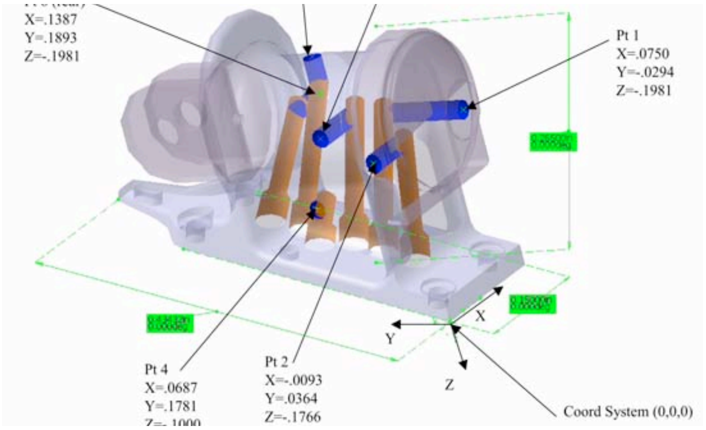
1.8M surface points

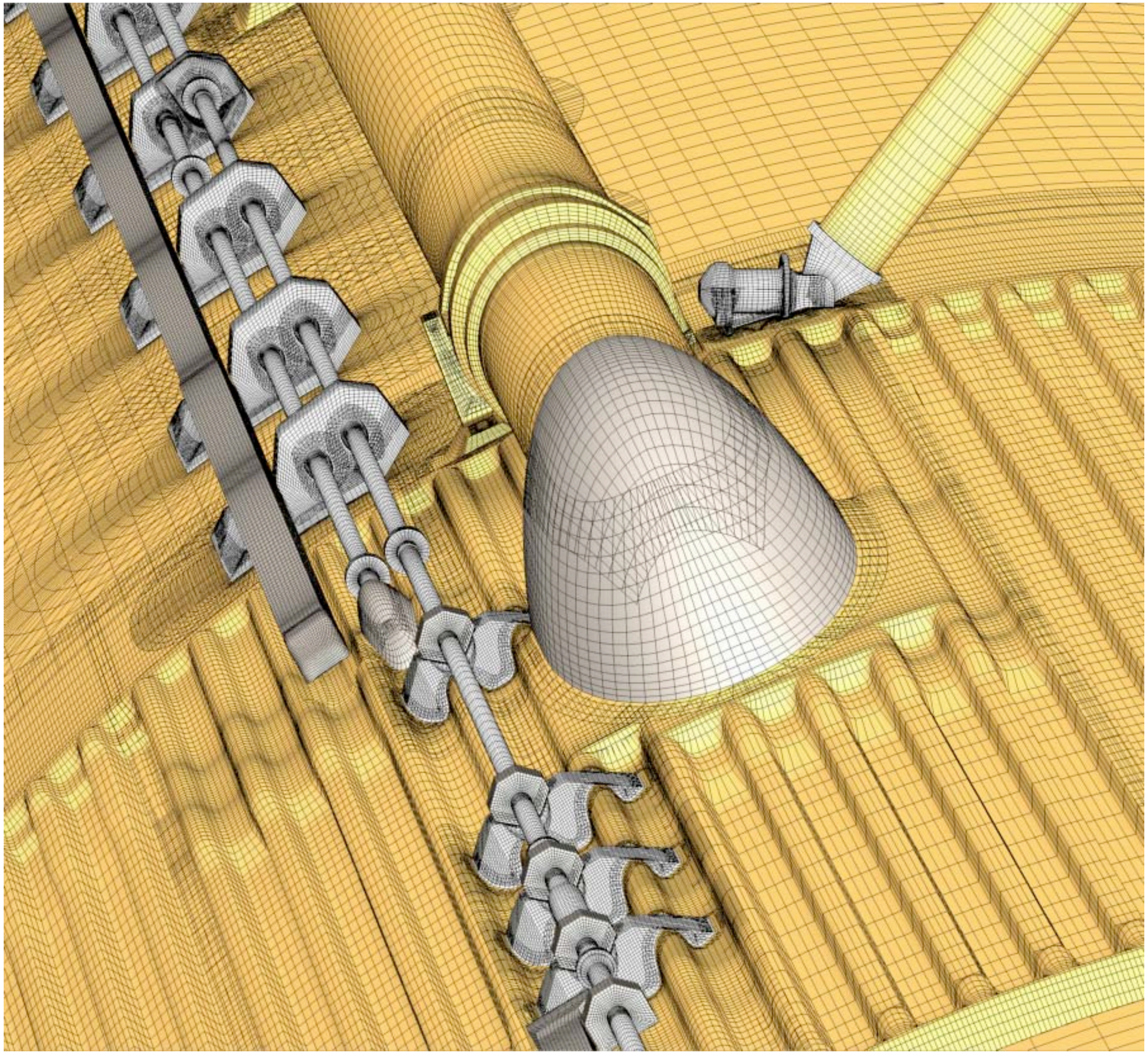
95+ million volume points

Wind tunnel validation and CFD extrapolation





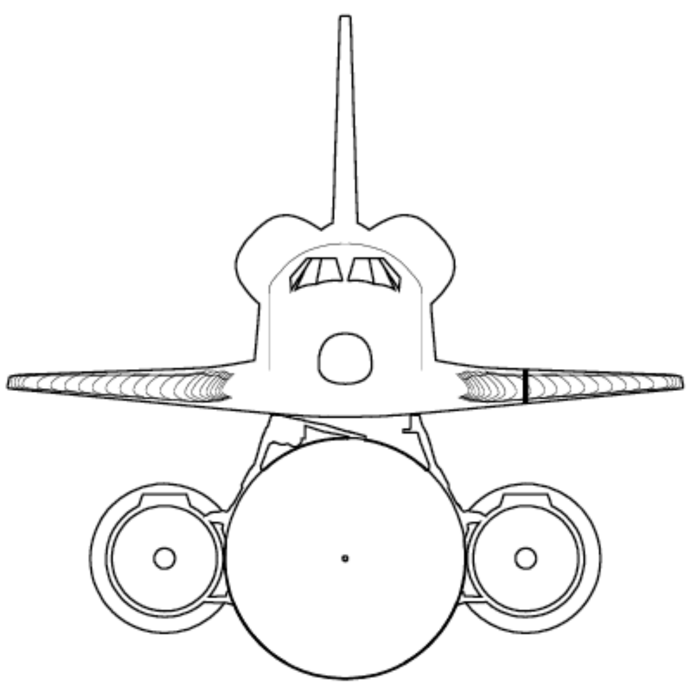


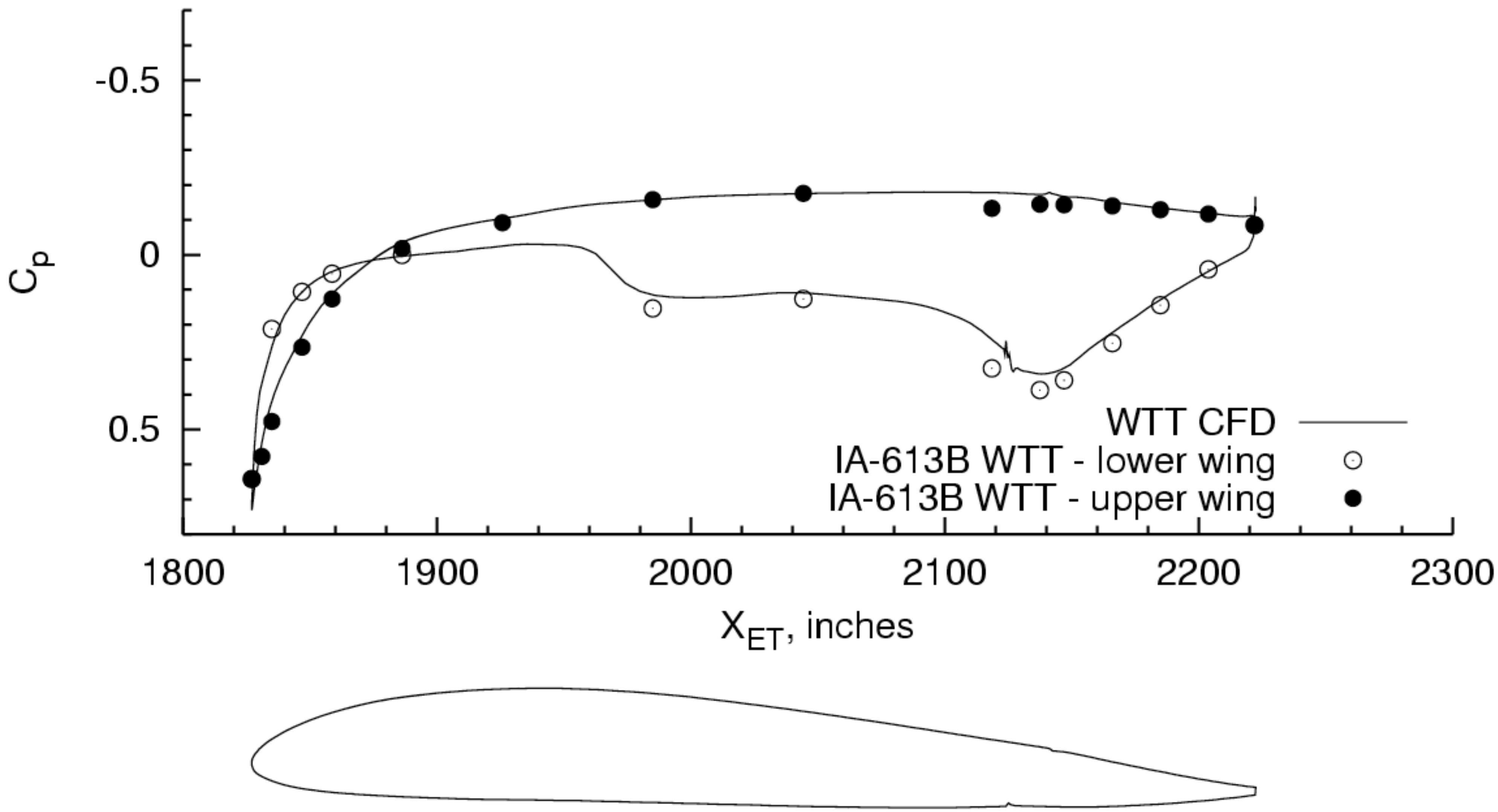


Previous wind tunnel comparisons focused on wing loads.

CFD conditions: $M_\infty = 2.50$, $\alpha = 2.03°$, $\beta = 0.00°$, Reynolds # = 2.50 $\times 10^6$/ft, IB elevon = 4.07°, OB elevon = -4.39°

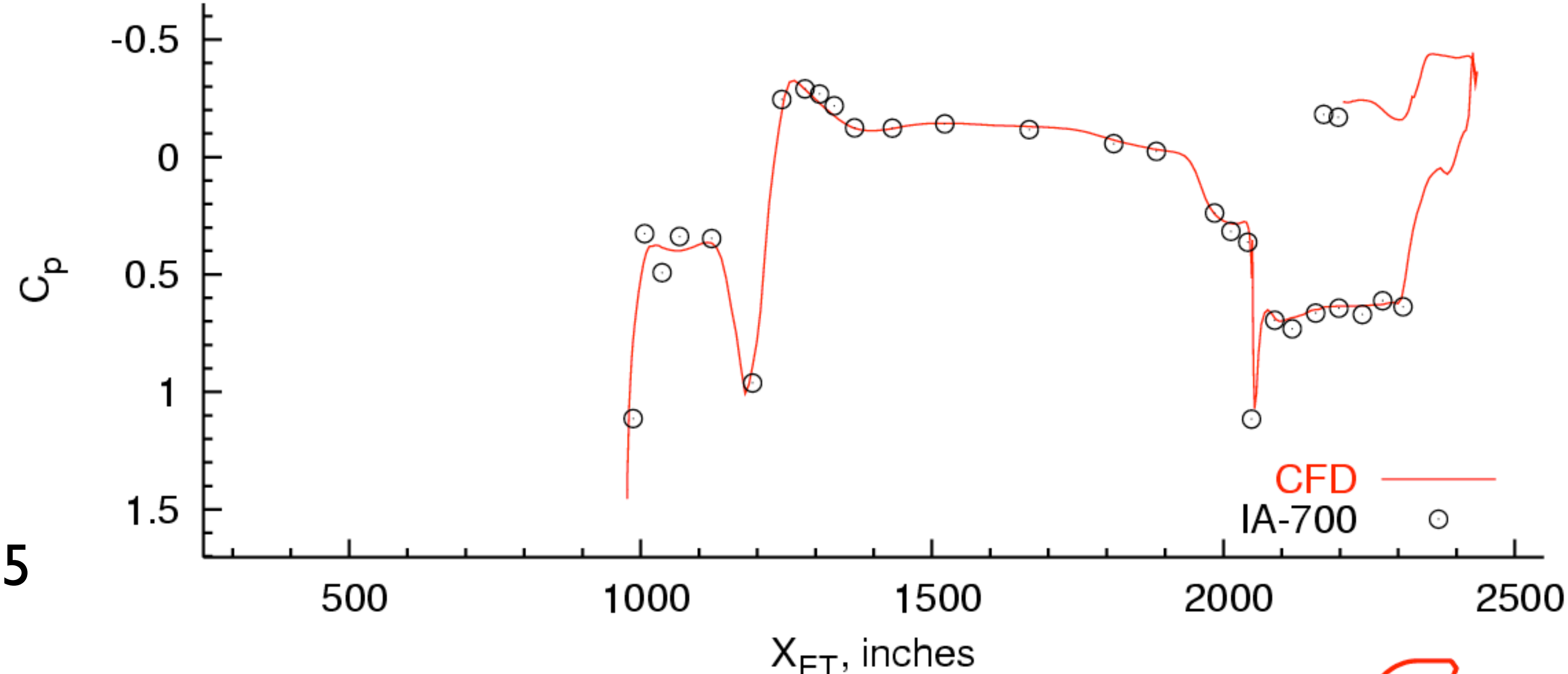
WTT conditions: $M_\infty = 2.50$, $\alpha = 2.03°$, $\beta = 0.00°$, Reynolds # = 2.50 $\times 10^6$/ft, IB elevon = 4.07°, OB elevon = -4.39°



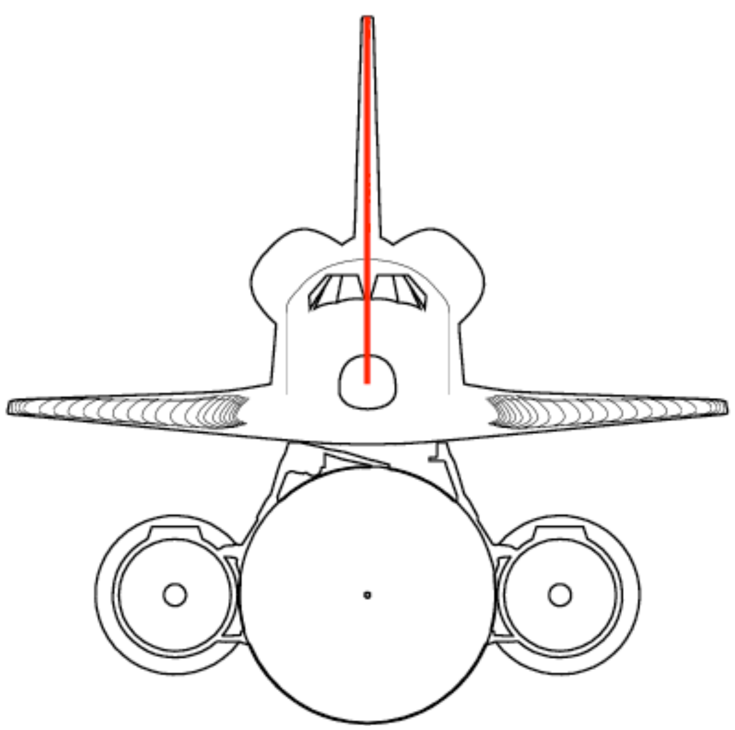


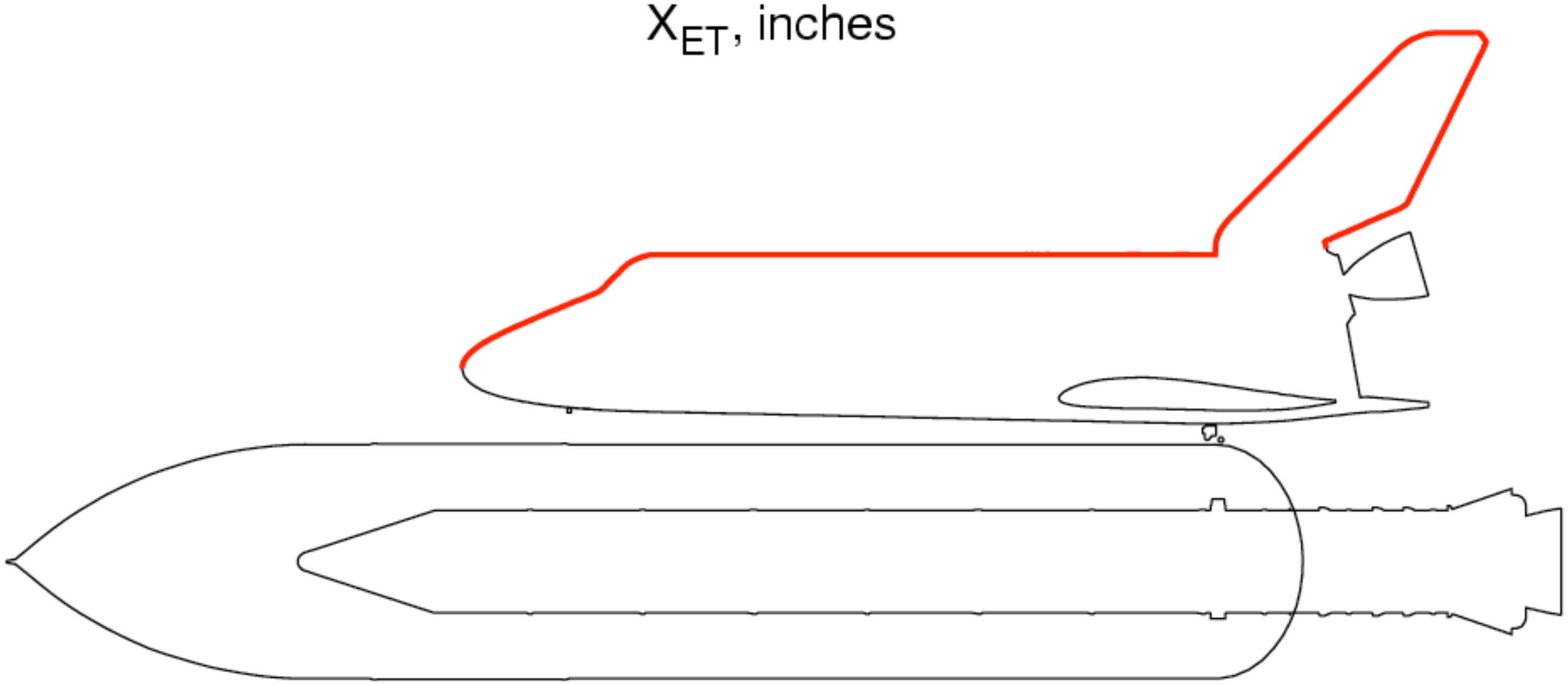
AIAA 2004-2226

Wind tunnel test pressure comparisons show good agreement with predictions

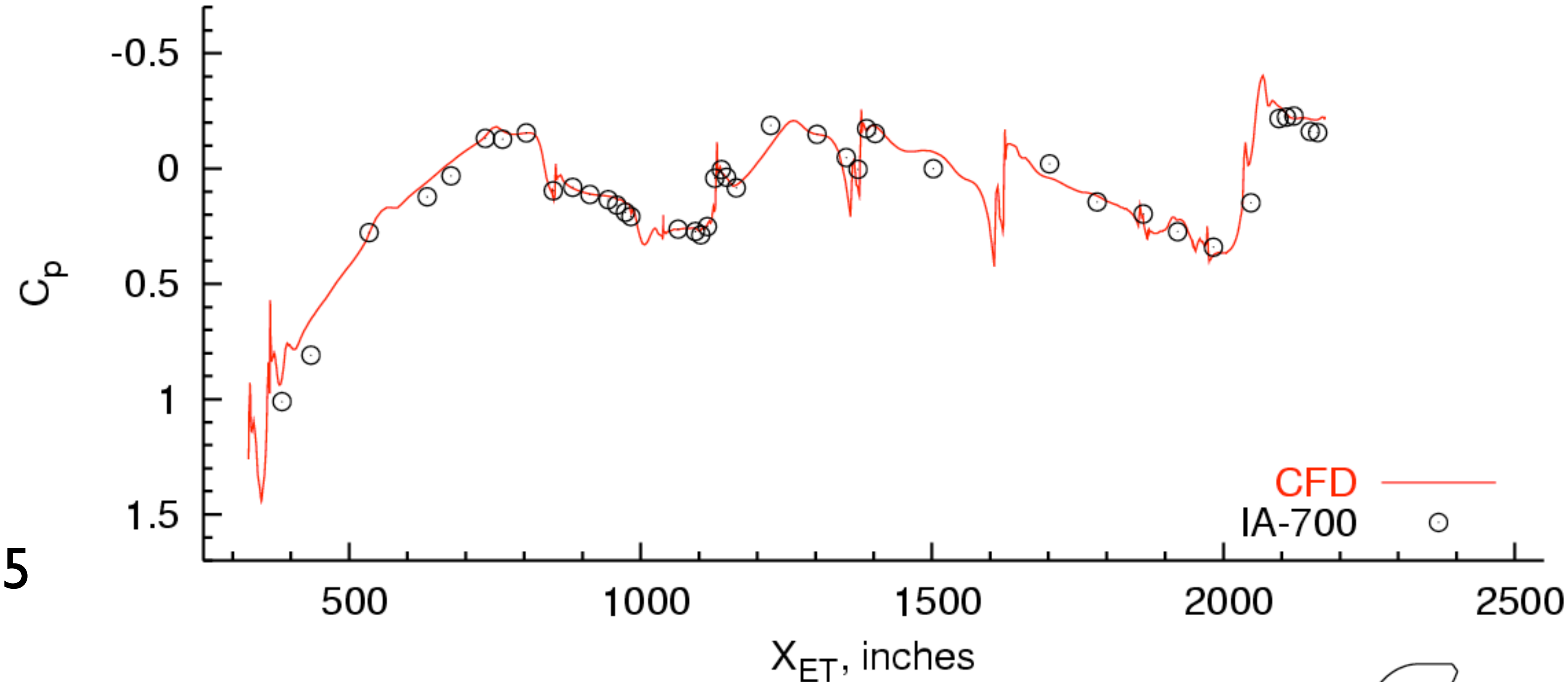


JSC 2005-62925

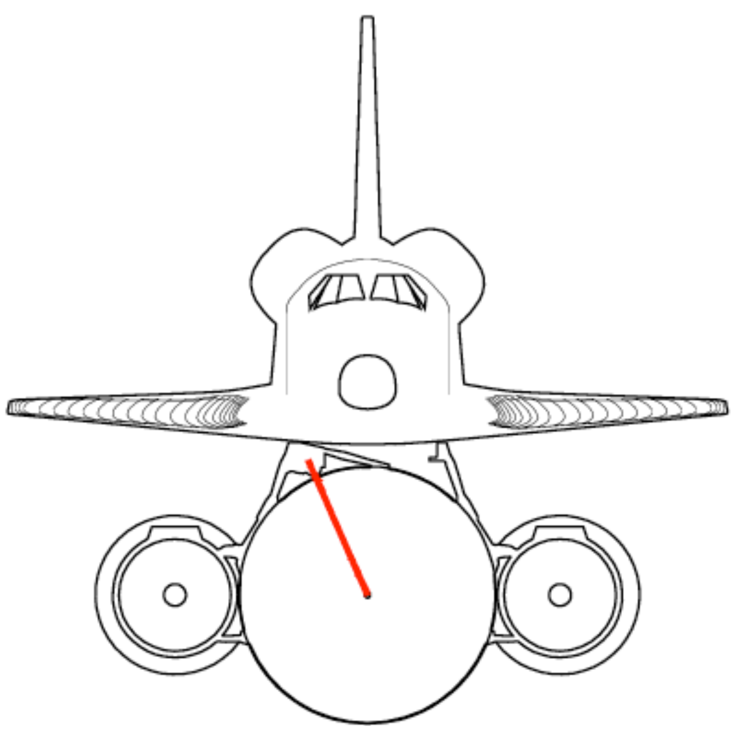


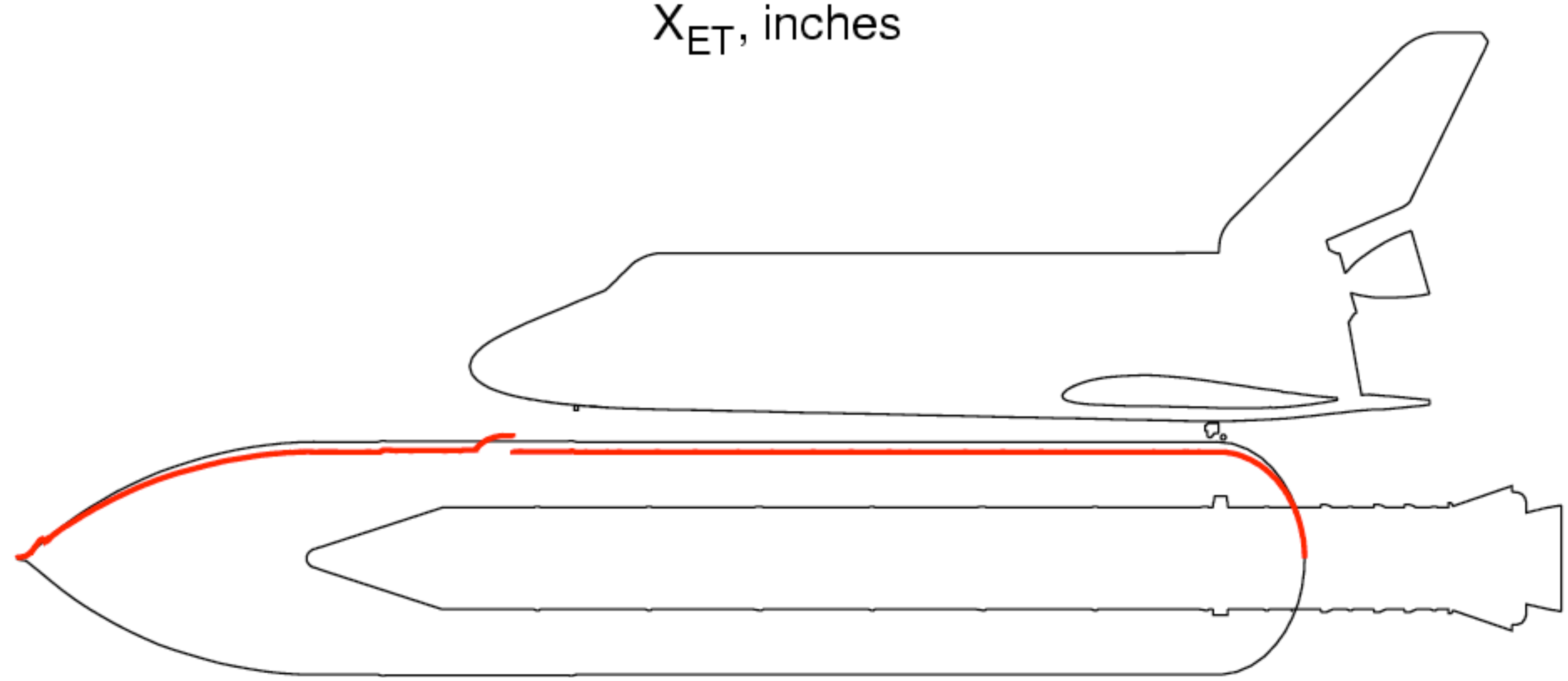


Detailed comparisons along the LO_2 feedline were key to understanding protuberance airloads.

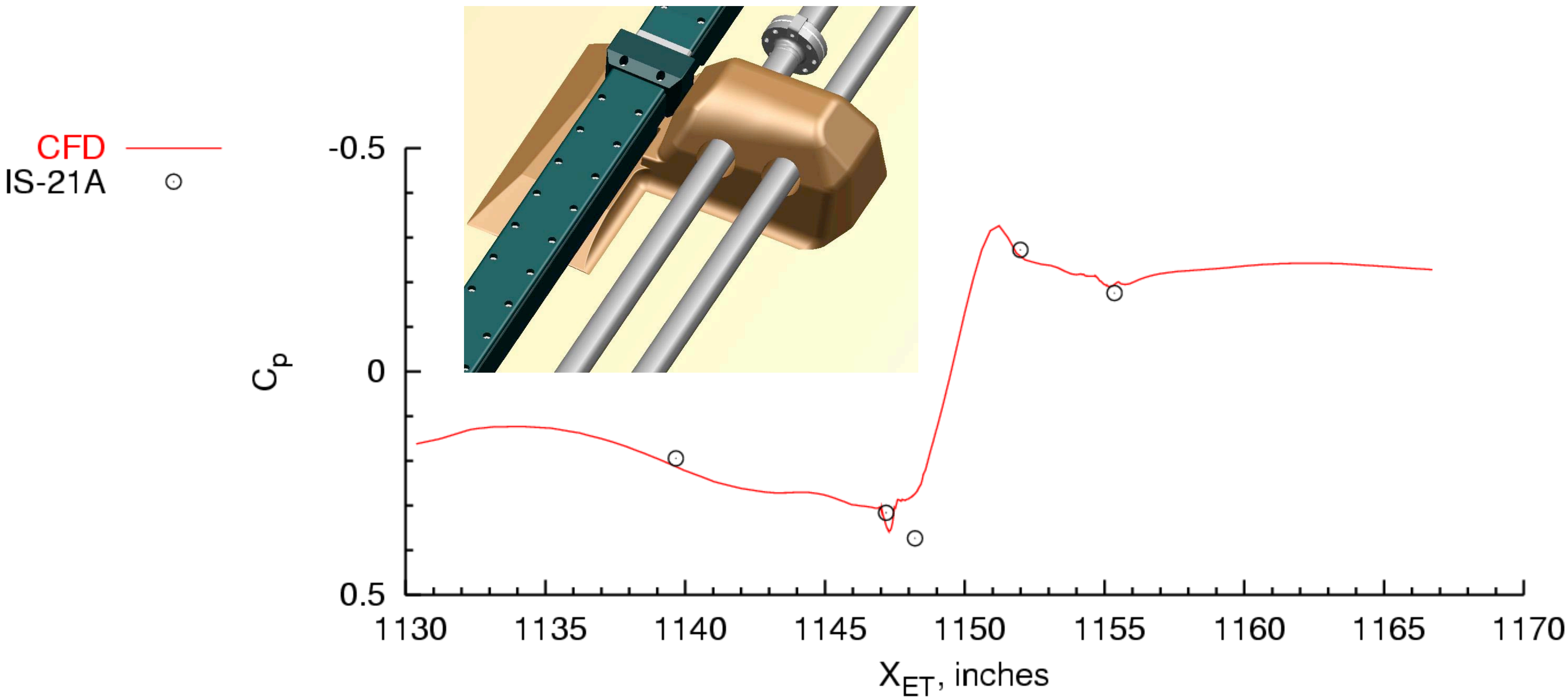


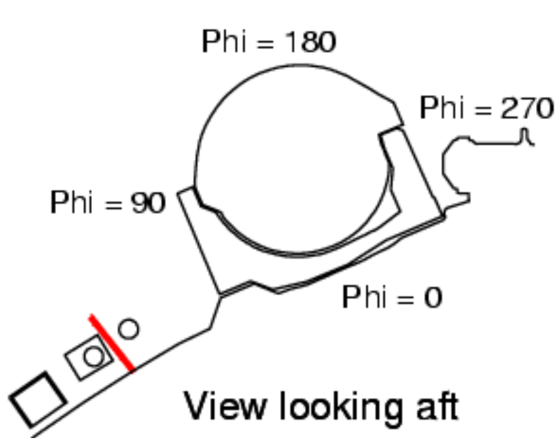
JSC 2005-62925

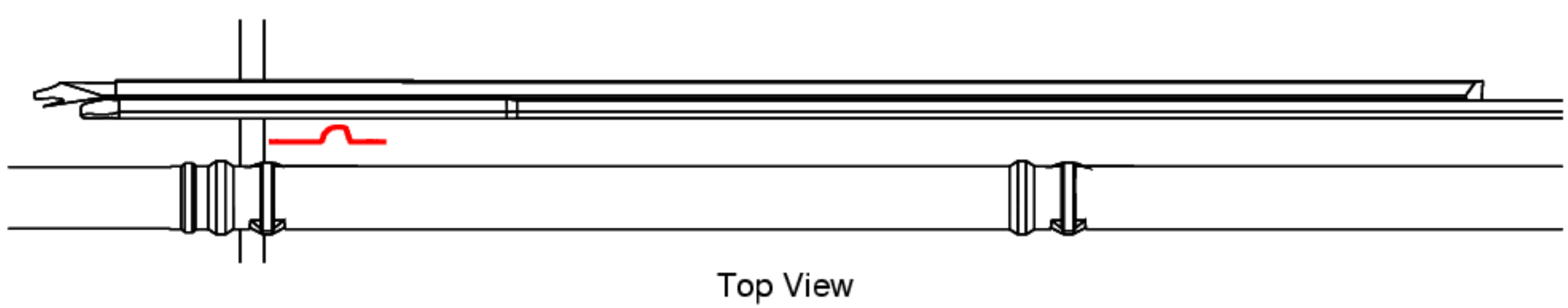




Proposed ice/frost ramp configuration, tested but not flown.

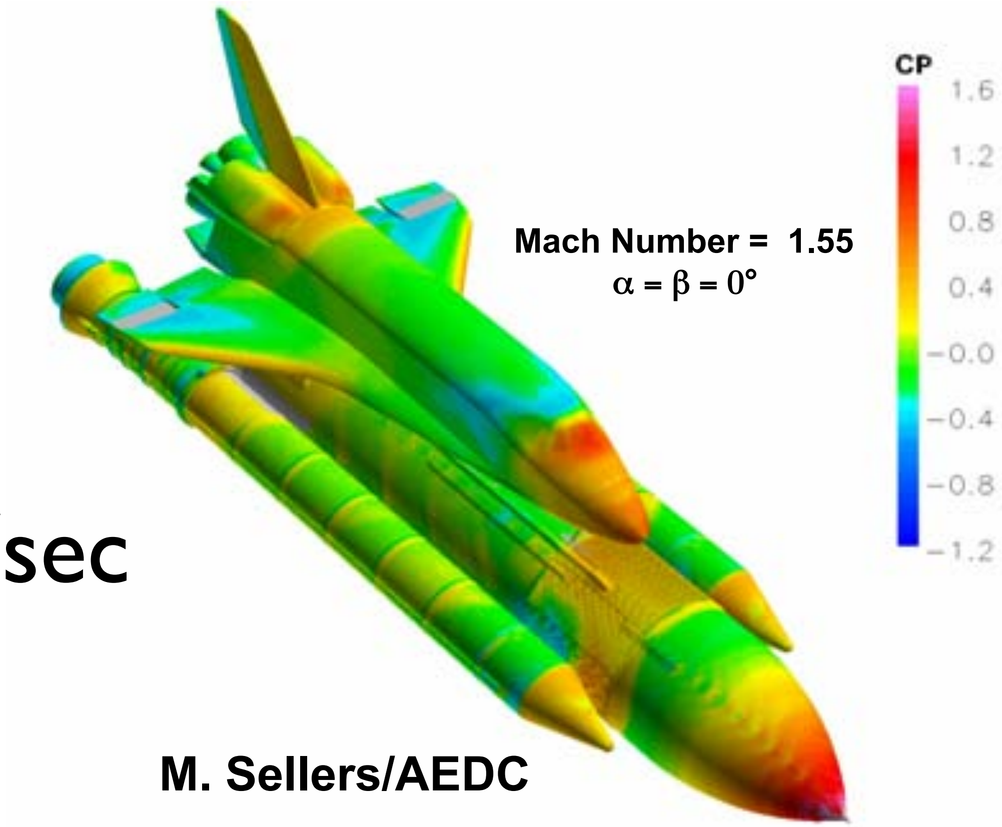




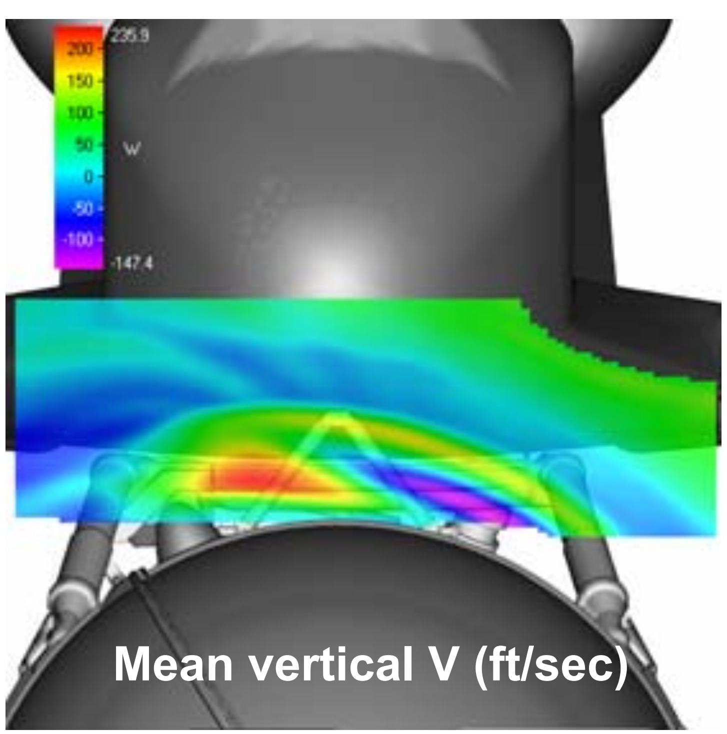


Offbody and integrated validation was required to support debris transport tools.

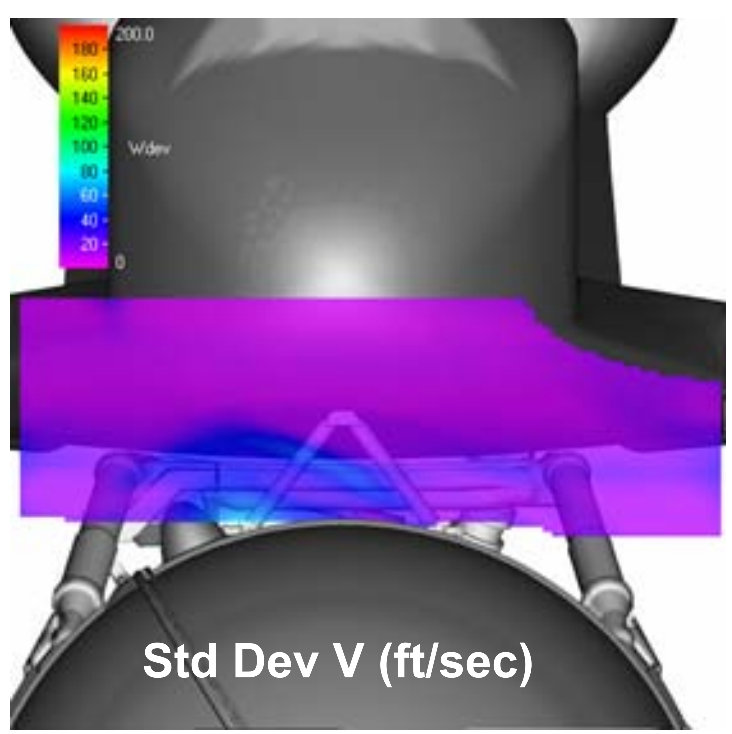
Pressure sensors vs. CFD ≈ 0.01 Cp
Integrated Loads vs. CFD ≈ 5% of flt
Pressure Sensitive Paint
Particle Imaging Velocimetry ± 20 ft/sec



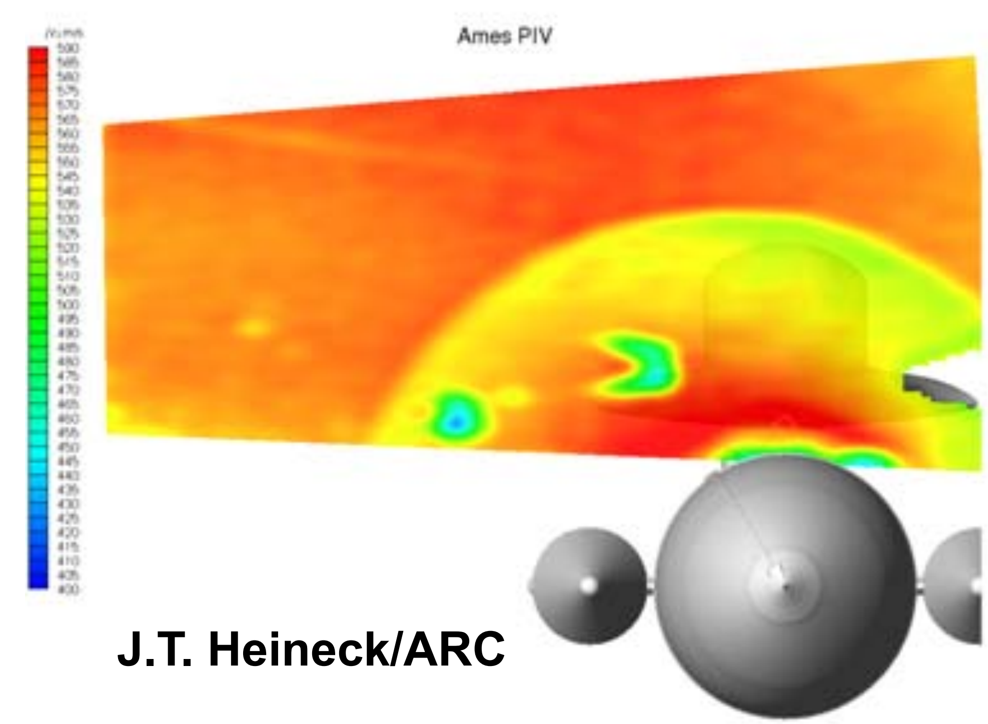
M. Sellers/AEDC



Mean vertical V (ft/sec)



Std Dev V (ft/sec)



J.T. Heineck/ARC

Grid generation automation enabled recreation of previous grid systems and generation of a range of configurations.

GlobalDefs.tcl

```
set Configuration OrbiterET

set ShockGrid    0
set PlumeGrid    0
set ETGrid       1
set BprGrid      1
set YokeGrid     1
set FwdIFRamps   0
set AftIFRamps   0

set BflapDeflection       0.000
set ObLeftElevonDefl      0.000
set IbLeftElevonDefl      0.000
set IbRightElevonDefl     0.000
set ObRightElevonDefl     0.000
set Gimbal(pitch,ssmet)  16.000
set Gimbal(pitch,ssmel)  10.000
set Gimbal(pitch,ssmer)  10.000
set Gimbal(pitch,lsrb)    0.000
set Gimbal(pitch,rsrb)    0.000
set Gimbal(yaw,ssmet)     0.000
set Gimbal(yaw,ssmel)     3.500
set Gimbal(yaw,ssmer)    -3.500
set Gimbal(yaw,lsrb)      0.000
set Gimbal(yaw,rsrb)      0.000

set TunnelRoll          -31.185
set TunnelPitch         -11.646

set InitialWallSpaceing 1.6e-4
```

Configuration

Intra-Configuration Options

Control Surface Deflections

Engine Gimbals

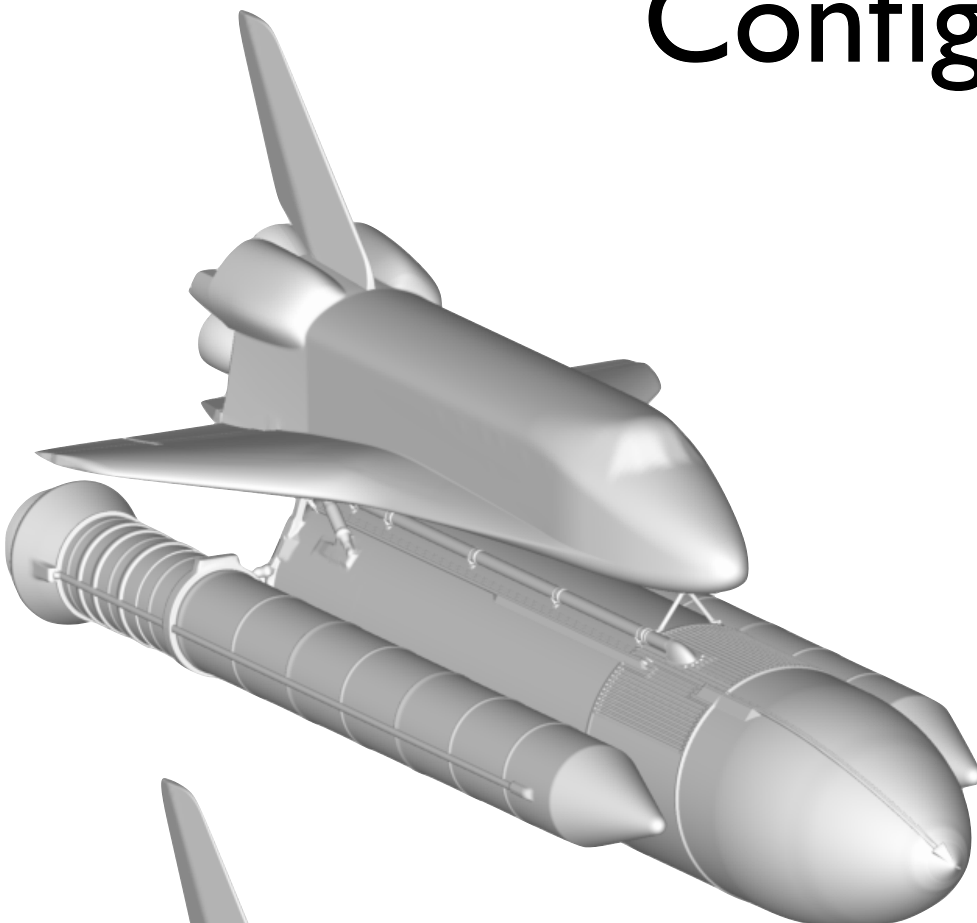
Tunnel Controls

Viscous Spacing

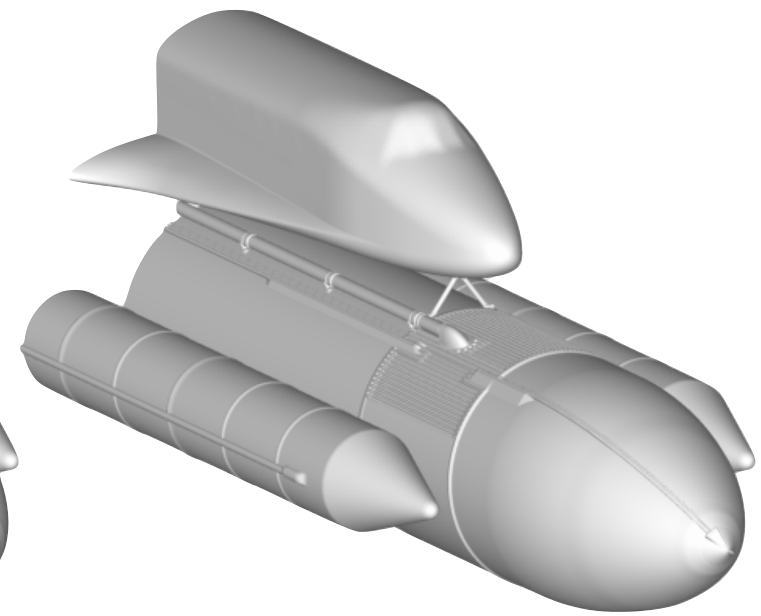
Overall build script:

```
% BuildControlSurf
% BuildGimbNoz
% BuildVol
% BuildPeg5i
% addmanual.pl
% pegasus5 < peg.i.mod
% BuildMixsuri
% BuildOveri
```

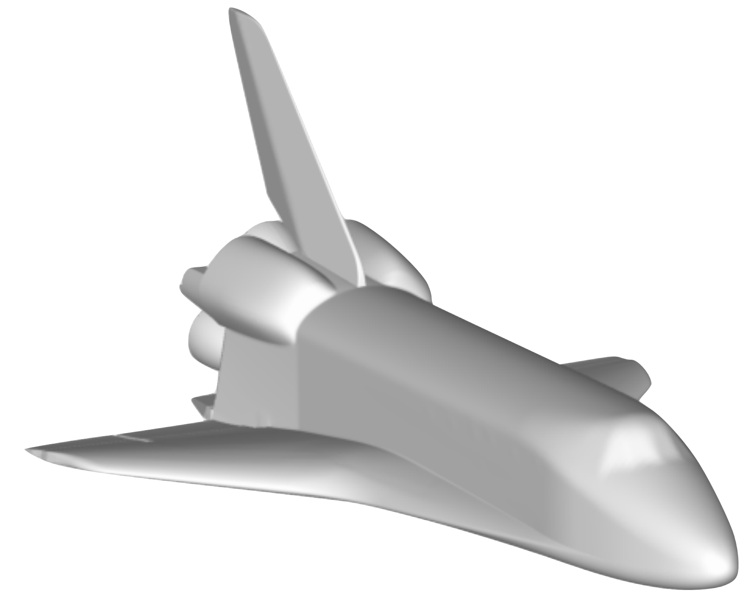
Configuration examples



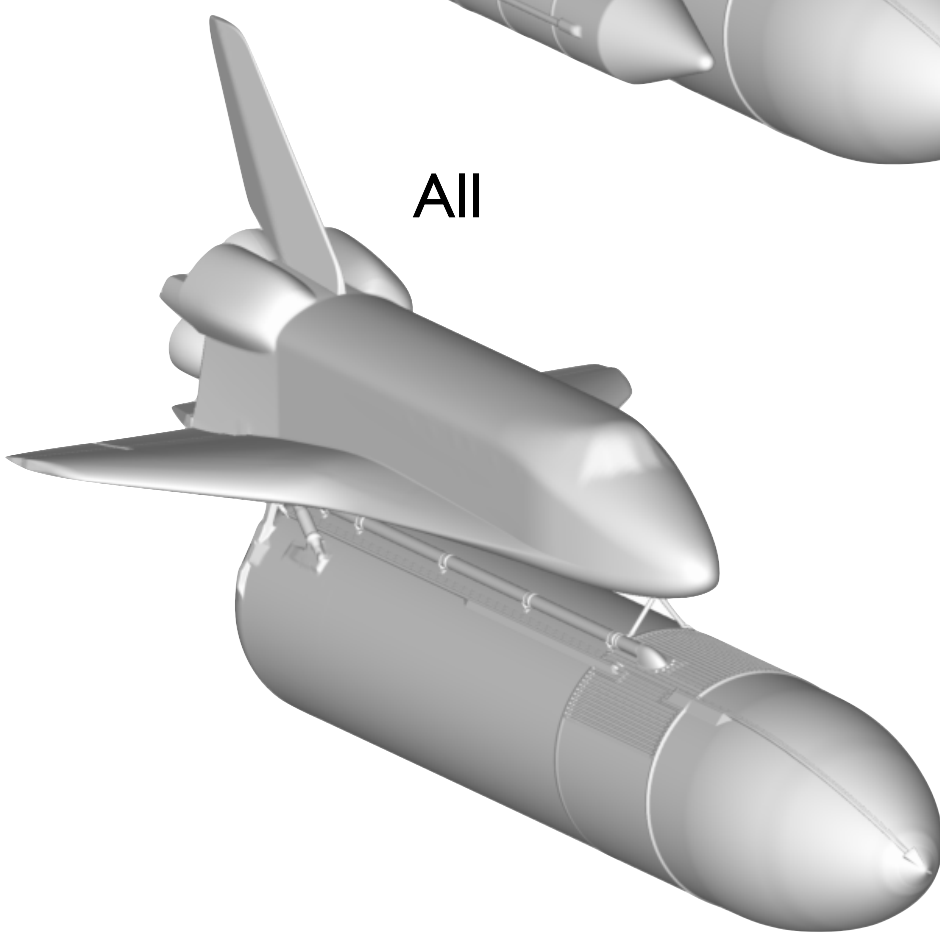
All



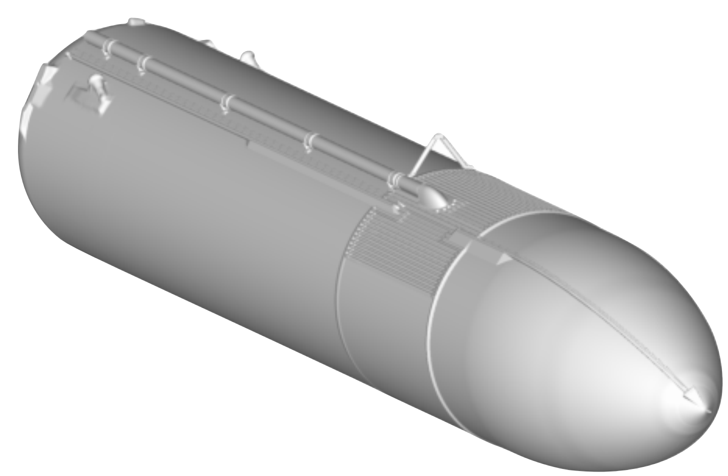
AllShort



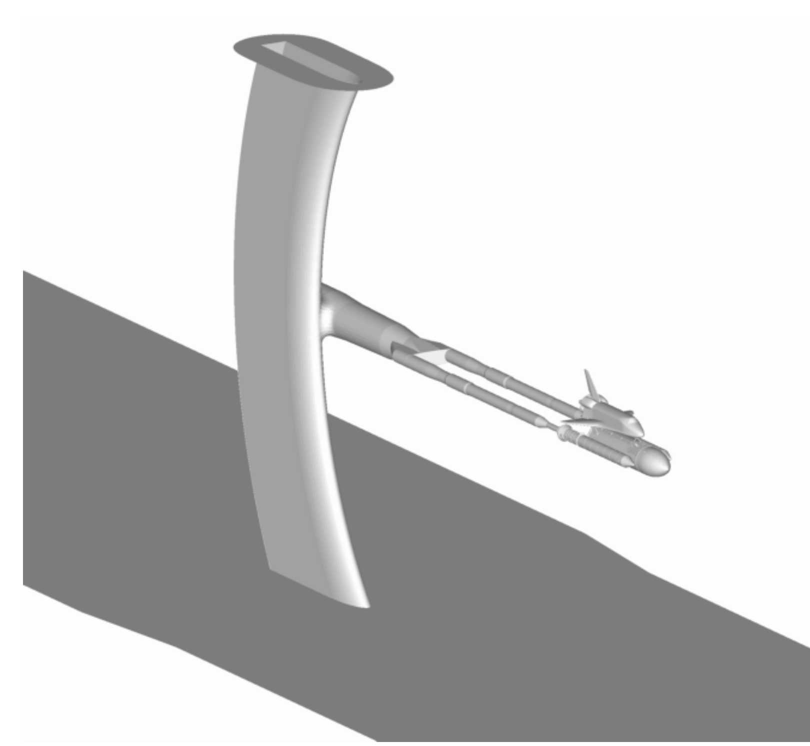
Orbiter



OrbiterET

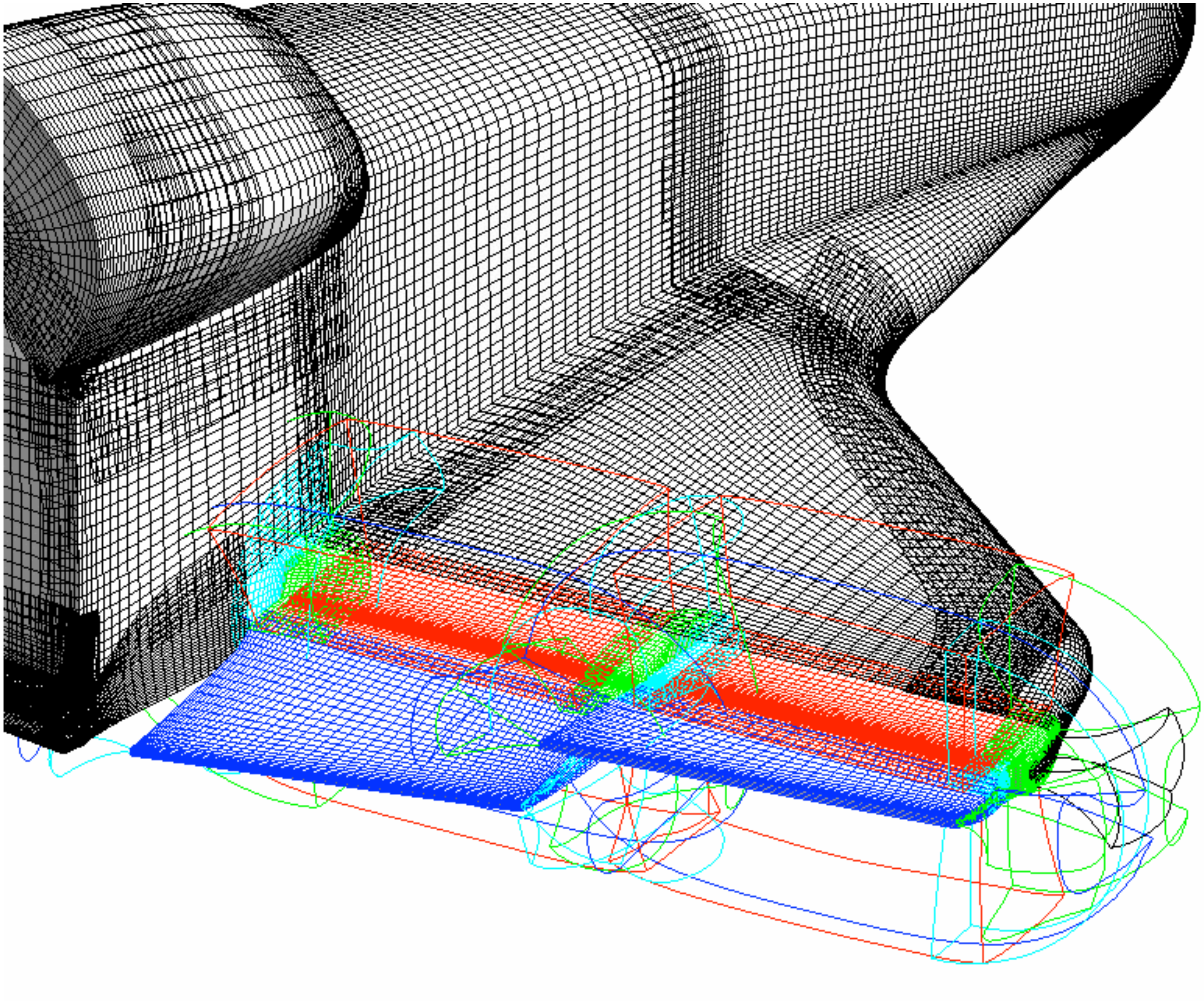


External Tank



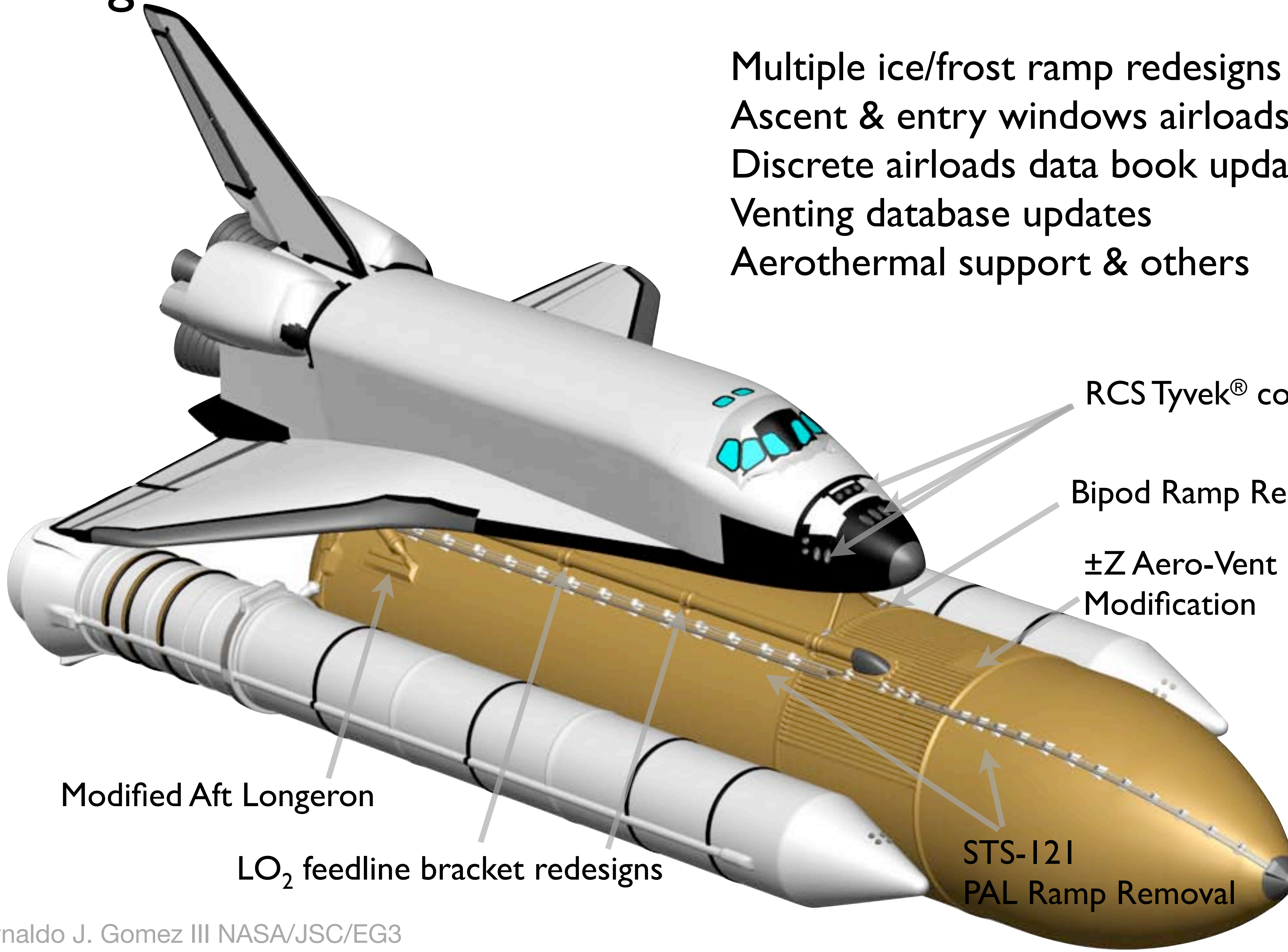
IA700A

Scripted control surface motion is a key part of automation.

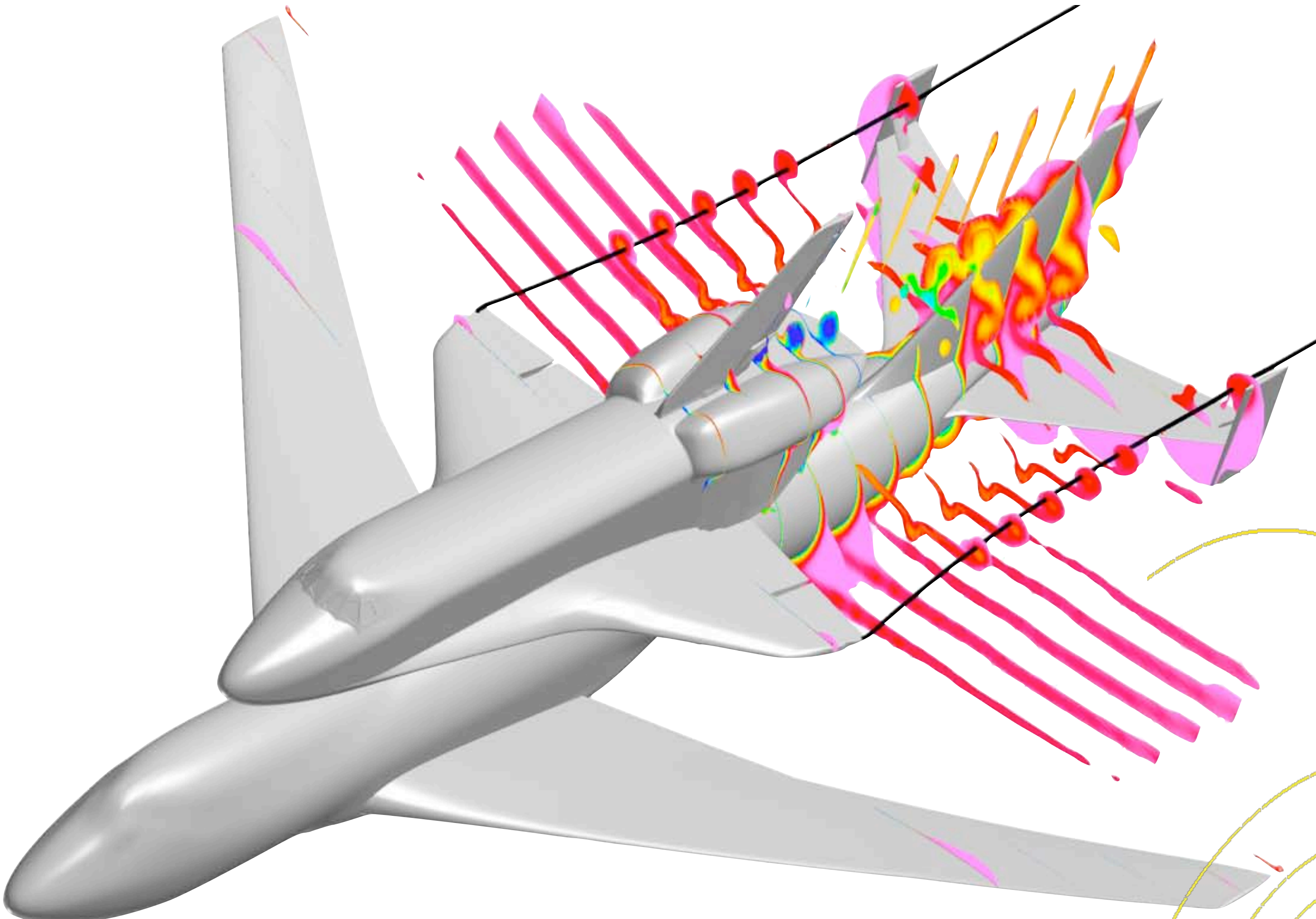


Overset CFD was a key part of many External Tank redesign assessments and debris assessments.

Multiple ice/frost ramp redesigns
Ascent & entry windows airloads
Discrete airloads data book updates
Venting database updates
Aerothermal support & others

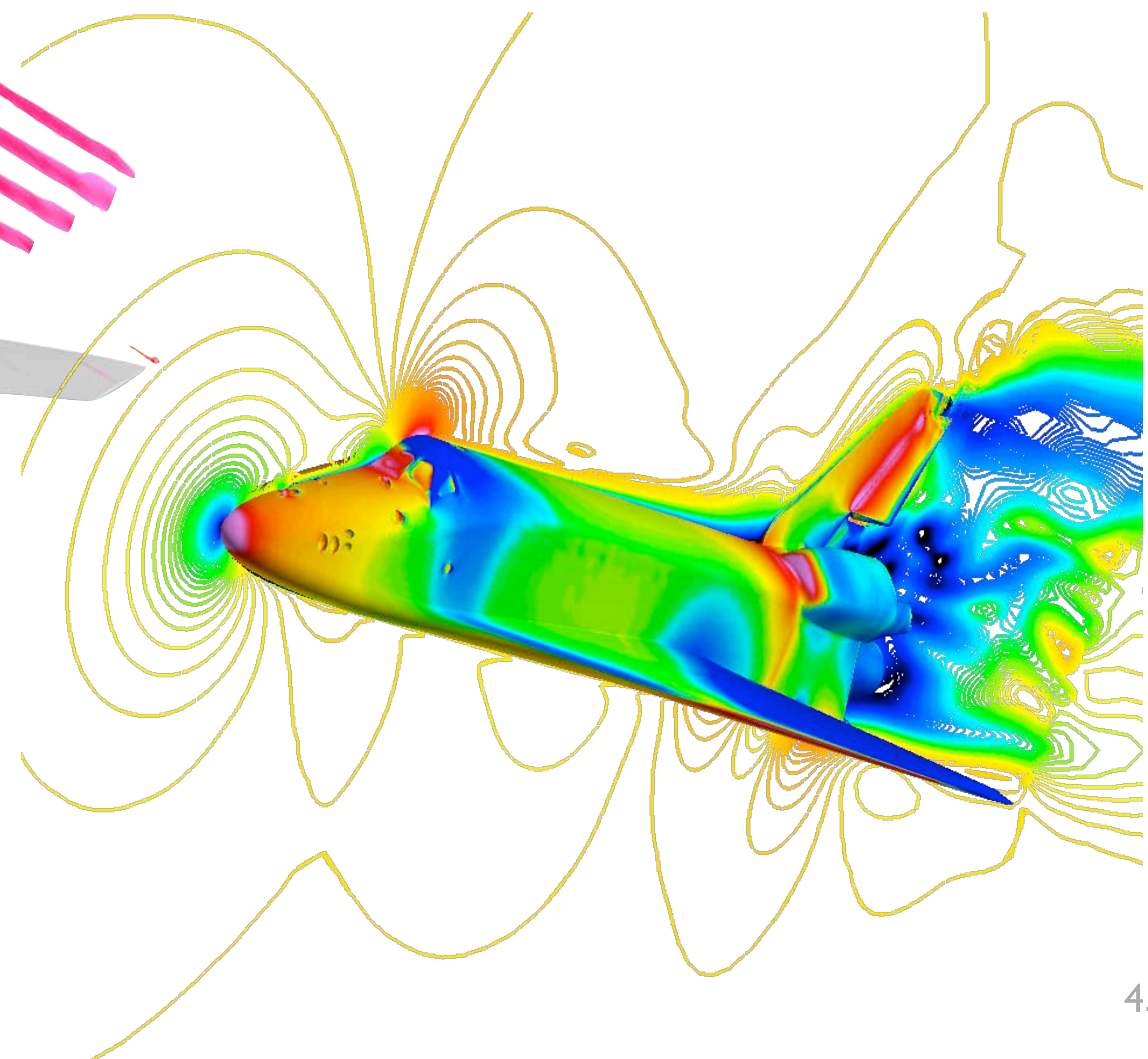


Other applications

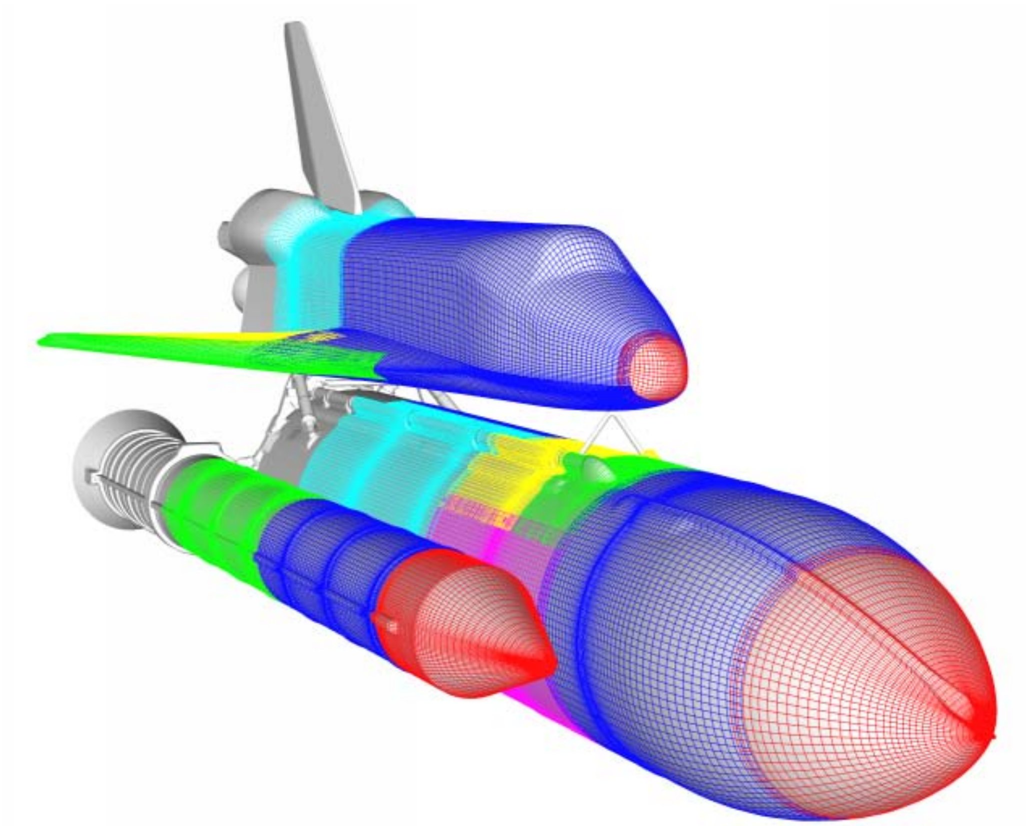


Shuttle Carrier Aircraft
Mach = 0.3, α = 3°
G. Schauerhamer

Entry Calculations
Mach = 0.8, α = 17°
L. Marek/JSC

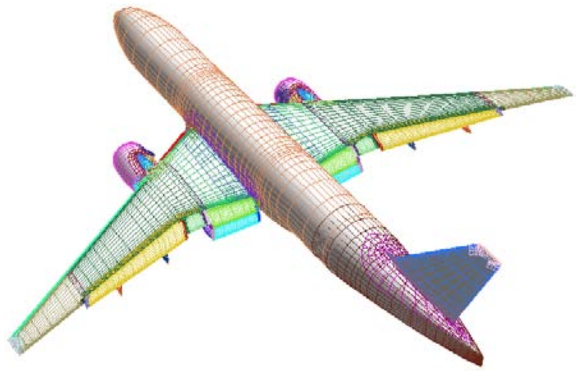


Overset Legacy

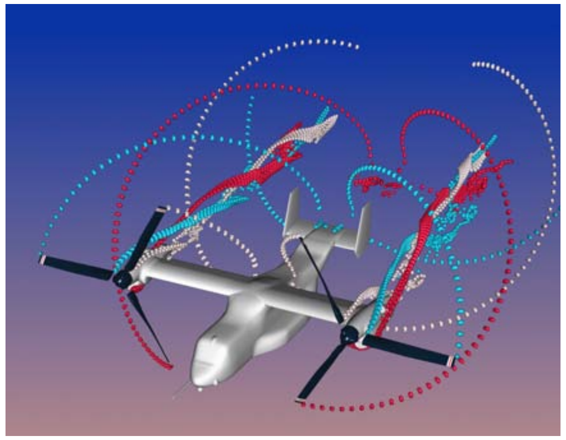


SSLV 1987-1994
Initial OVERFLOW development, collar grids, complex geometry issues, plumes

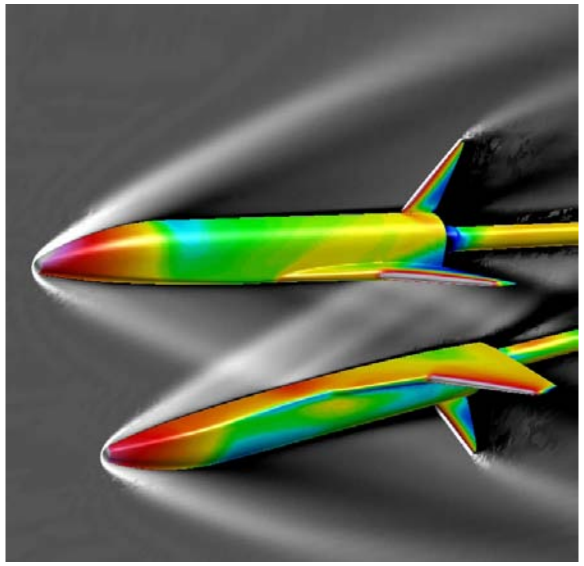
Many individuals and groups contributed to this effort including NASA ARC, JSC, LaRC, MSFC and AEDC.



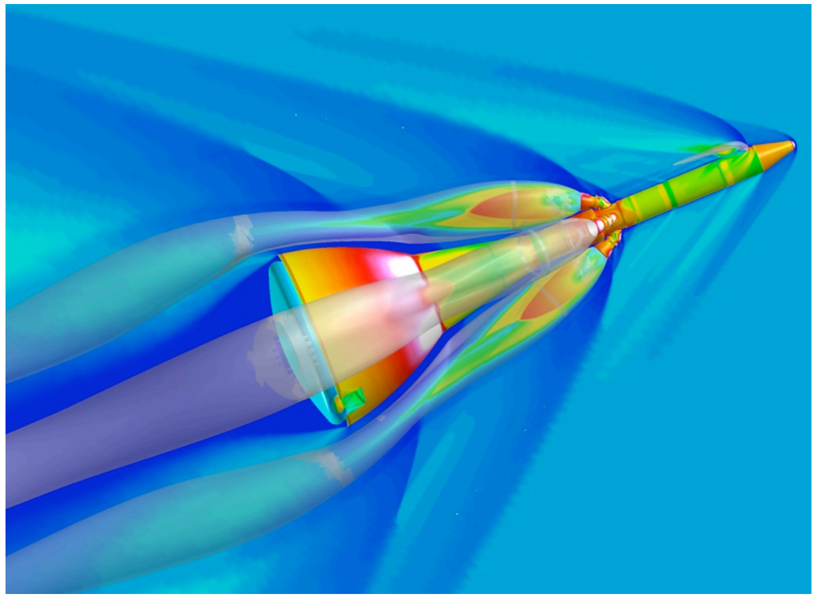
Advanced Subsonic Transport 1992-2000
Chimera Grid Tools, tcl scripting, turbulence modeling, PEGASUS 5



DoD High Performance Computer Modernization Project 1992-present
OVERGRID, OVERFLOW-D, rotorcraft applications.

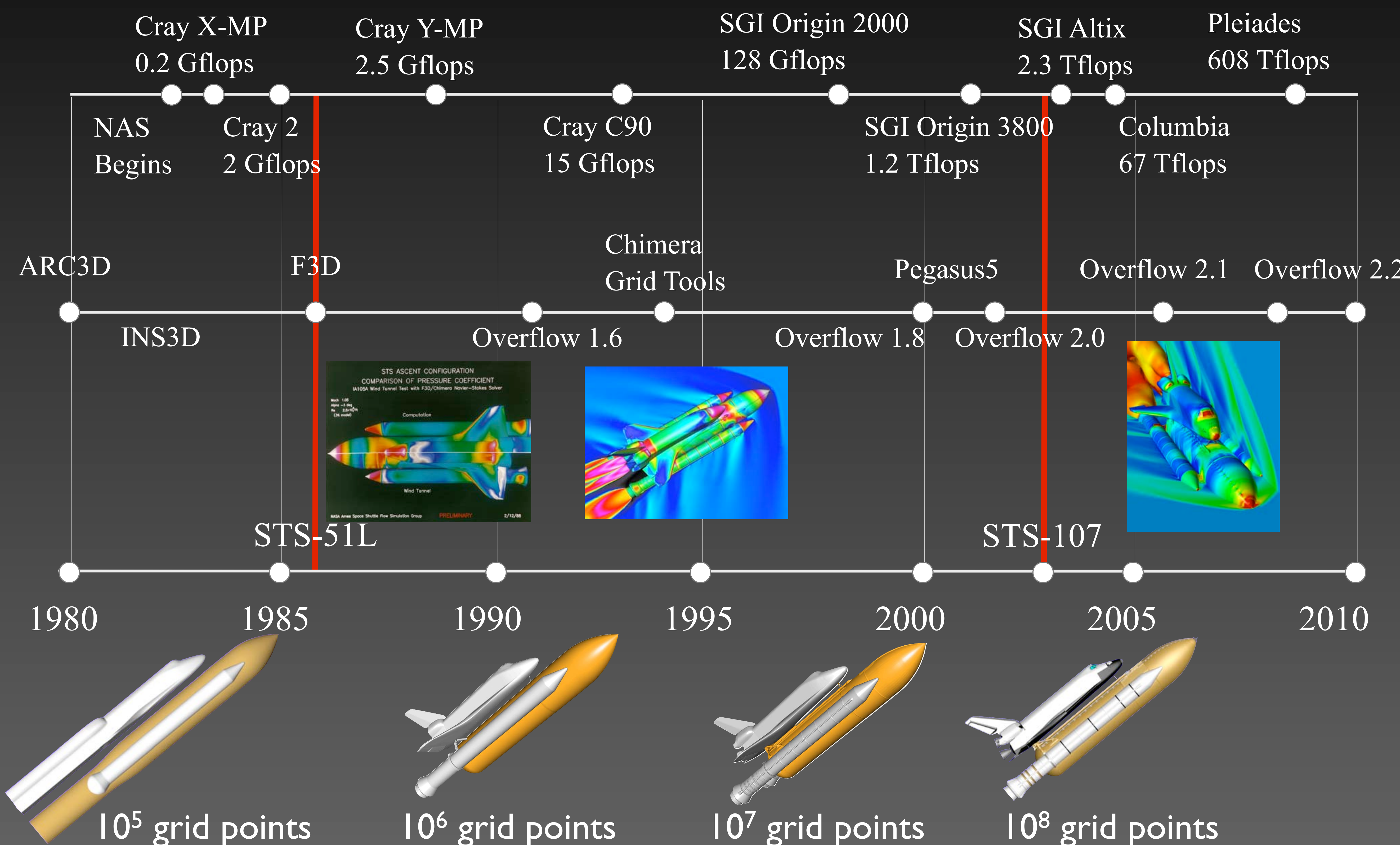


Space Launch Initiative 2000-2002
OVERFLOW 2.0, moving body tools



Constellation 2004-2010
OVERFLOW 2.1, robustness improvements for high gradient plume driven unsteady flows.

Timeline of Computing & Overset Space Shuttle Applications



After 20+ years was overset a good choice?

Weaknesses

- Relatively steep learning curve for new users.
- Double valued surface issues.

Strengths

- Accuracy - Structured grids without block zonal constraints
- Efficiency - Structured grids, grid scripts
- Flexibility - Nearly ideal for Shuttle redesign work.

Overall overset was a pragmatic choice for our application.

But there is still more work to be done...

STS-133, STS-134, STS-135?

Some STS-1 flight anomalies are still beyond current CFD tool capabilities, e.g.

- Acoustics and heating on complex configurations with strong shock wave-boundary layer interactions
- Physical models (turbulence, chemistry, multiphase flows,...) are key limitations that need to be improved.

Future programs will need 10s to 100s of millions of CPU-hours to characterize external environments

- There is evidence that we need 10x more resolution and 10x more solutions than we can currently produce to generate grid converged solutions and populate databases.