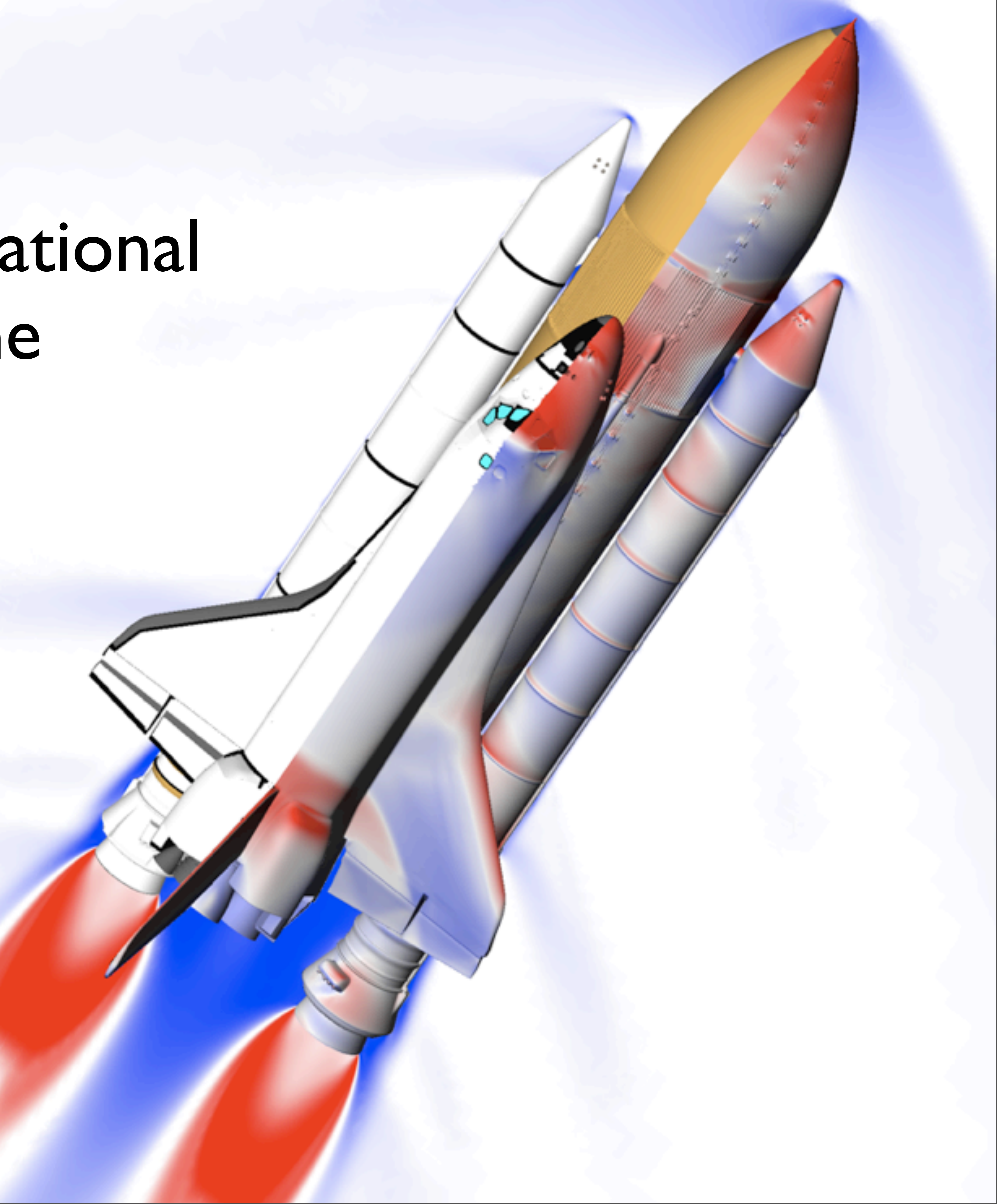
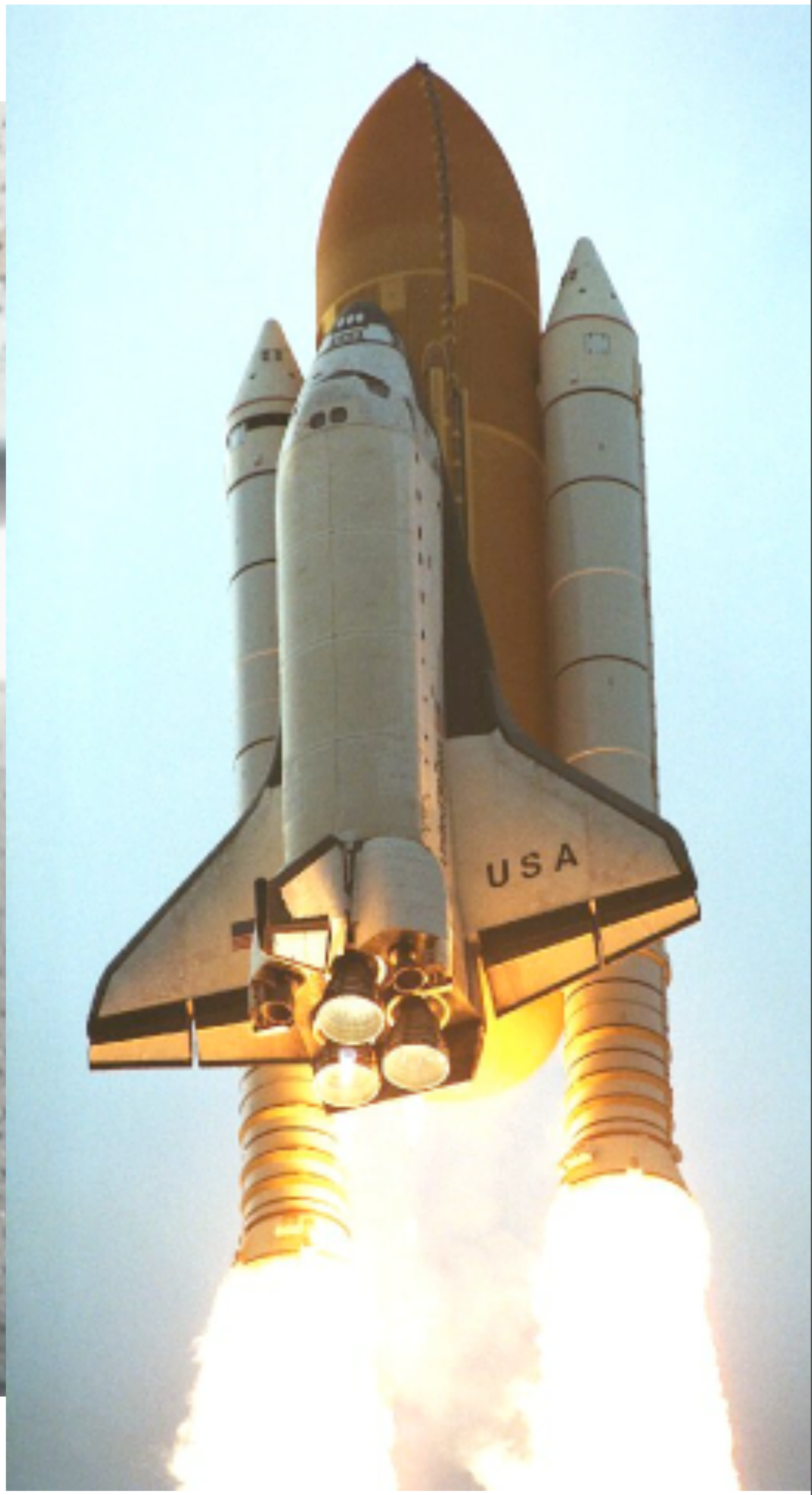
20+ Years of Computational Fluid Dynamics for the Space Shuttle



Reynaldo J. Gómez III
EG/Aeroscience & Flight Mechanics
NASA Johnson Space Center
Houston, Texas
April 2011

Aerodynamic Tools



Modeling & Simulation

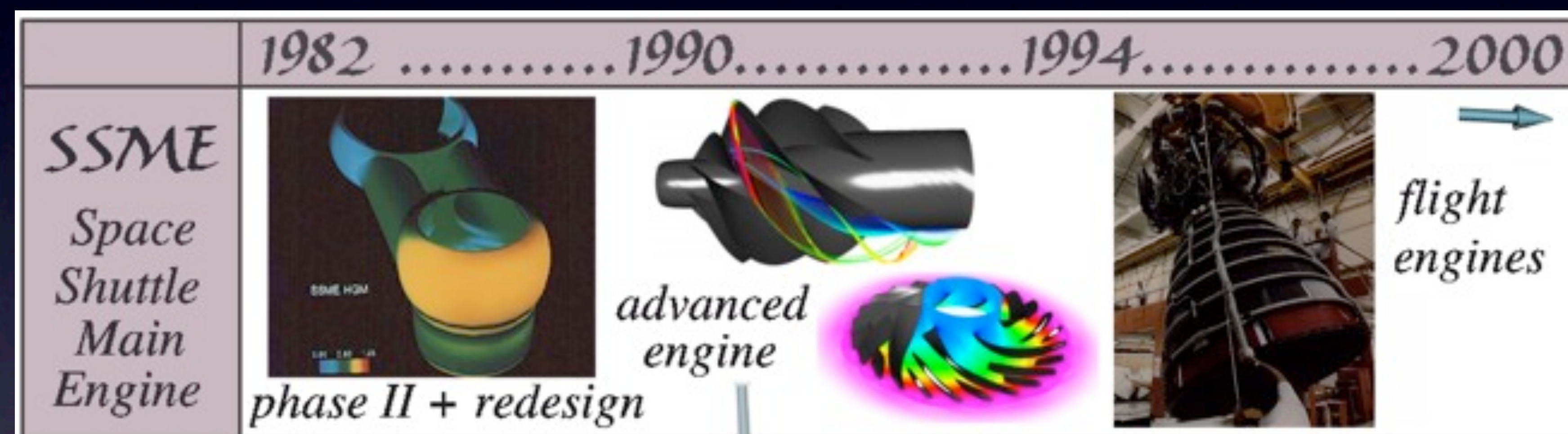
Ground Test

Flight Test

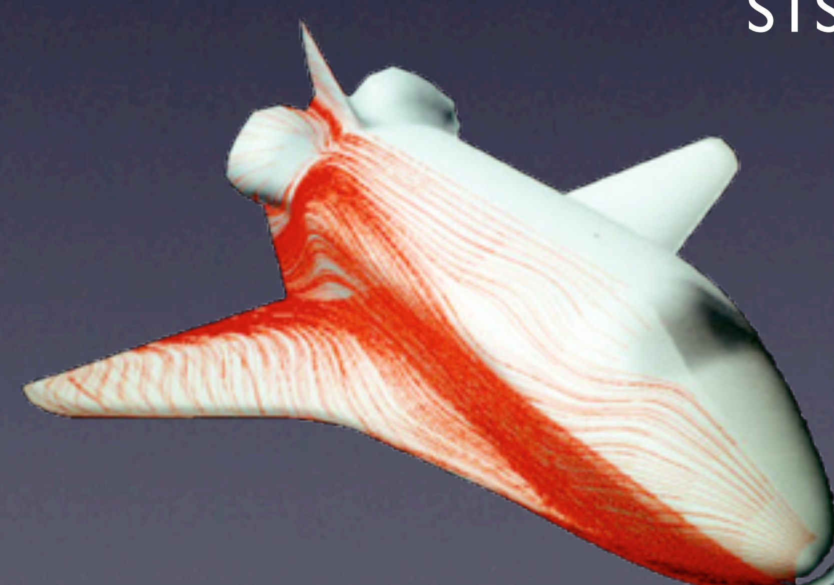
Space Shuttle Program Aerodynamics & Fluid Dynamics

Design	**Development**	**Operations**	**Retirement**
ARC wind tunnel tests		Test + CFD	FY 2011
44 A/B	176 C/D	1982-present	

OA-12 / IA9 1973 Unitary Tests

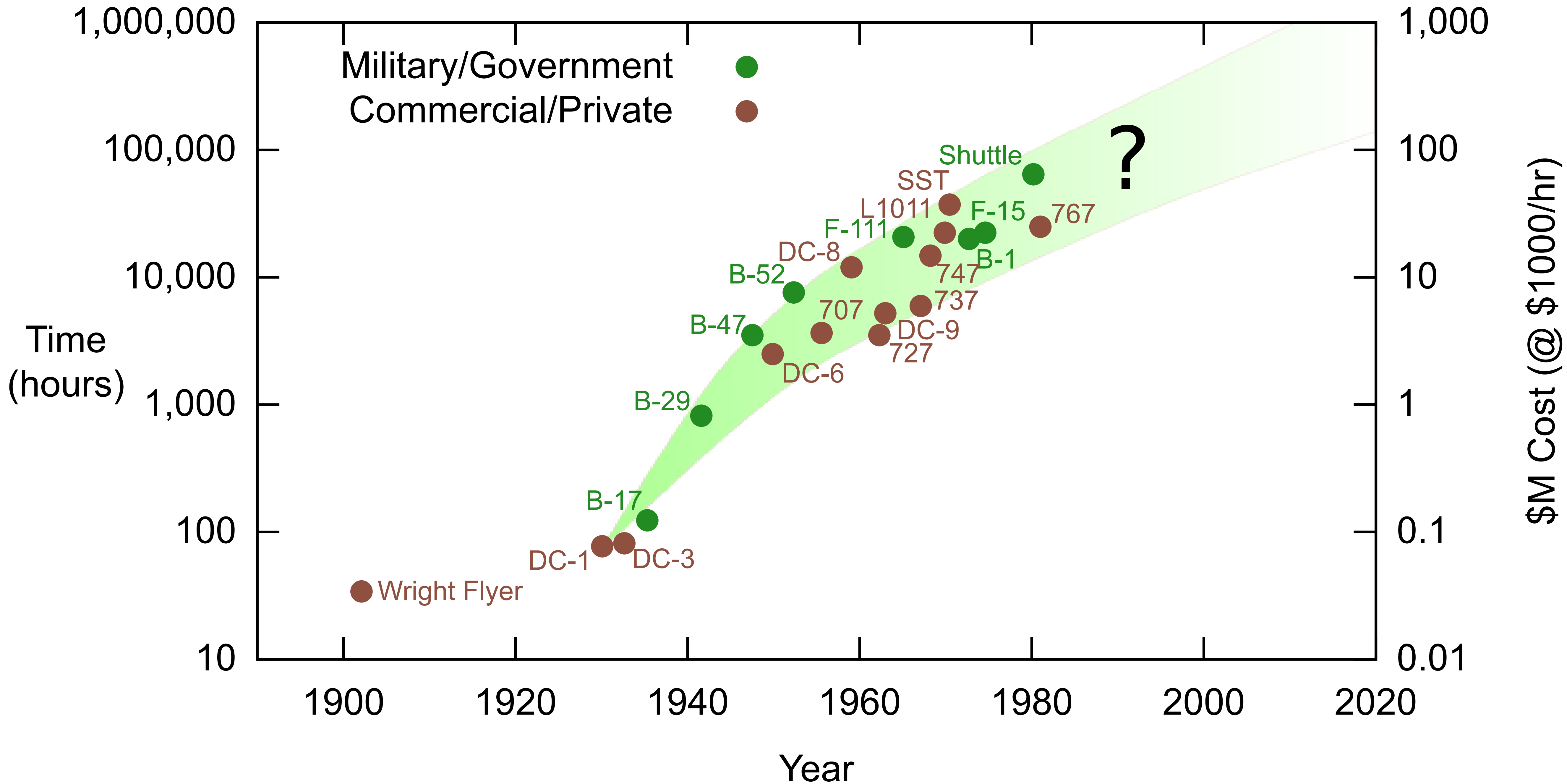


STS-70 & subs



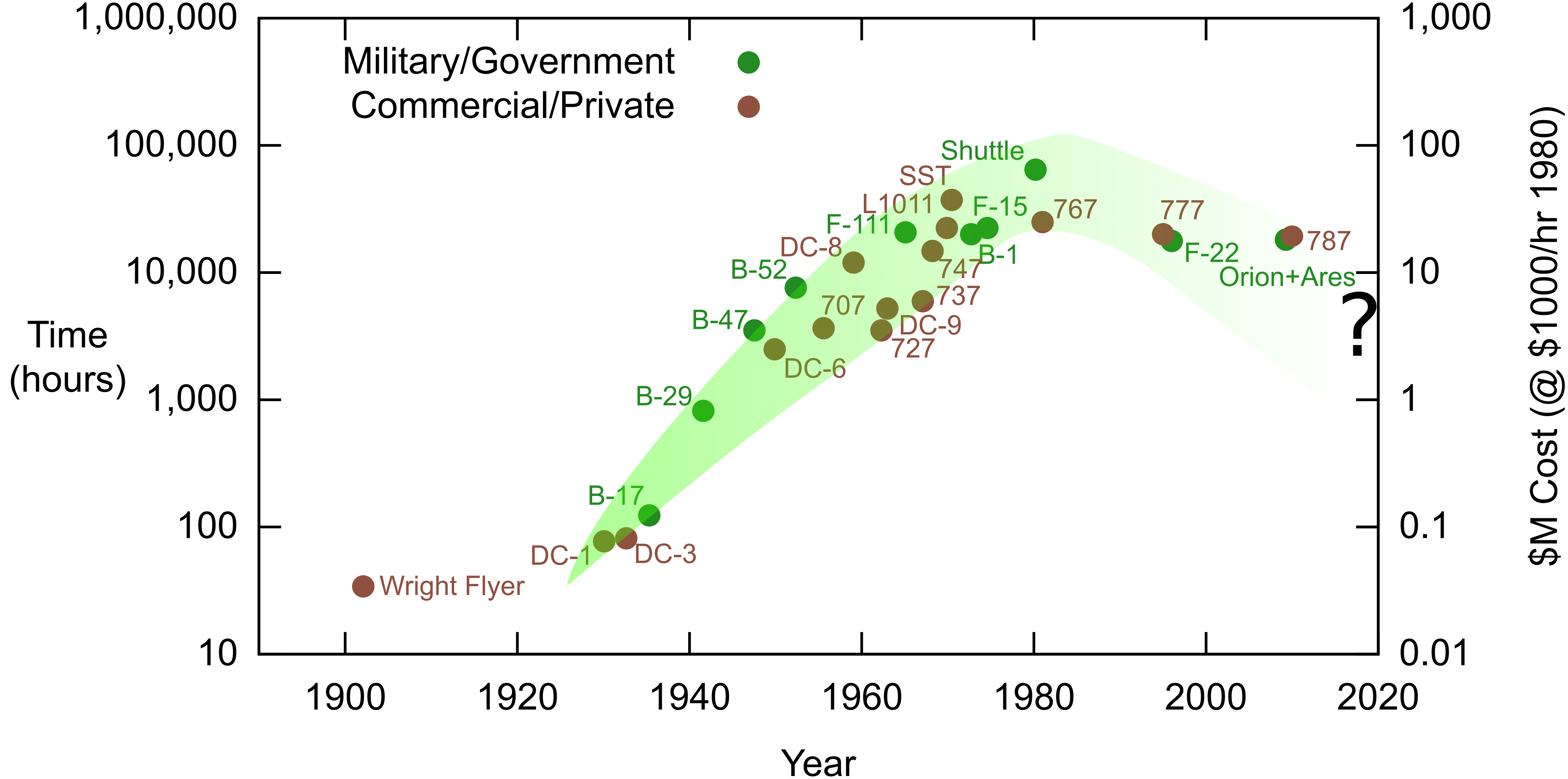
1984 Bancroft & Merritt graphic
Cray X-MP solution

Wind tunnel costs and times dominated aerodynamic database development before 1980.



Data from NASA SP-440 & online sources

But trends can change . . .



Current wind tunnel costs $3,000 - $10,000/hour.

Length 56.14 meters/184.2 feet

Mass 2,041,166 kilograms/4.5 million pounds

Shuttle External Environments

Ground winds

Ignition Over Pressure

- 7.8 million lbs thrust

Ascent airloads

- Design $\overline{q}$ = 819 psf

Separation Dynamics

Orbital debris

Hypersonic Entry

- 1650 °C/3000 °F

Ground Effects

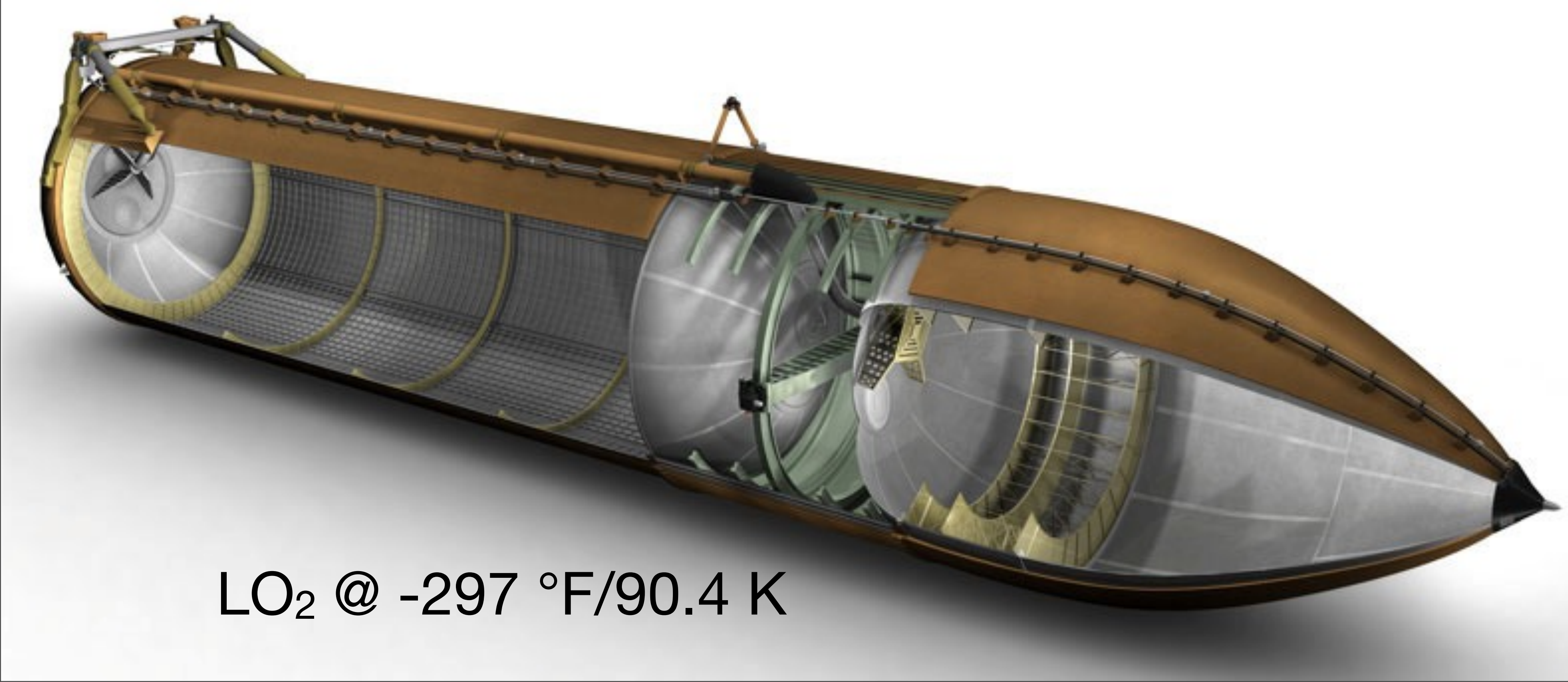
“Engineering is the art of compromise,” Henry Petroski

Design goal
Lightest structure that can survive a harsh environment and maximize payload to orbit.

External Tank

- 154 ft/47 m long
- 60,000 lbs empty/1,600,000 lbs filled
- 27,215 kg empty/725,748 kg filled
- Empty/filled = 1/27
- Typical soda can, 1/28, 14 gm/394 gm

LH_2 @ -423 °F/20.4 K



LO_2 @ -297 °F/90.4 K

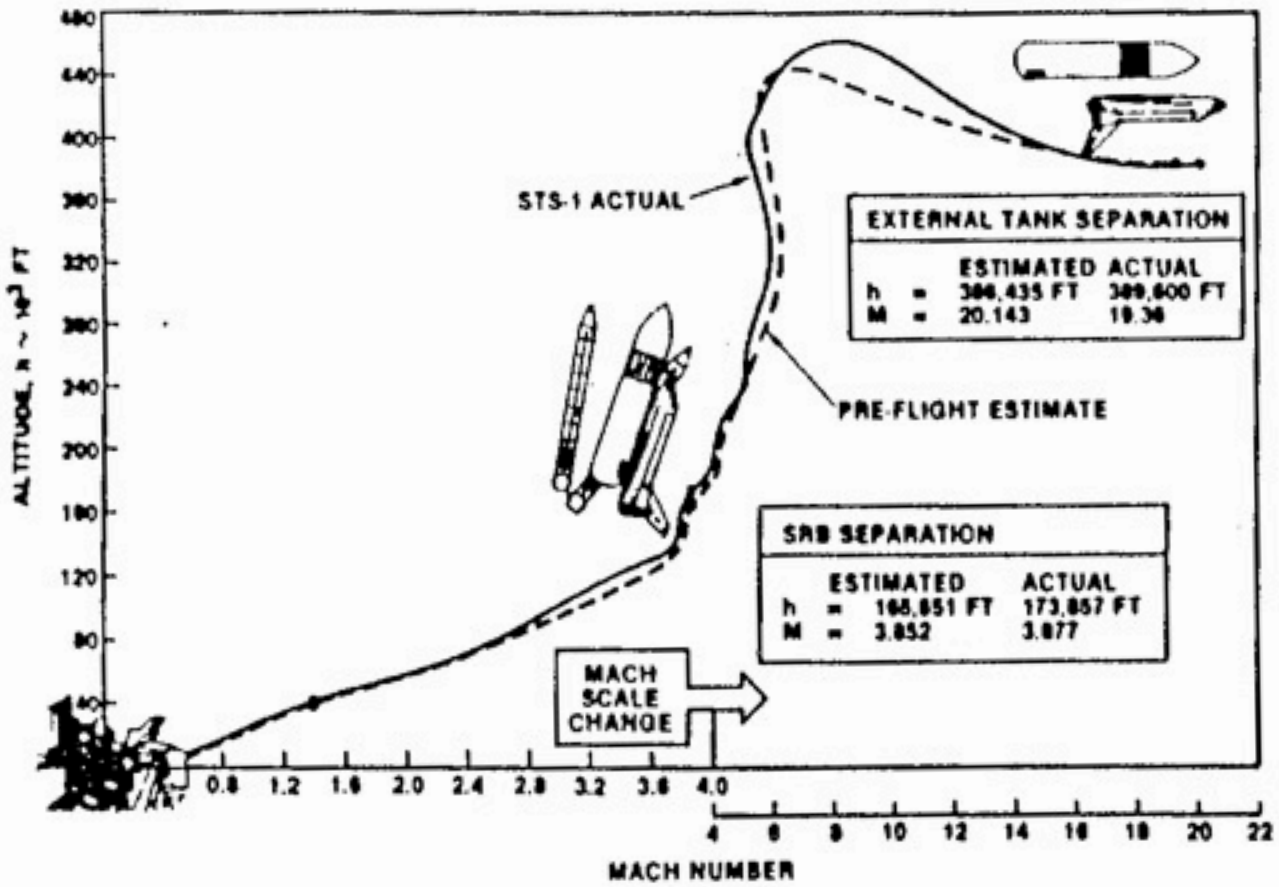
Post Challenger Shuttle Problems

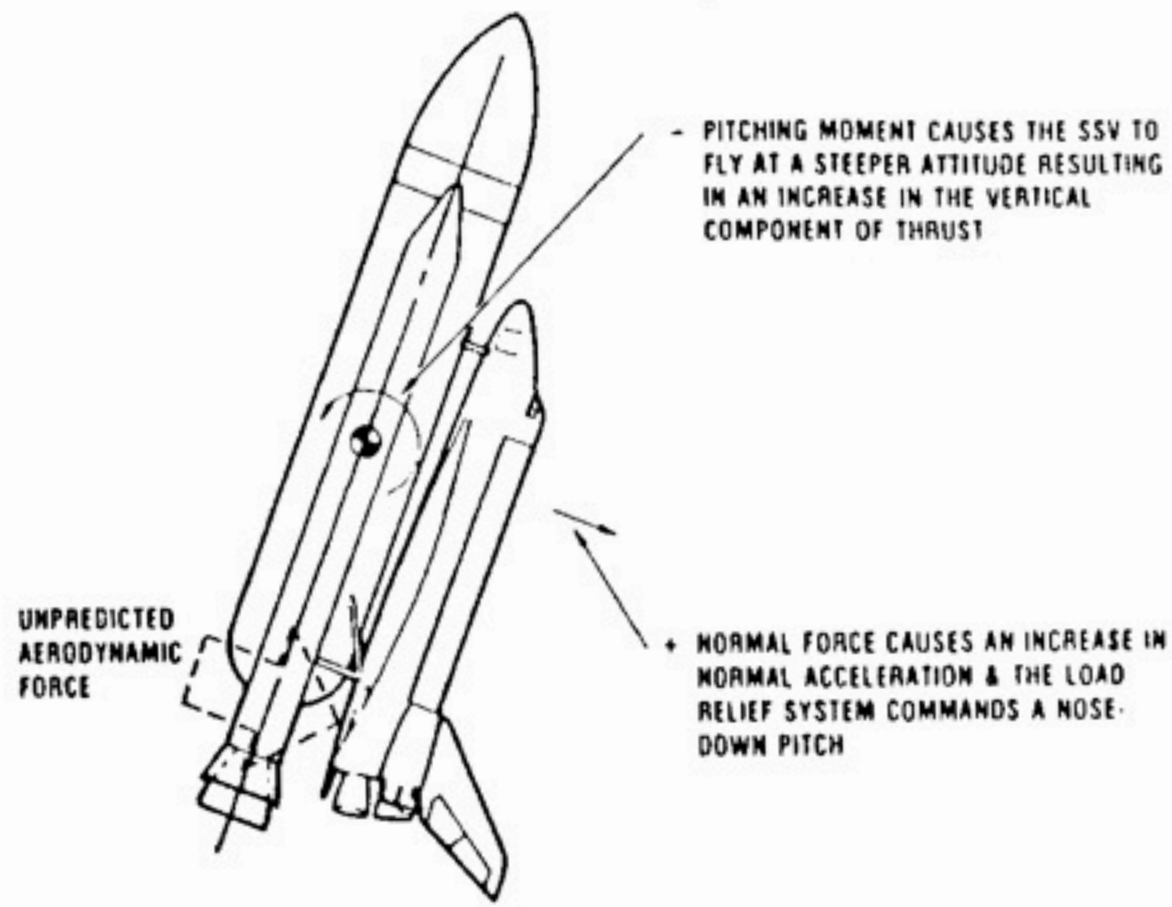
- January 1986 No analytical capability to predict aerodynamics
- 1987 Joseph Steger & Pieter Buning/NASA ARC proposed development of an overset capability to simulate the Shuttle ascent configuration
- Initially focused on fast-separation abort and STS-1 trajectory lofting base pressure issues.
- Payload 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

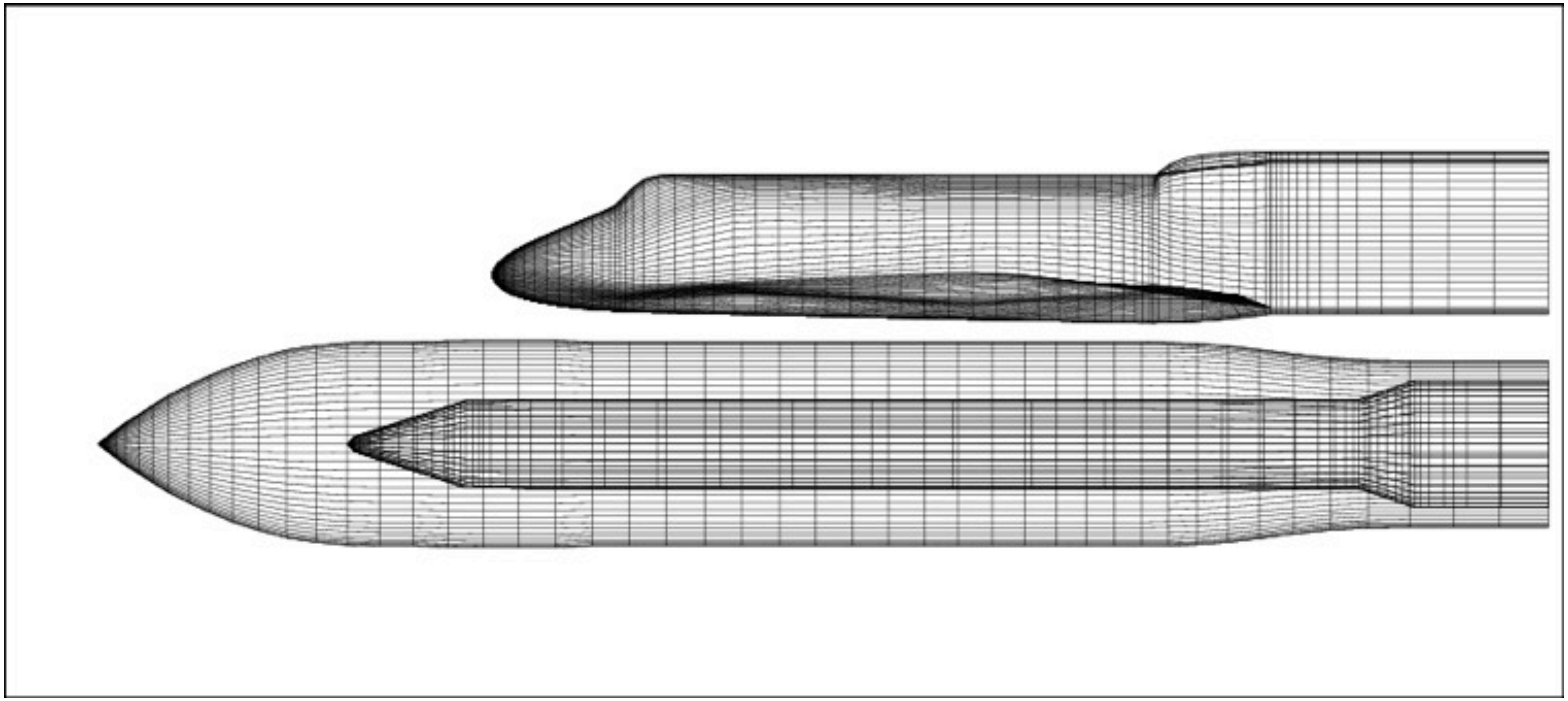
- Discrepancies exist between aerodynamic predictions and flight experience.

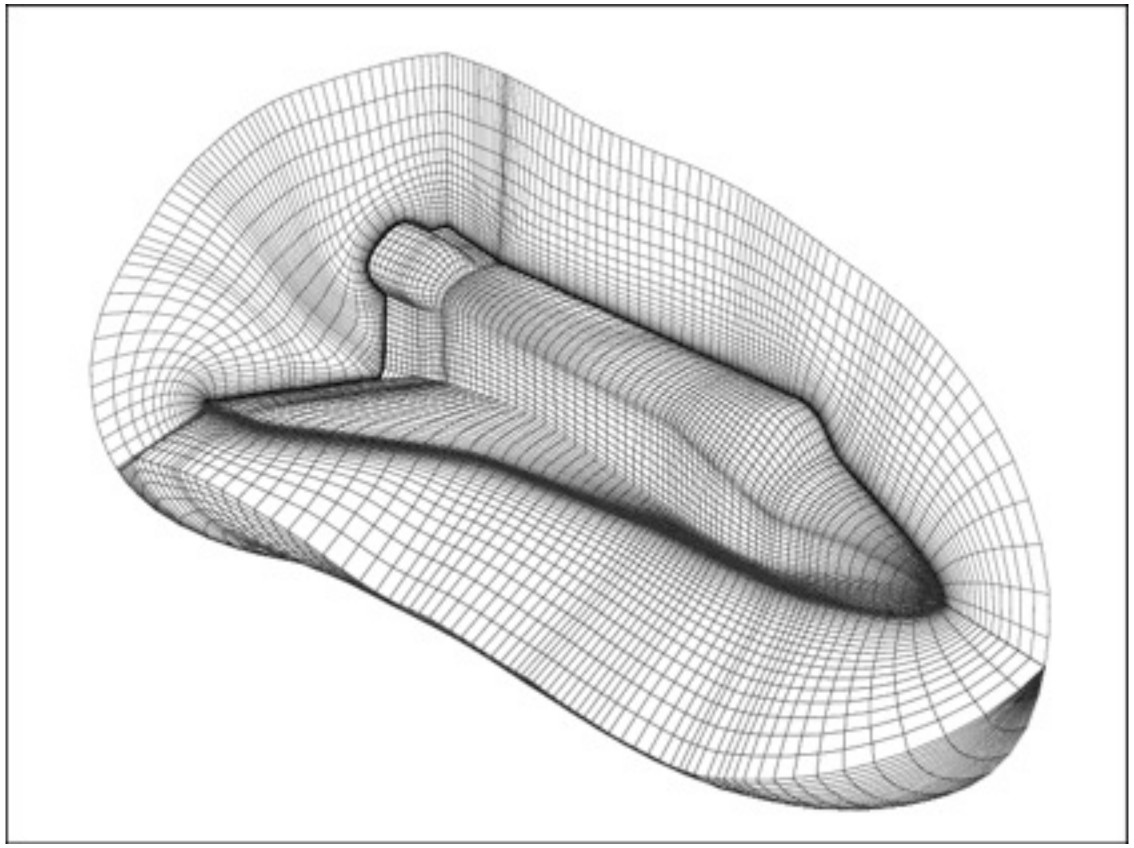


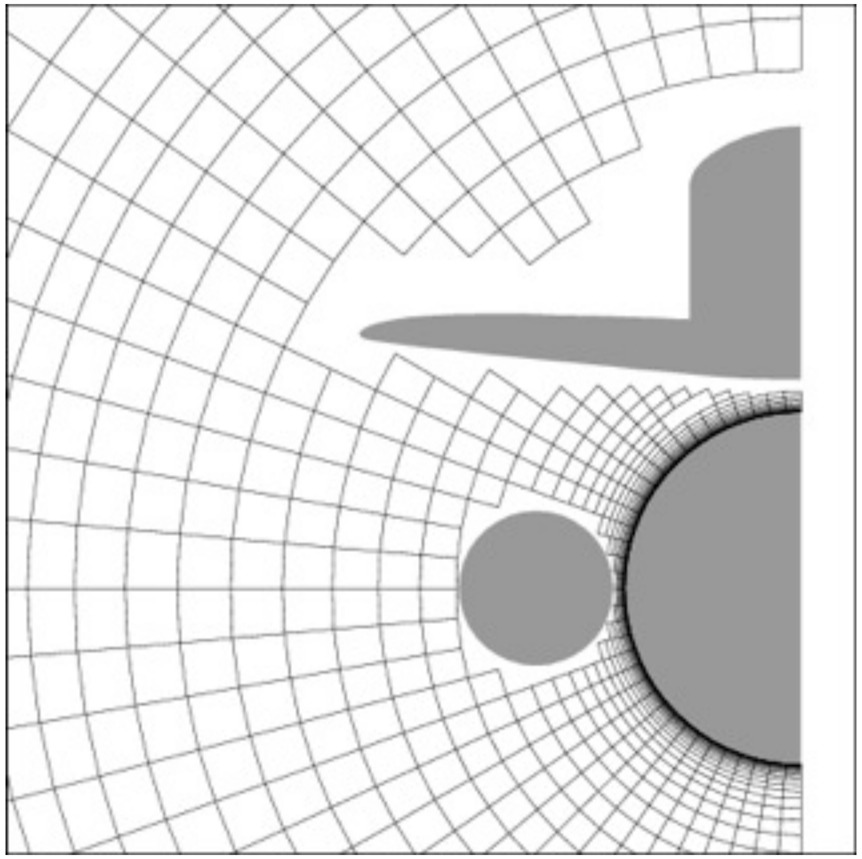


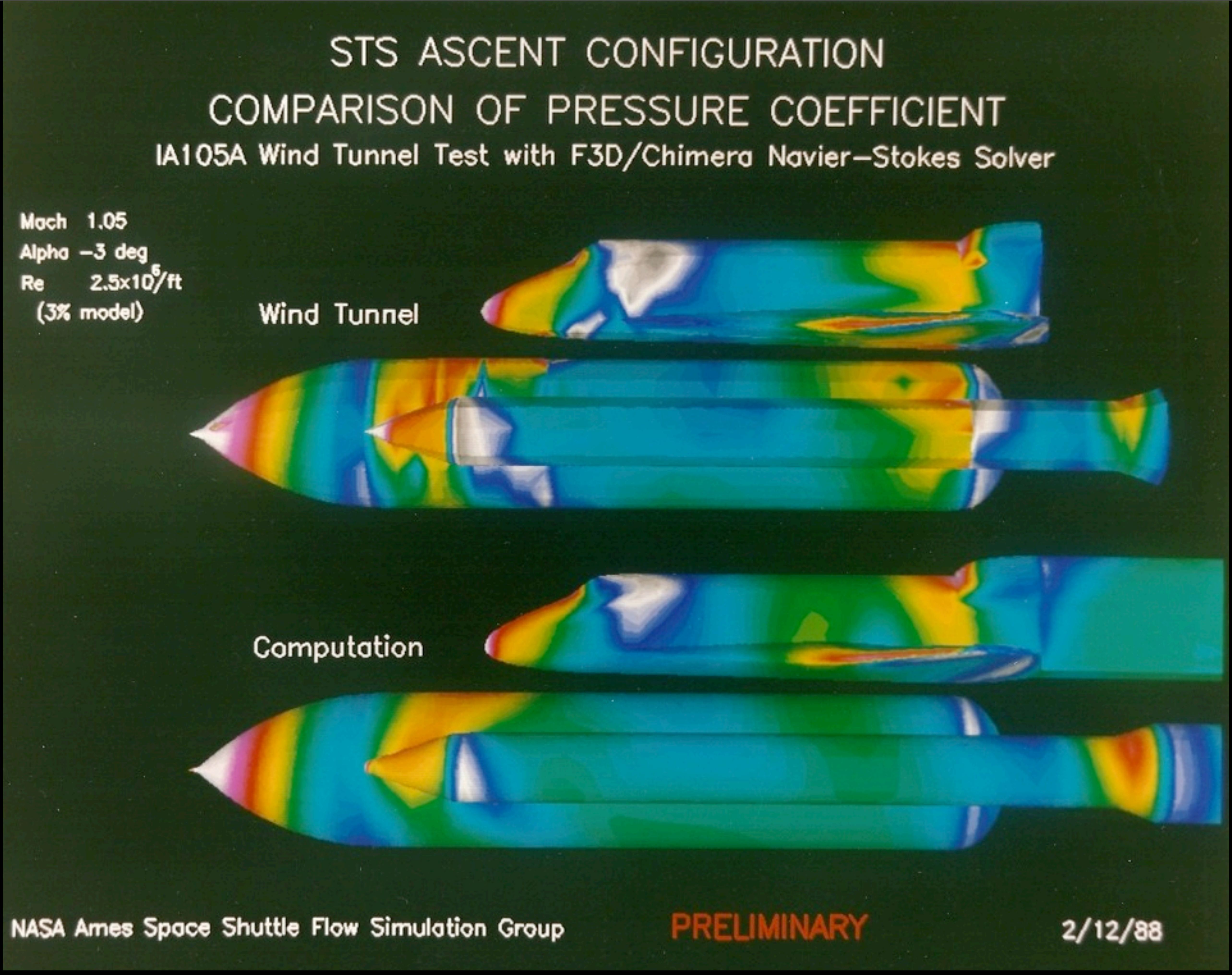
- Force and moment data was easily corrected with flight derived aerodynamic increments.
- Aerodynamic loads (pressure distribution) cannot be readily corrected because of *limited* flight pressure measurements.

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



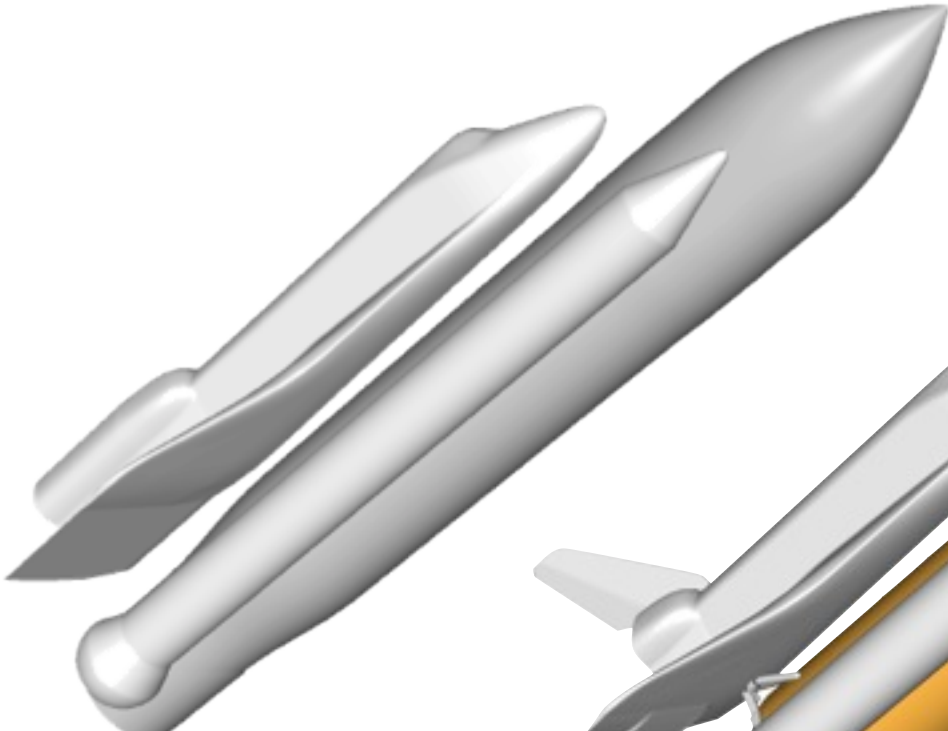




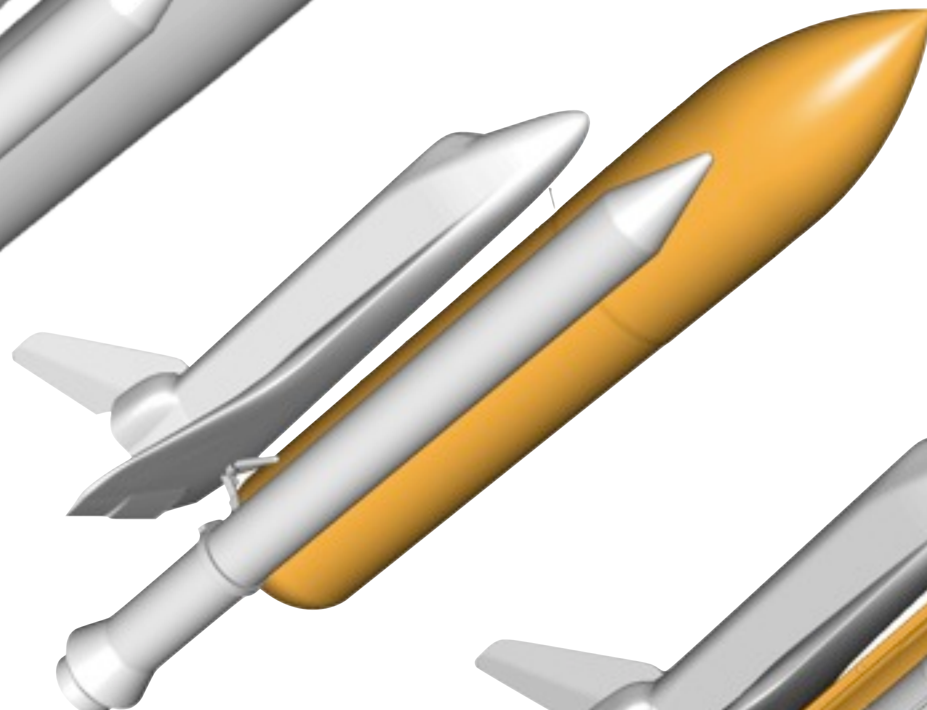


STS ASCENT CONFIGURATION
COMPARISON OF PRESSURE COEFFICIENT
IA105A Wind Tunnel Test with F3D/Chimera Navier-Stokes Solver
Mach 1.05
Alpha -3 deg
Re 2.5x10^6/ft
(3% model)
Wind Tunnel
Computation
NASA Ames Space Shuttle Flow Simulation Group
PRELIMINARY
2/12/88

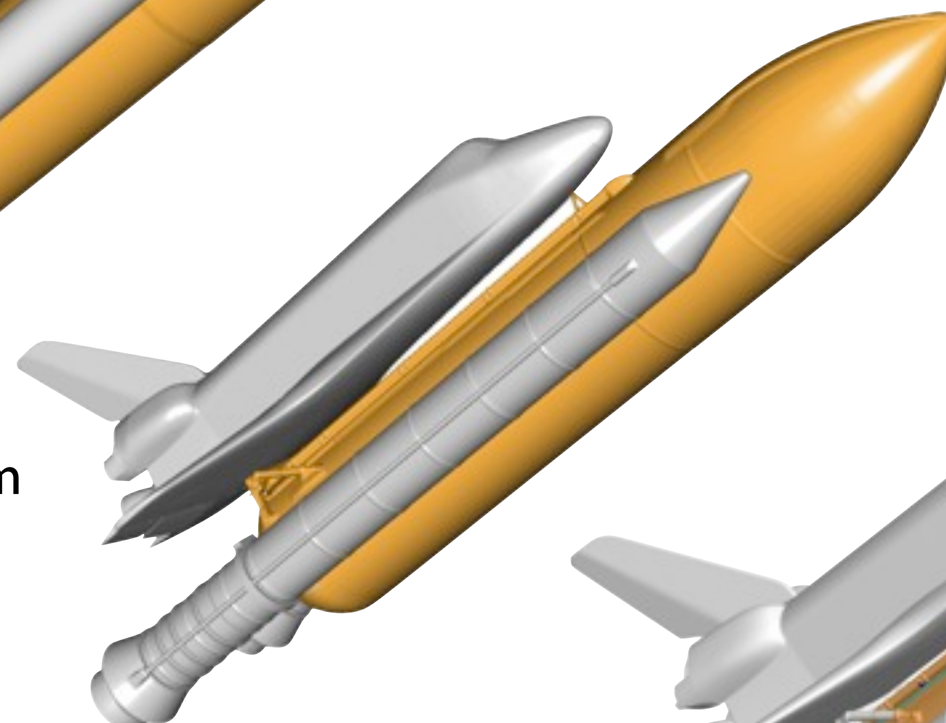
Space Shuttle Launch Vehicle (SSLV) Grid System Evolution



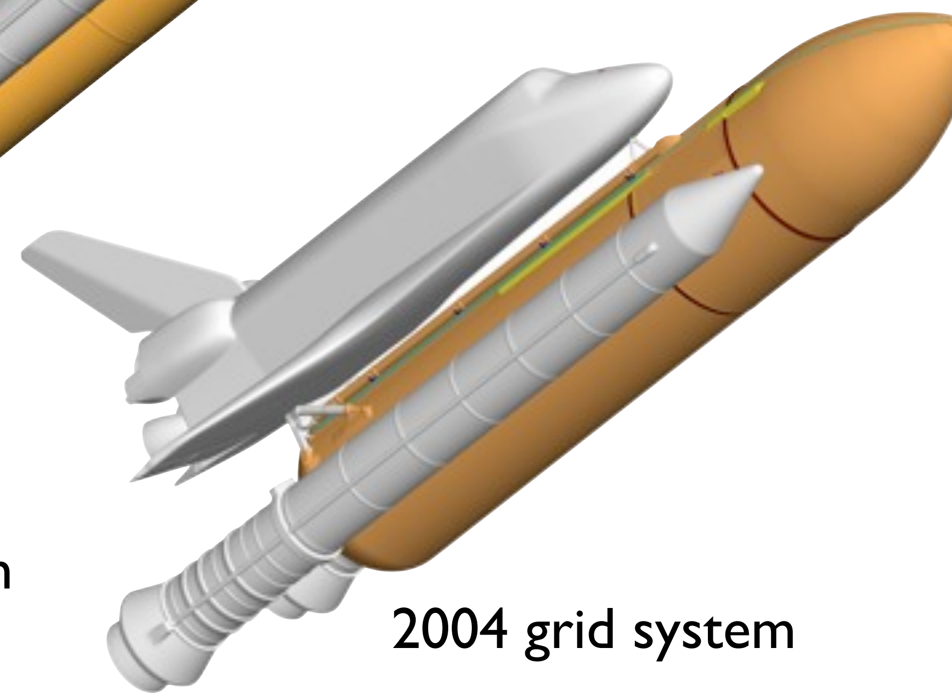
Early 80's grid system
3 Grids
10k surface points
0.3 million volume points



Late 80's grid system
14 Grids
35k surface points
1.6 million volume points

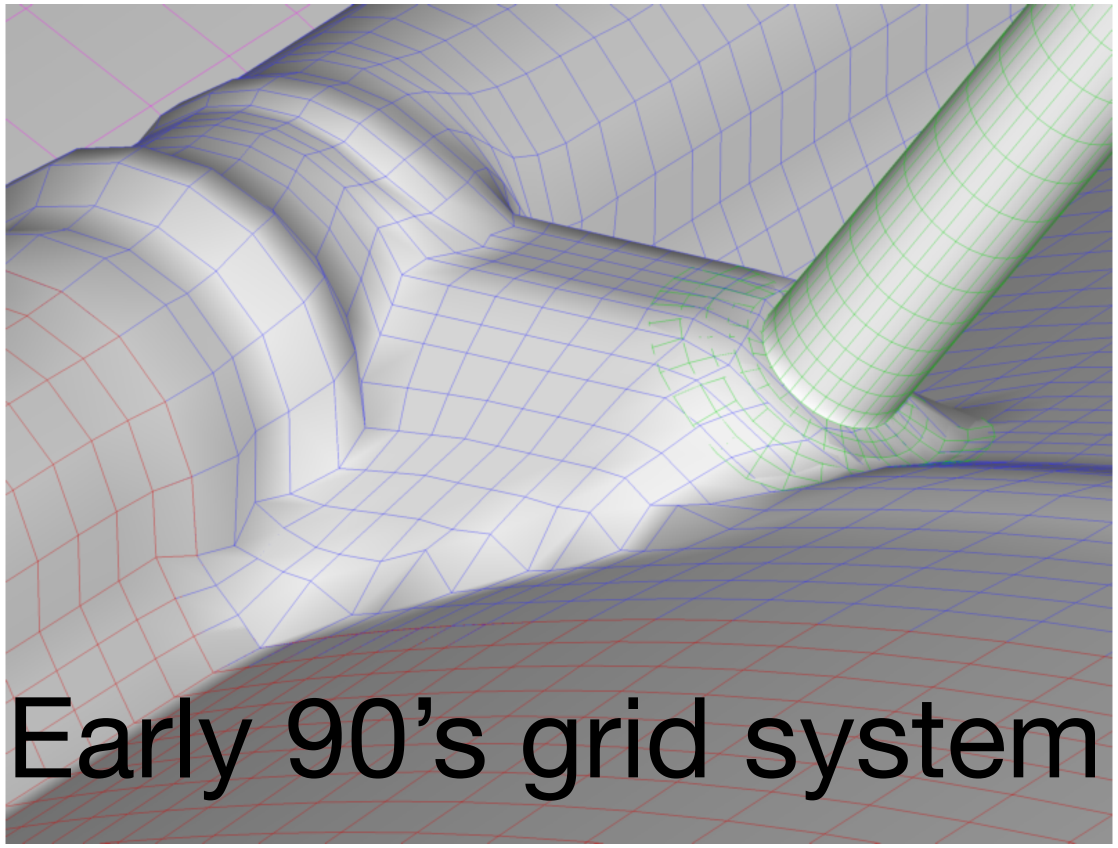


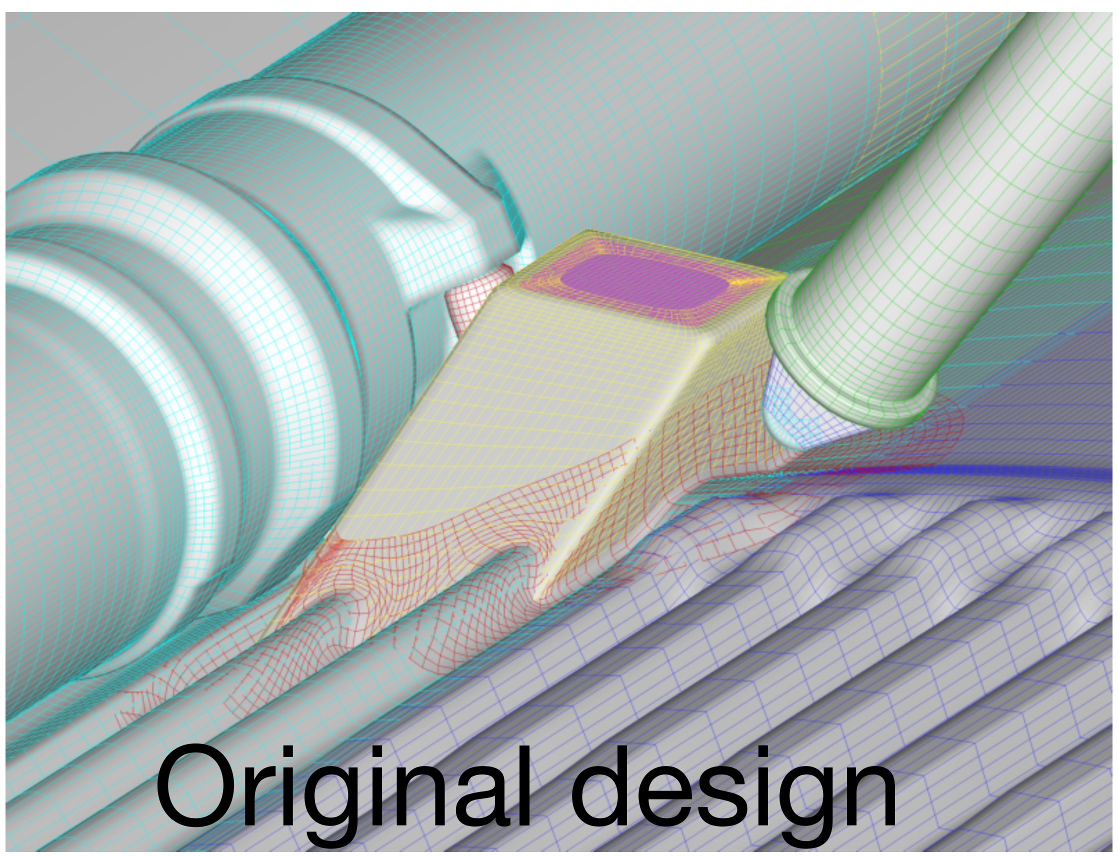
Early 90's grid system
113 Grids
268k surface points
16.4 million volume points

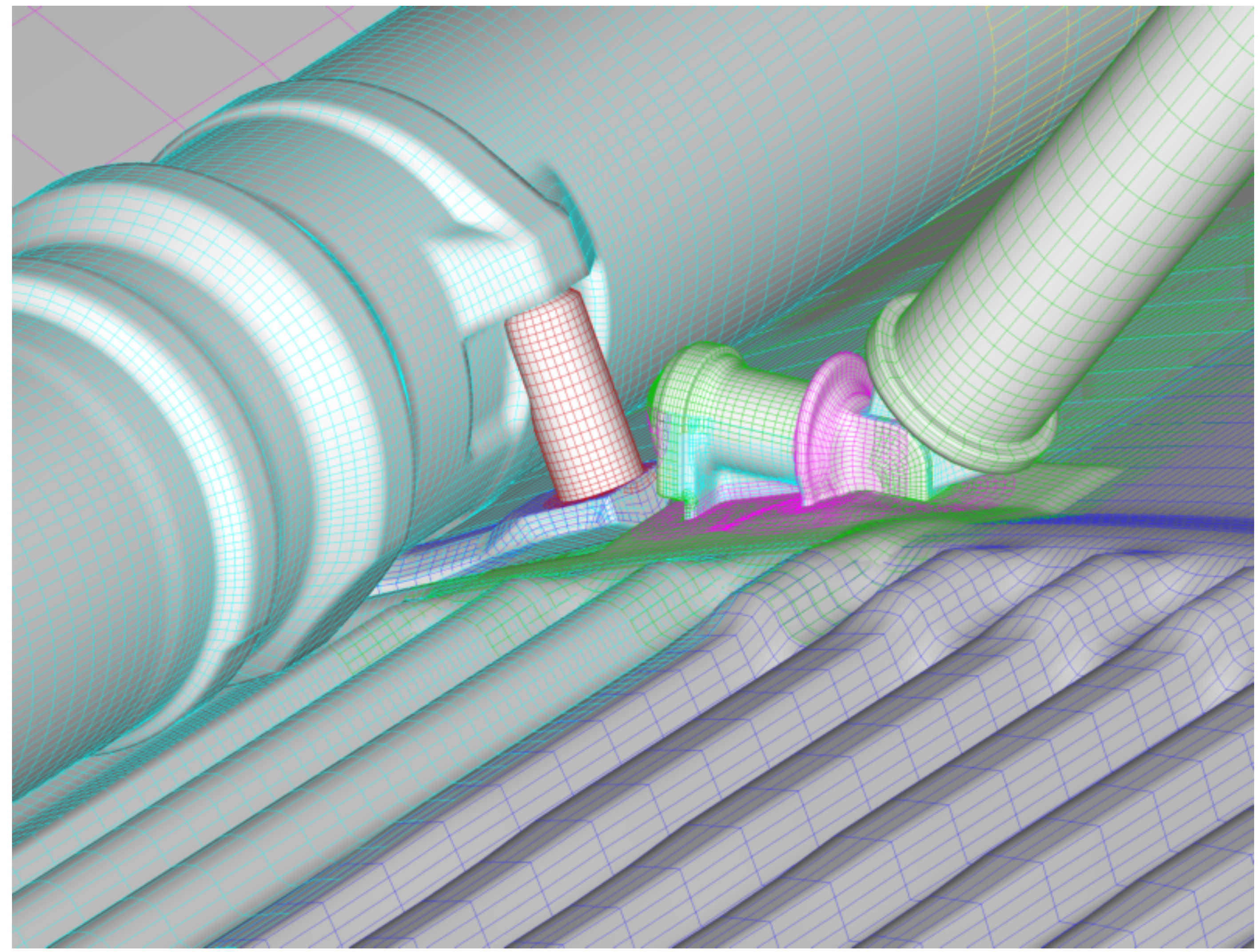


2004 grid system
267 Grids
636k surface points
34.8 million volume points

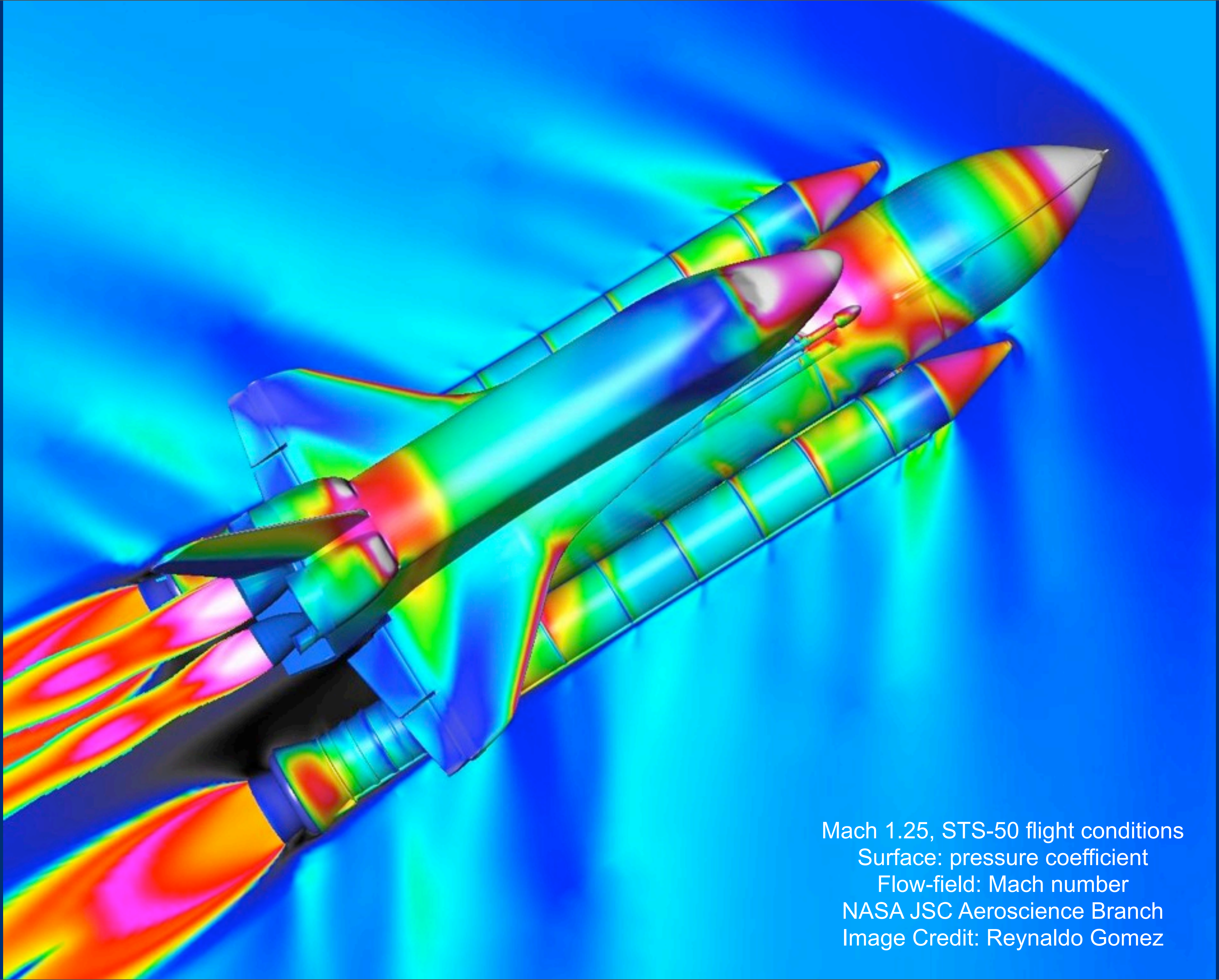
Bipod Ramp Redesign





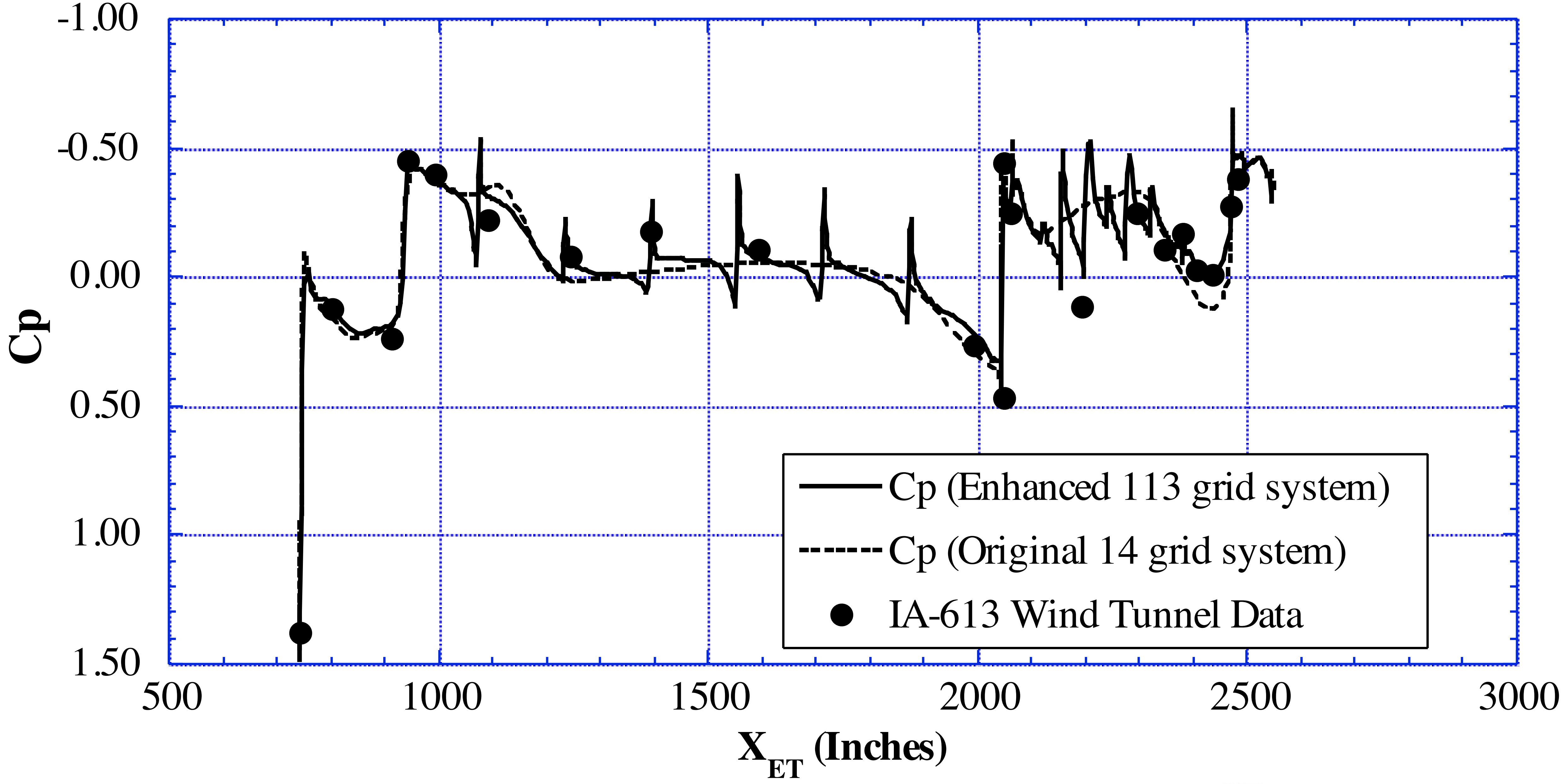


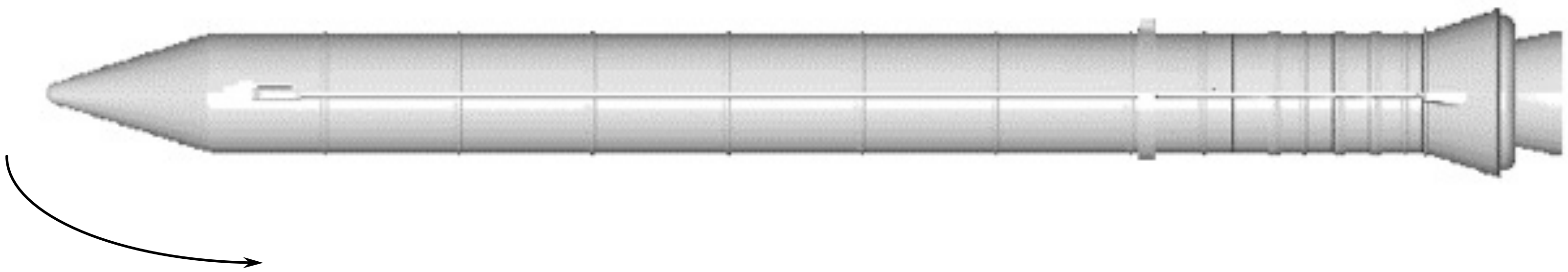
Current configuration


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

Solid Rocket Booster Surface Pressures

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

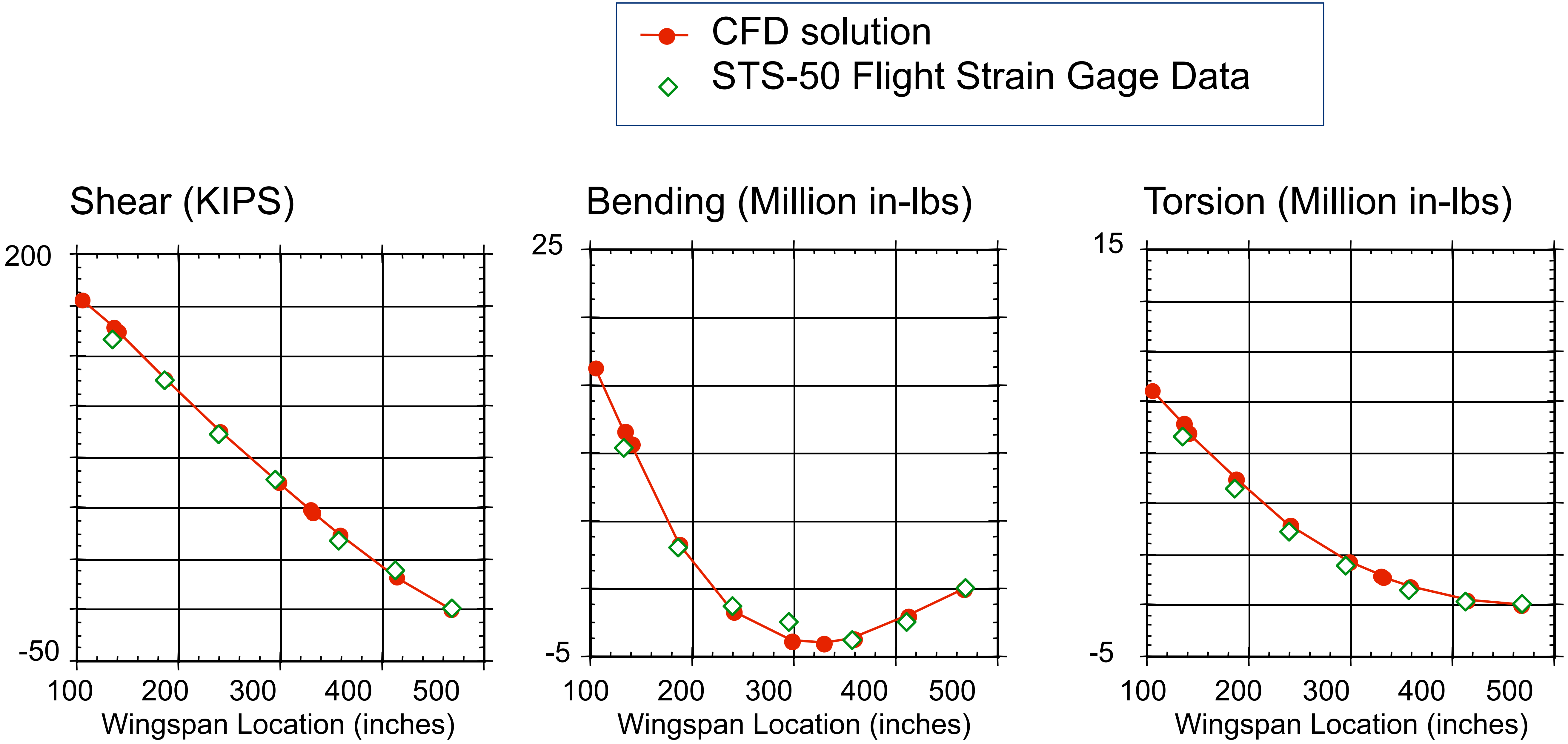




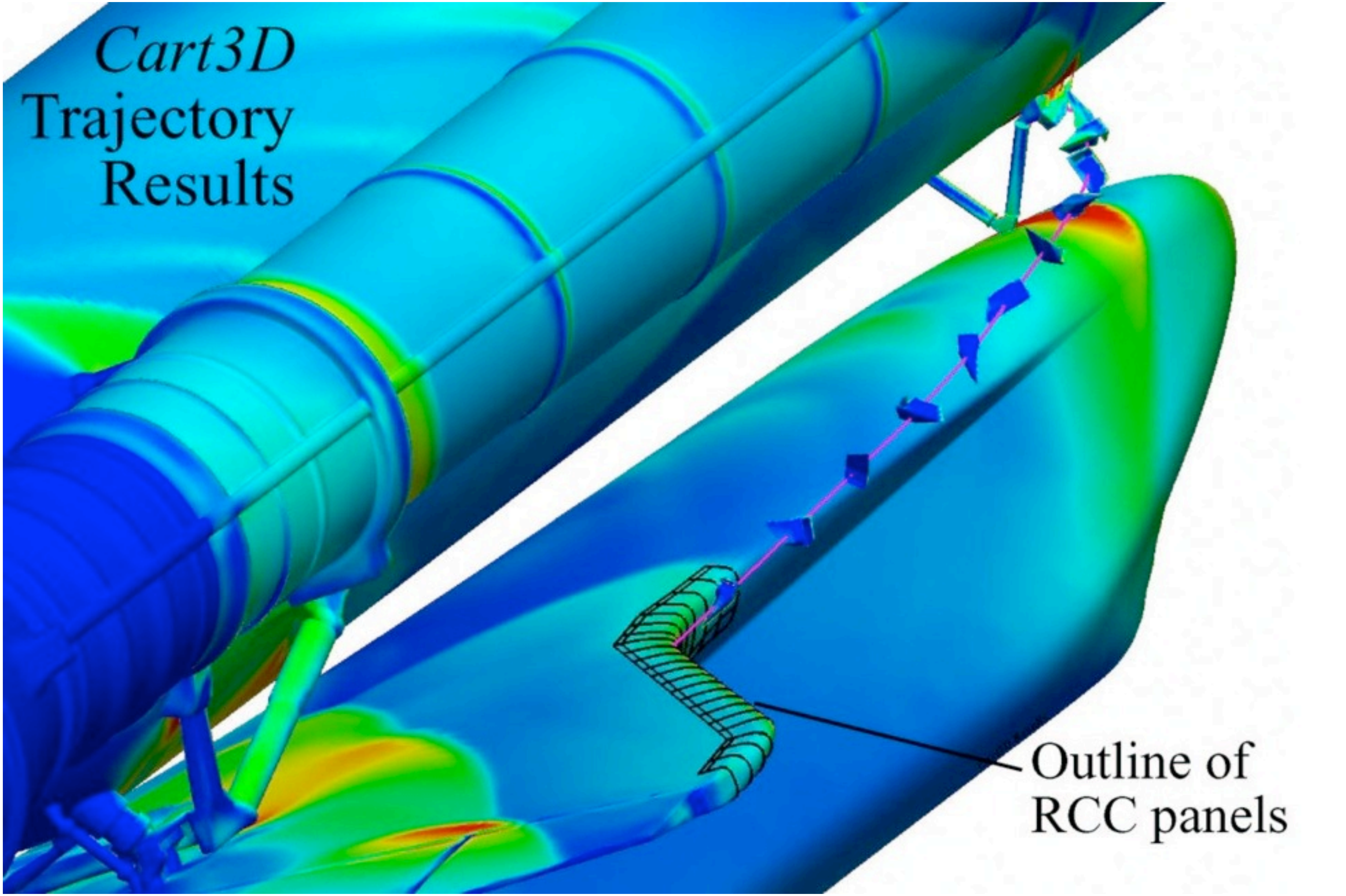
Flight Orbiter Wing Loads (Left Wing)

Mach 1.25, Flight Re

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



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.

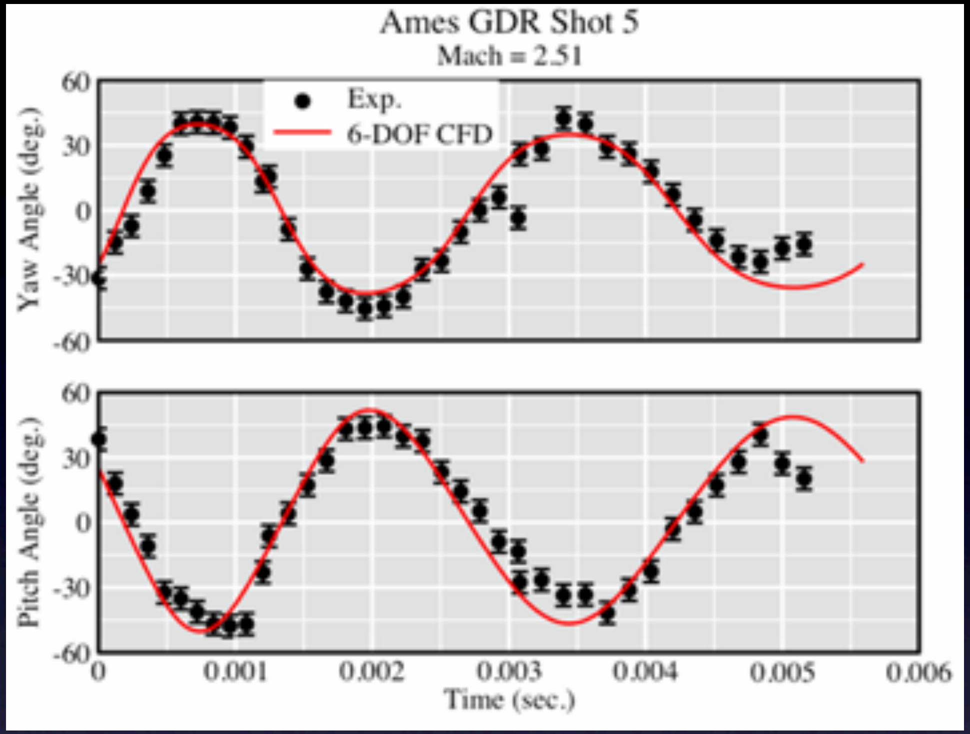
Greatly increased emphasis on verification & validation.

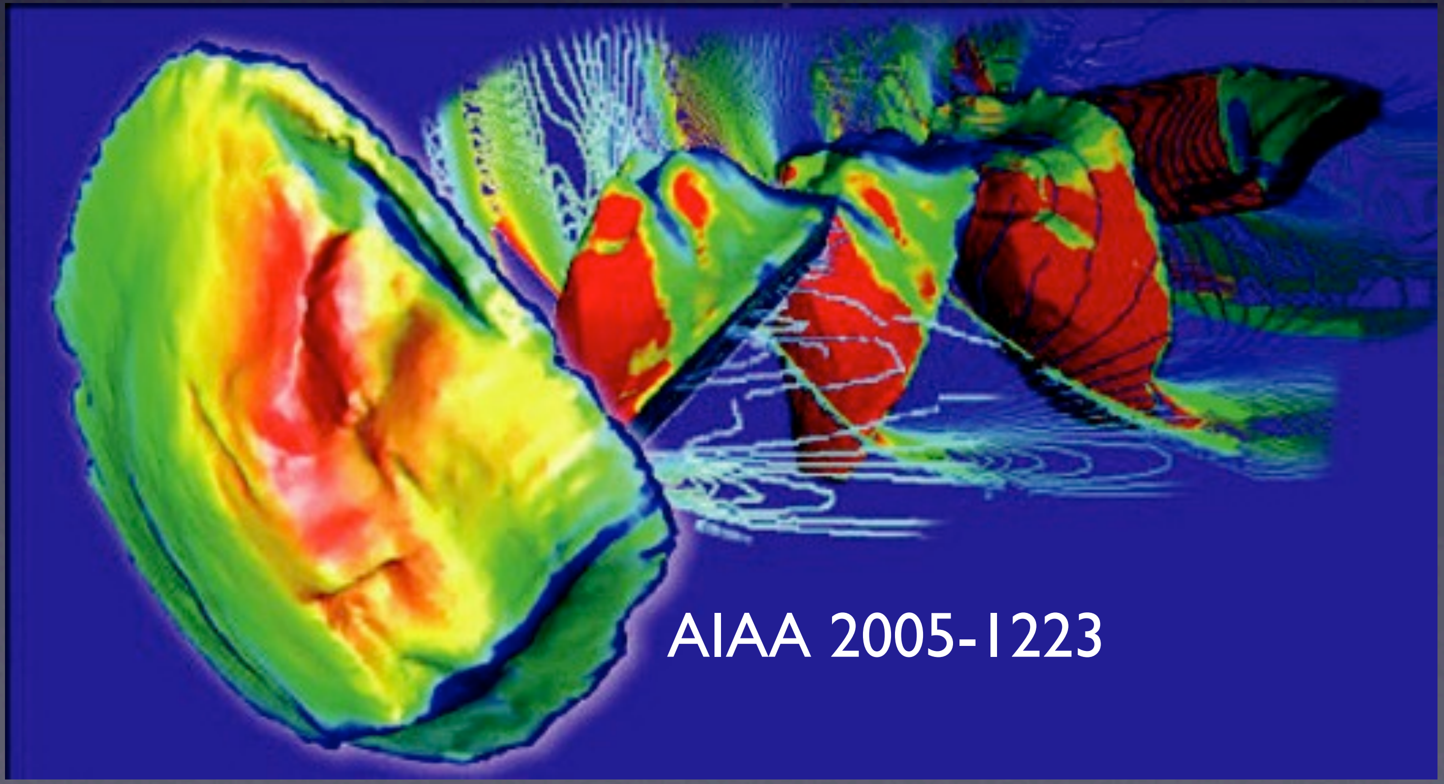
STS-114 and subsequent missions

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

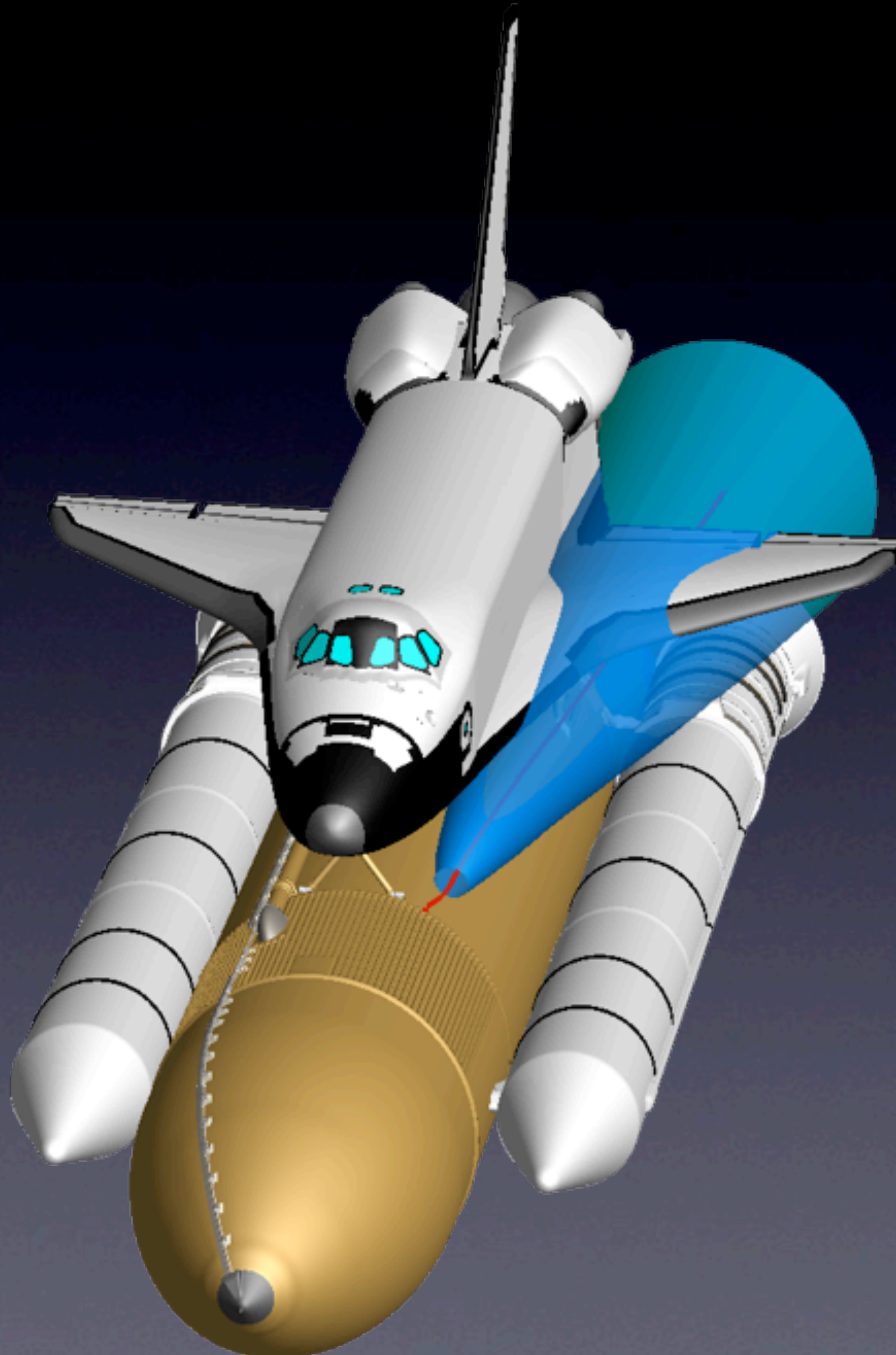
Debris transport aerodynamic models & prediction tools developed

AIAA-2006-0662

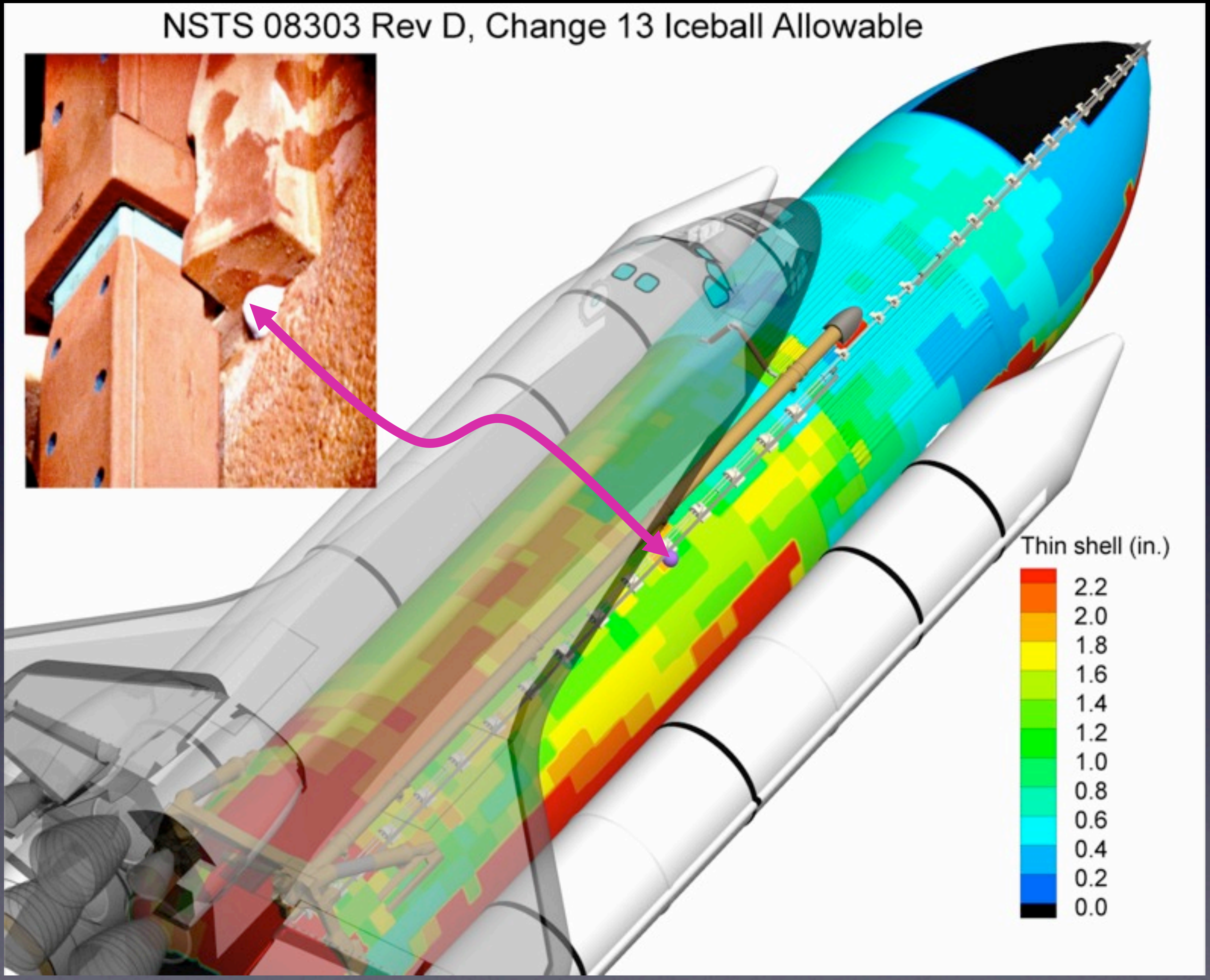




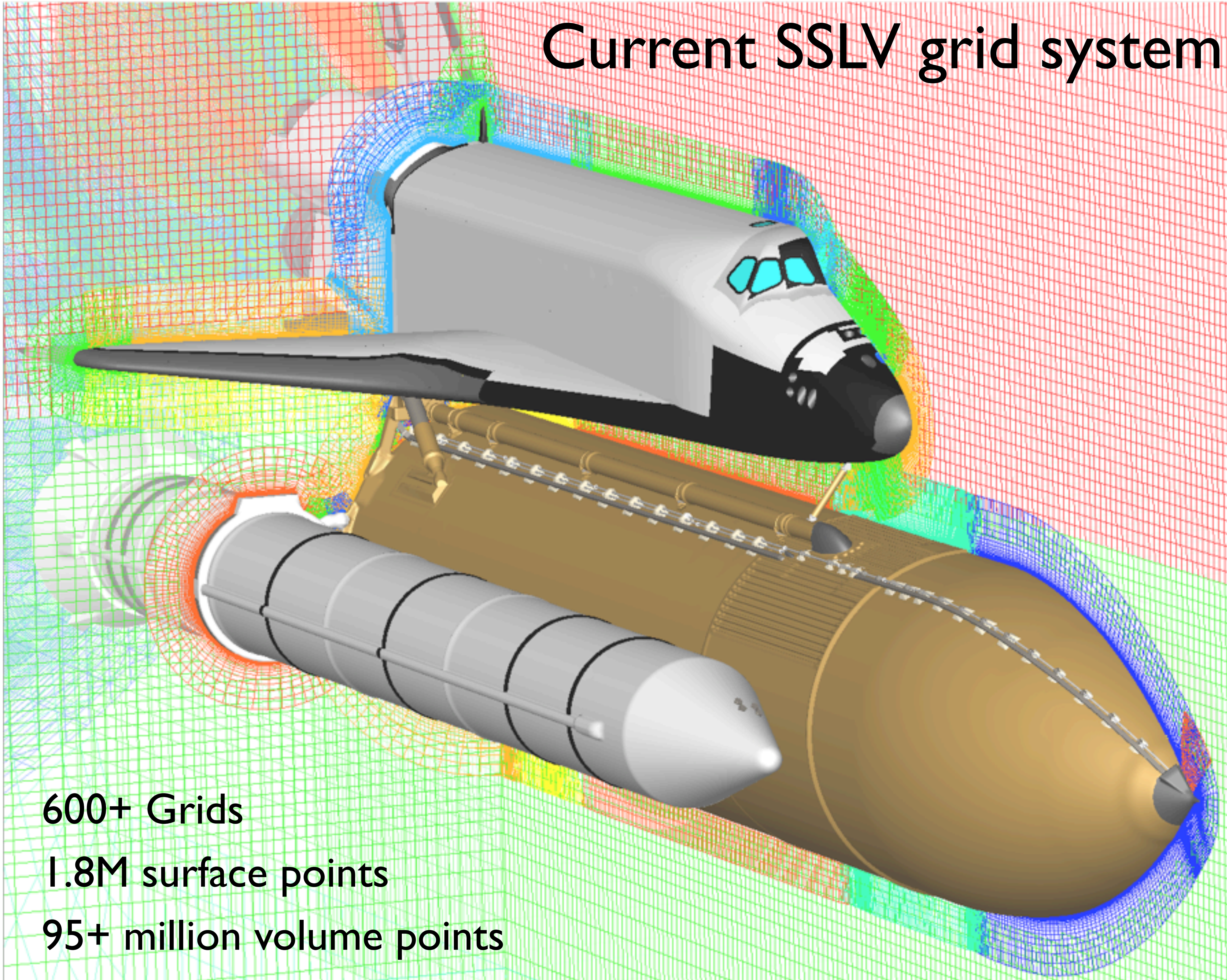
AIAA 2005-1223



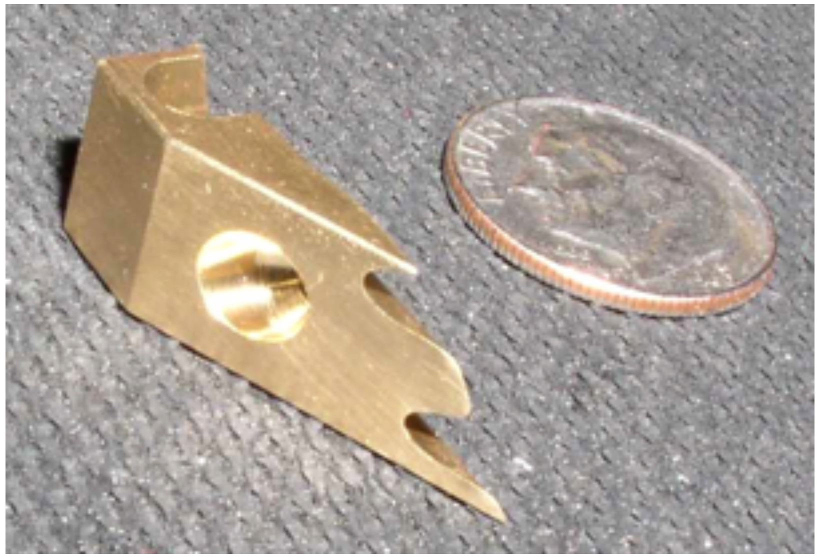
NSTS 08303 day of launch ice ball launch commit tool developed by Stuart Rogers/ARC NAS-07-004

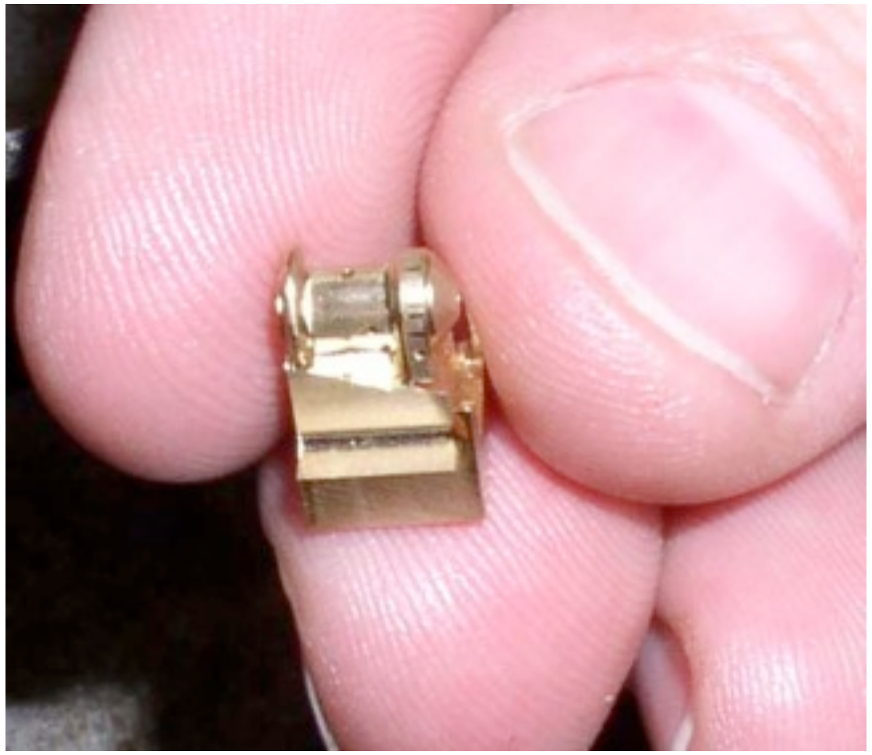


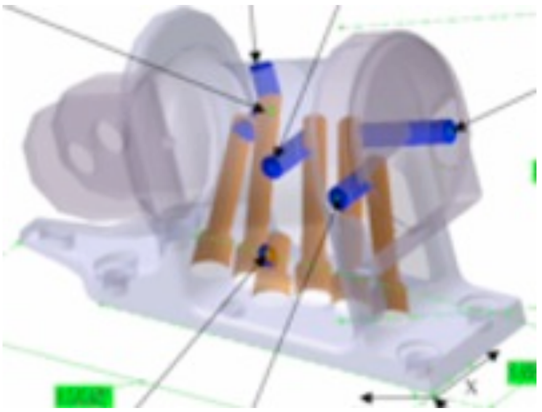
Current SSLV grid system

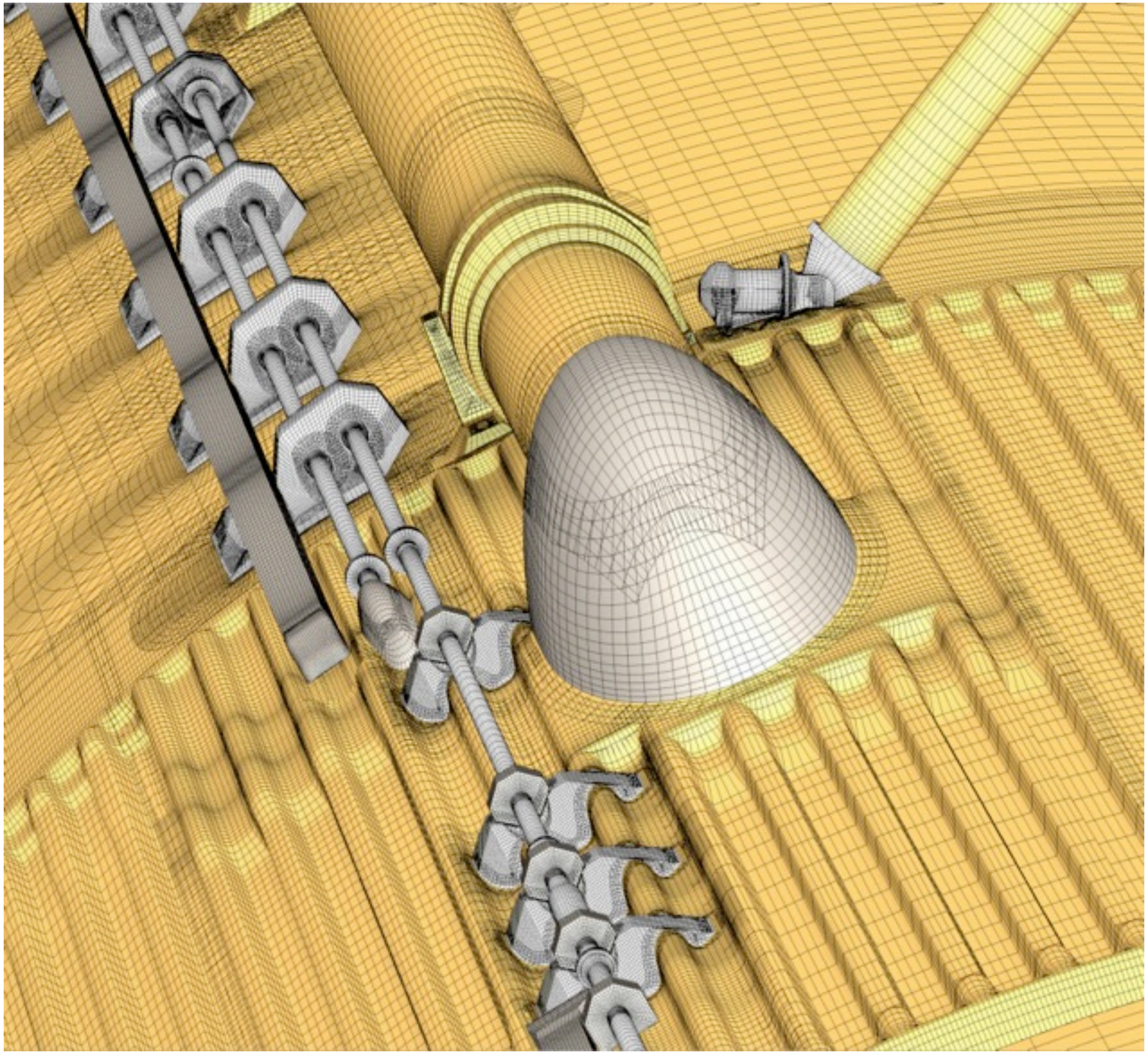


Wind tunnel validation and CFD extrapolation

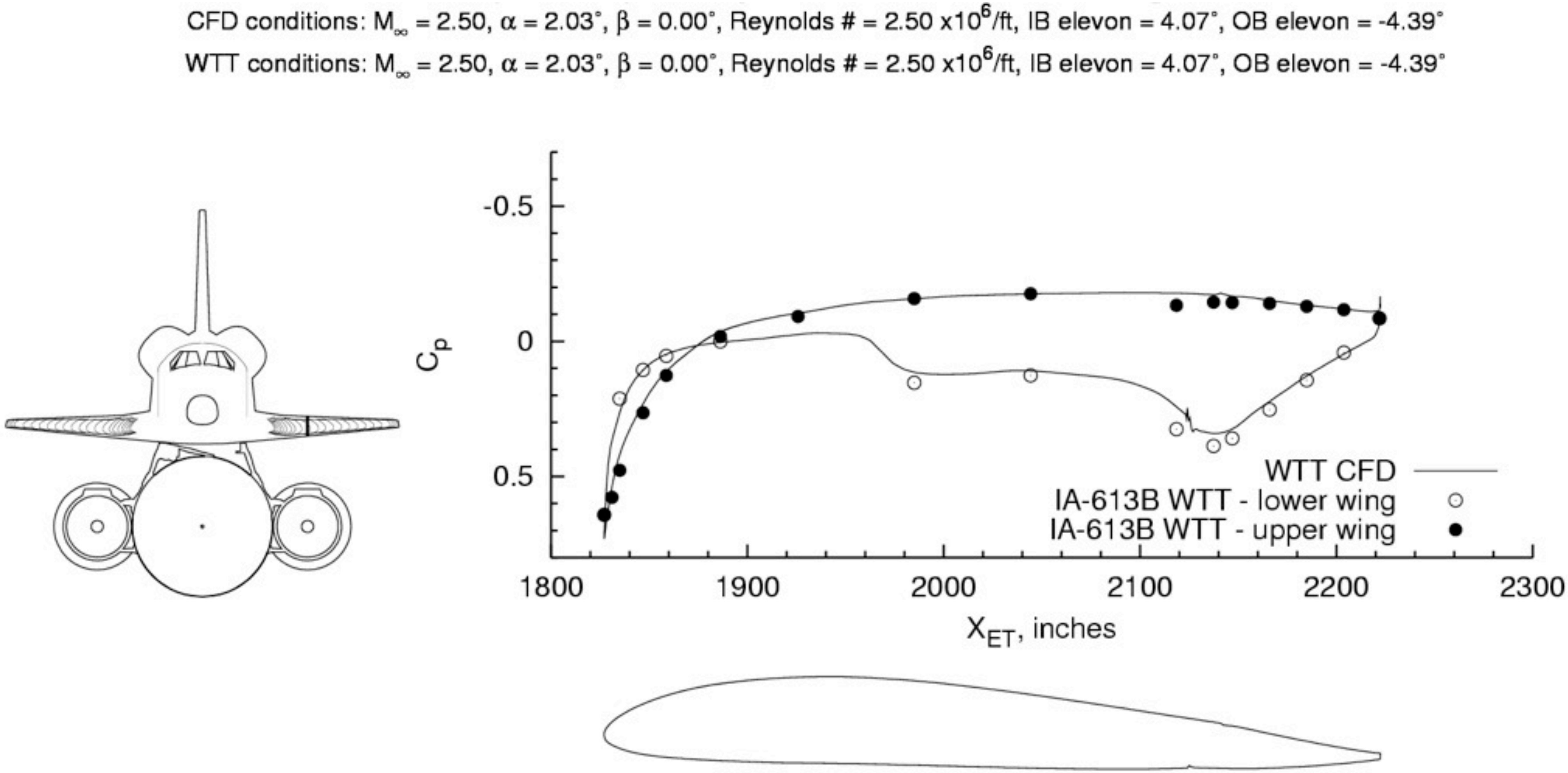






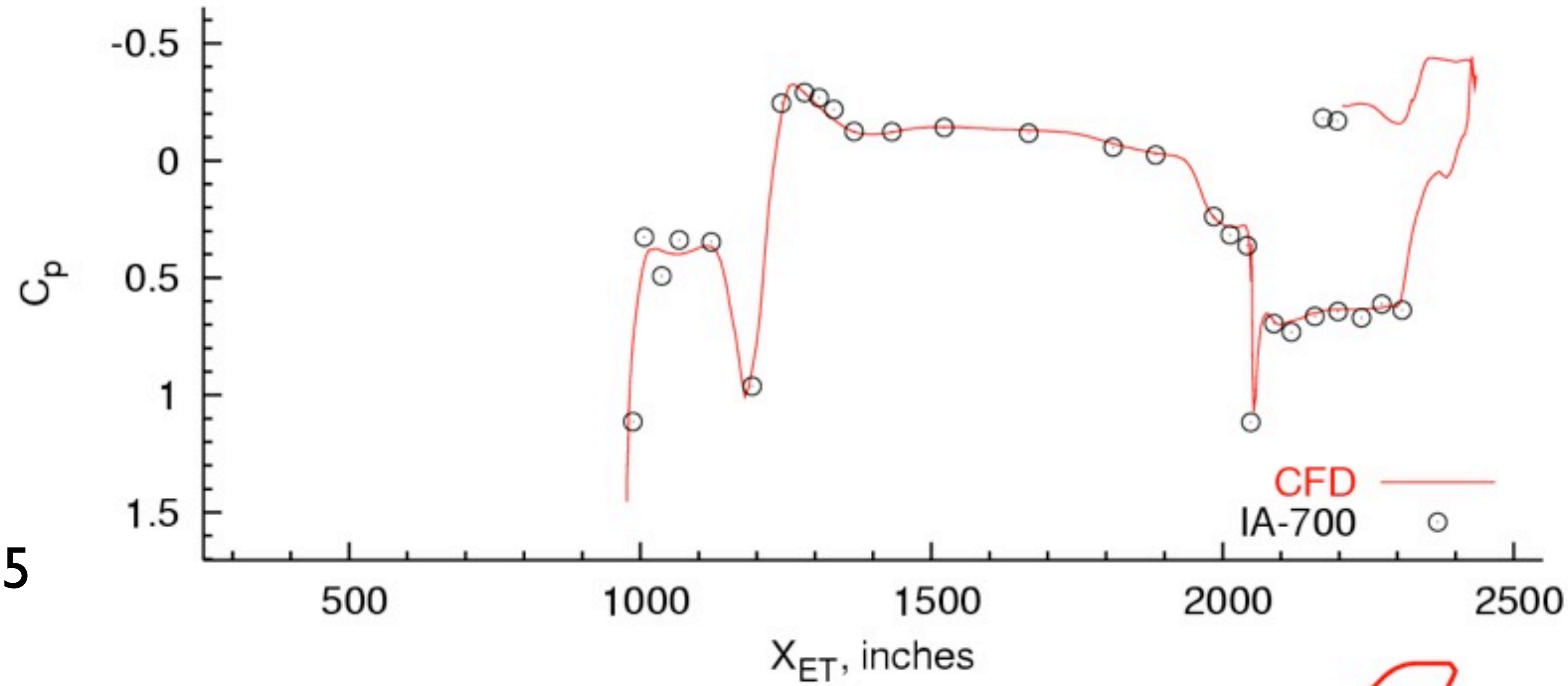


Previous wind tunnel comparisons focused on wing loads.

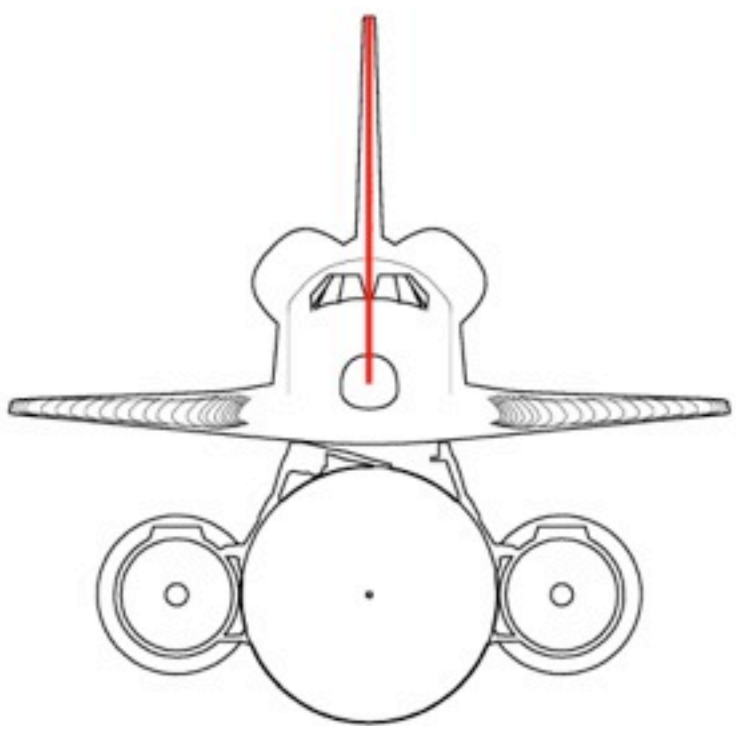


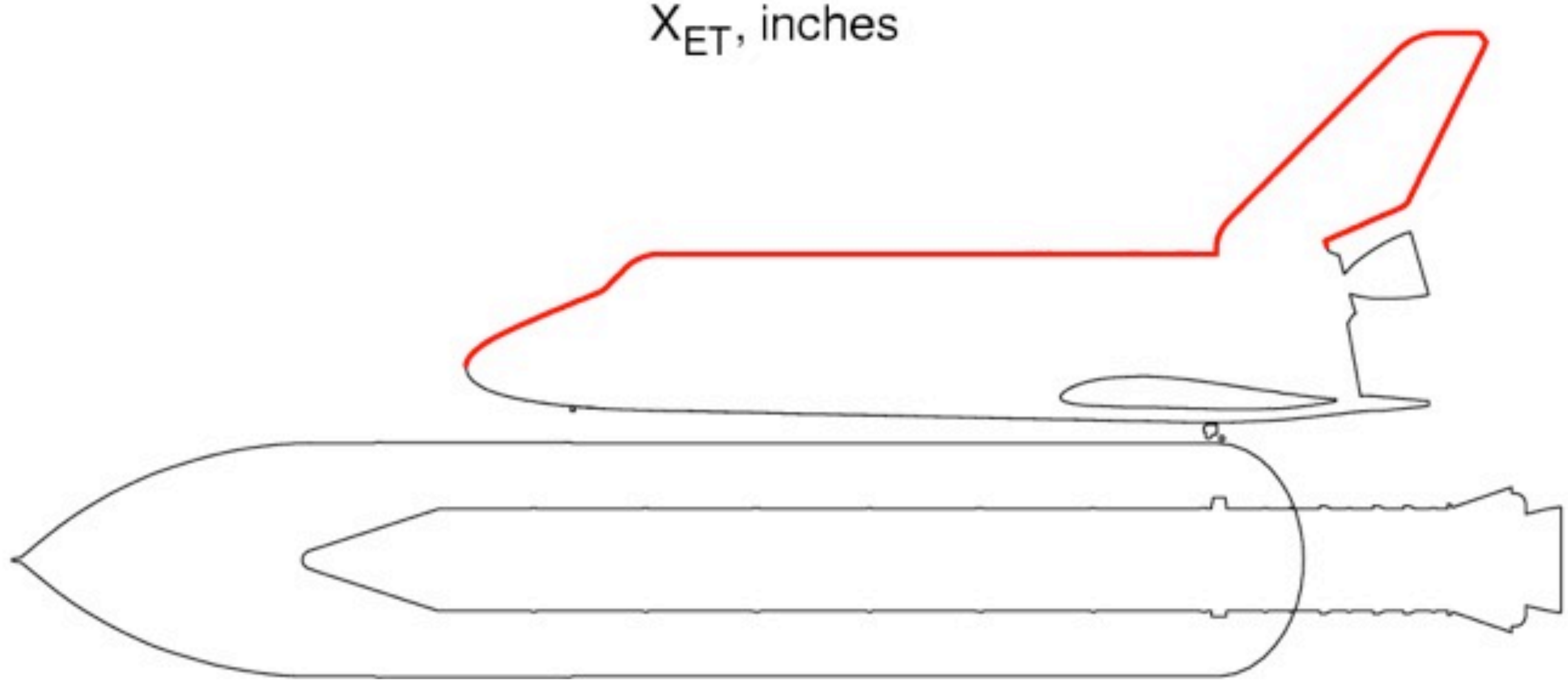
AIAA 2004-2226

Wind tunnel test pressure comparisons show good agreement with predictions

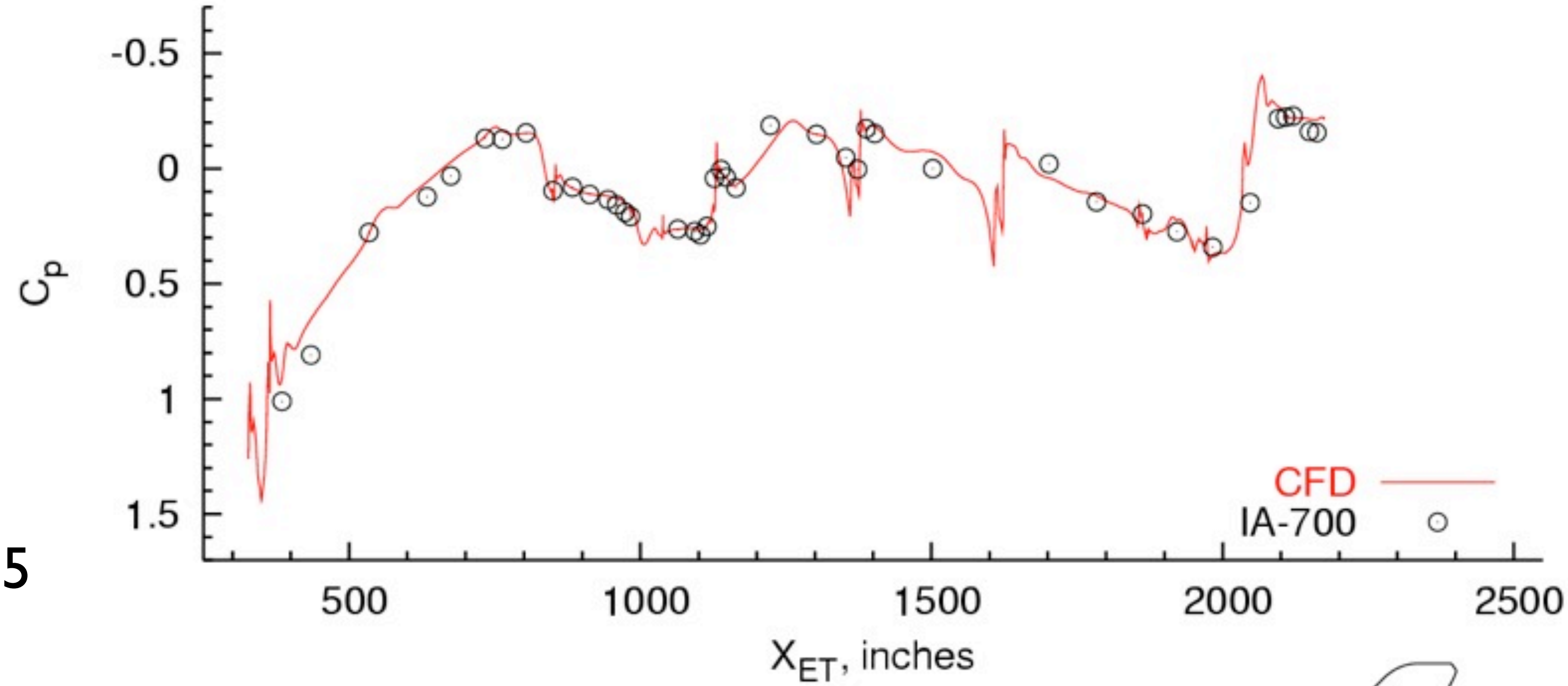


JSC 2005-62925

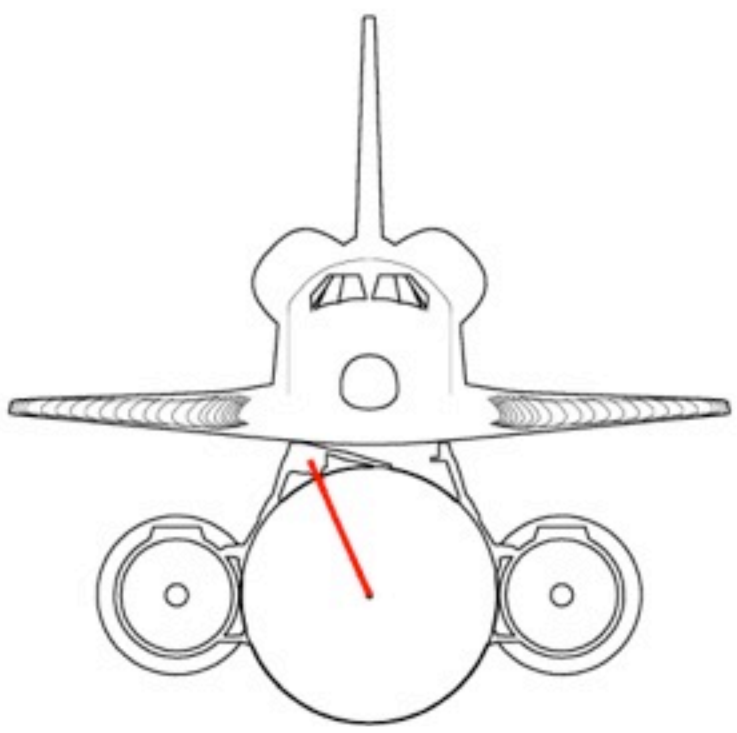


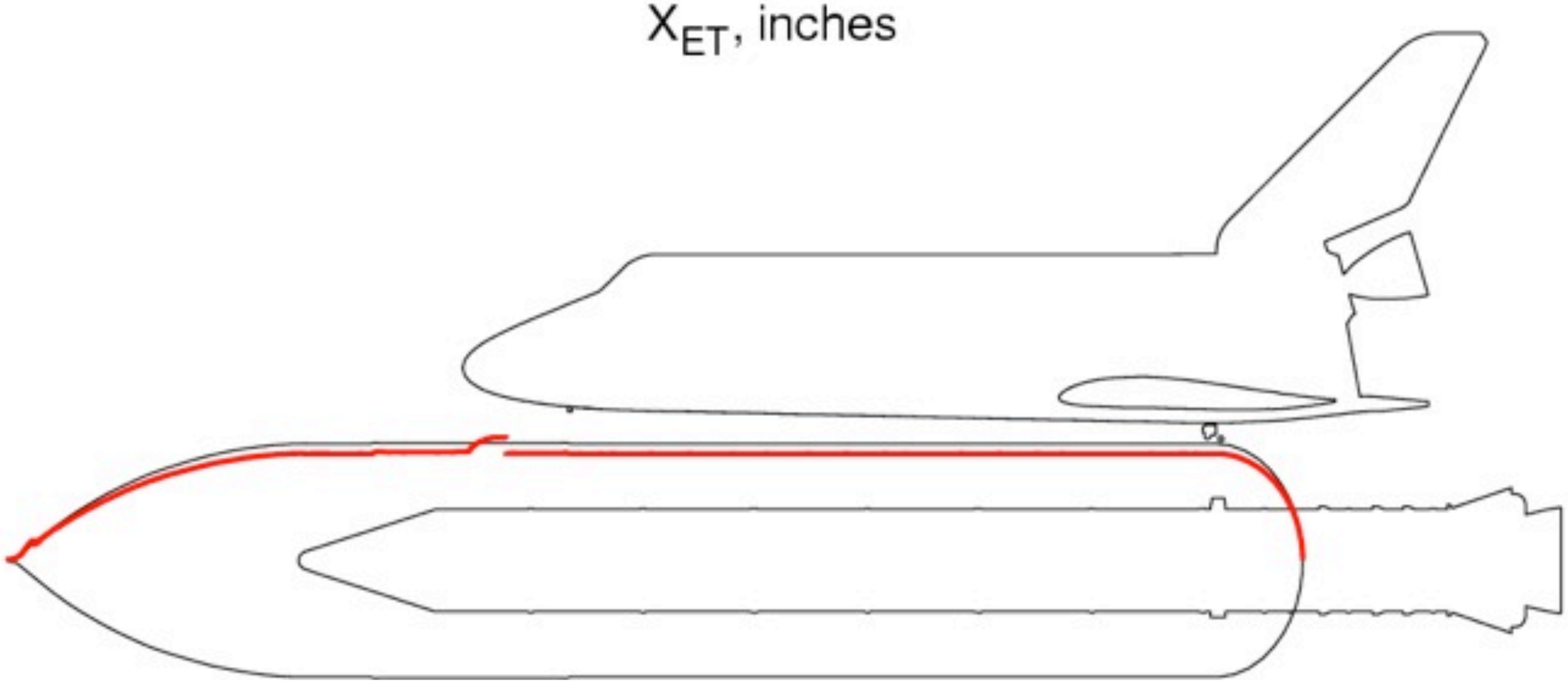


Detailed comparisons along the LO_2 feedline were key to understanding protuberance airloads.

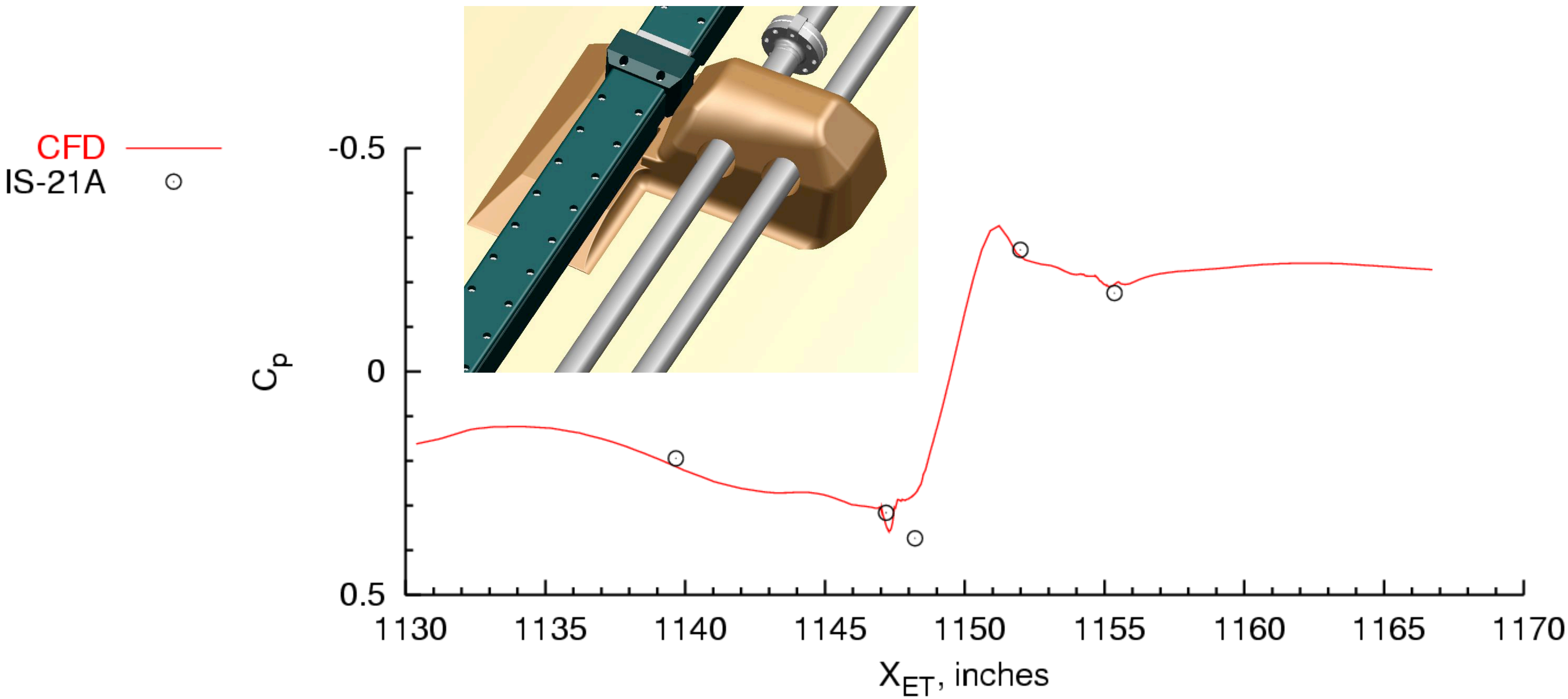


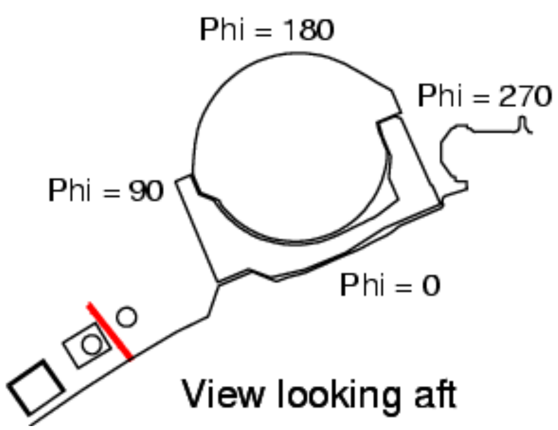
JSC 2005-62925

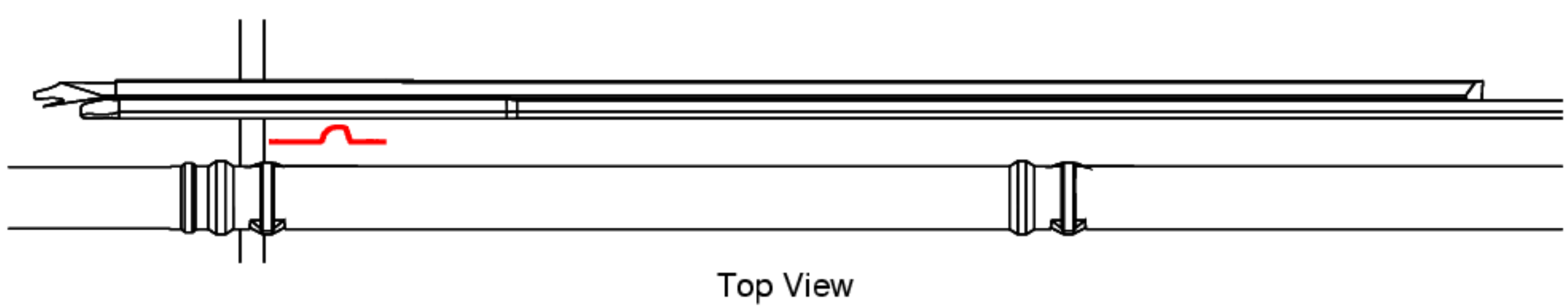




Proposed ice/frost ramp configuration, tested but not flown.

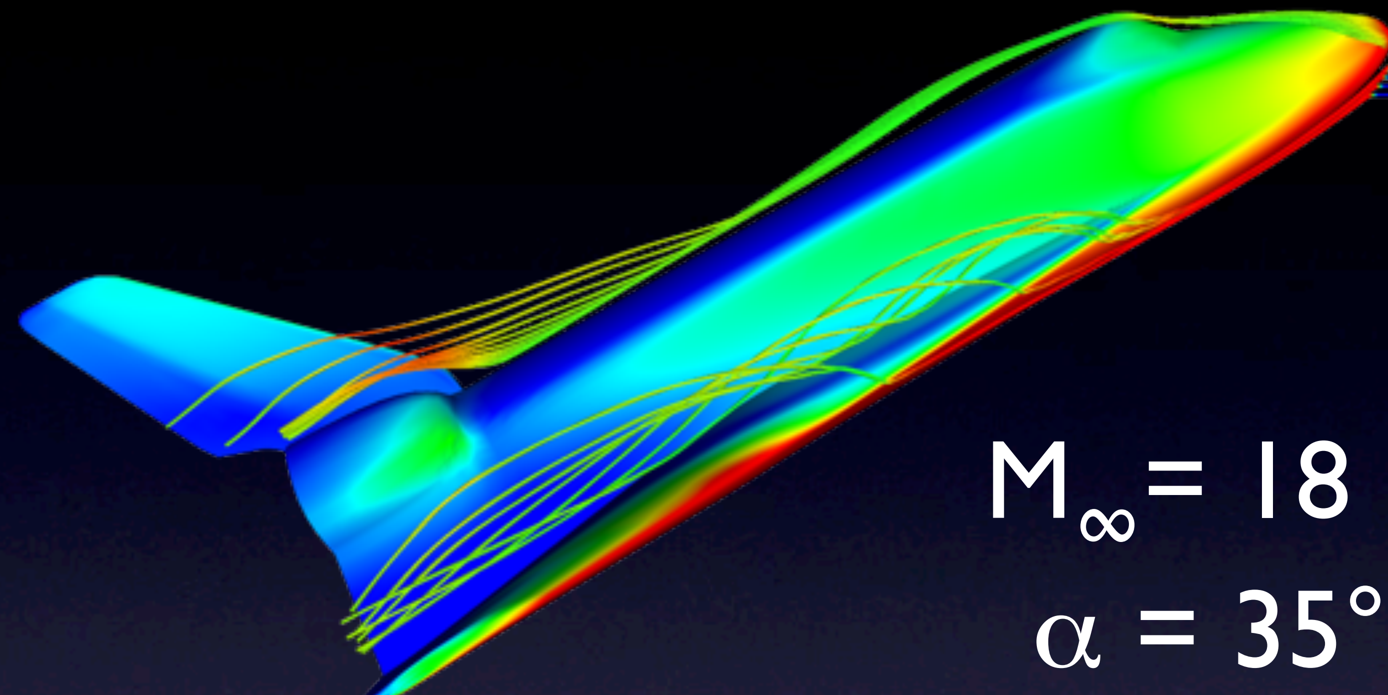




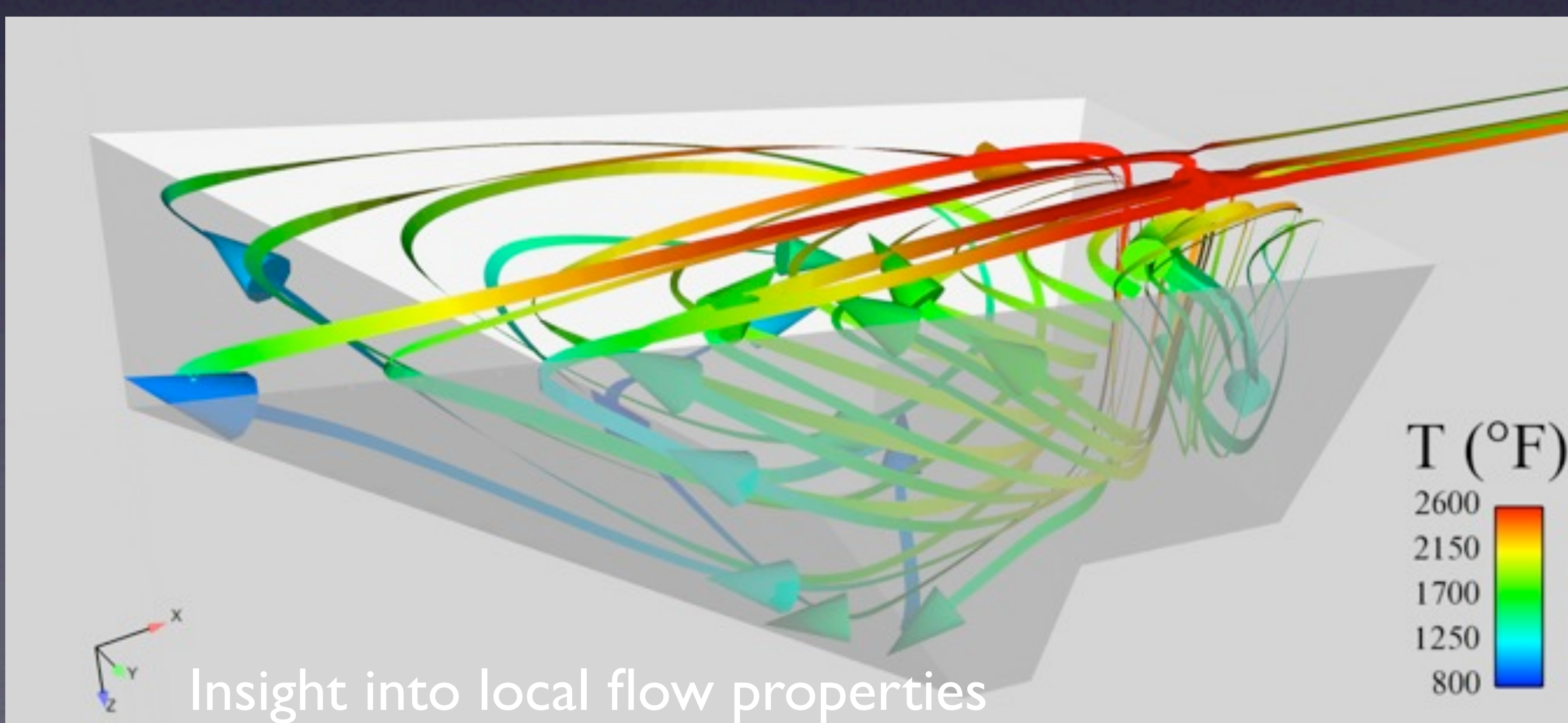


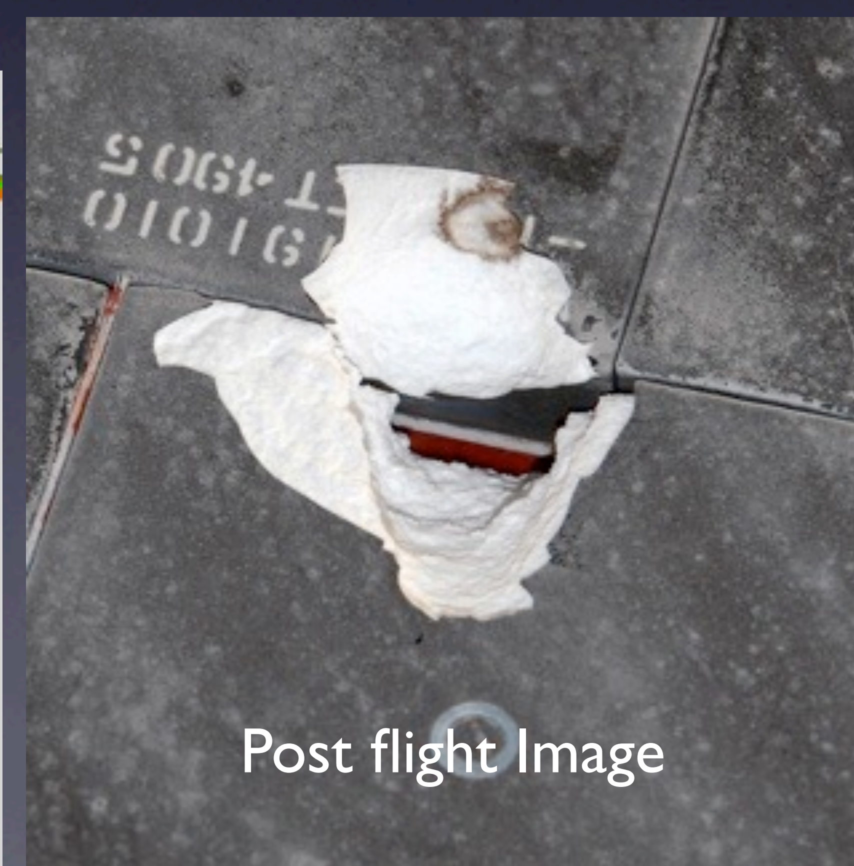
Inflight entry analyses

AIAA 2008-4246



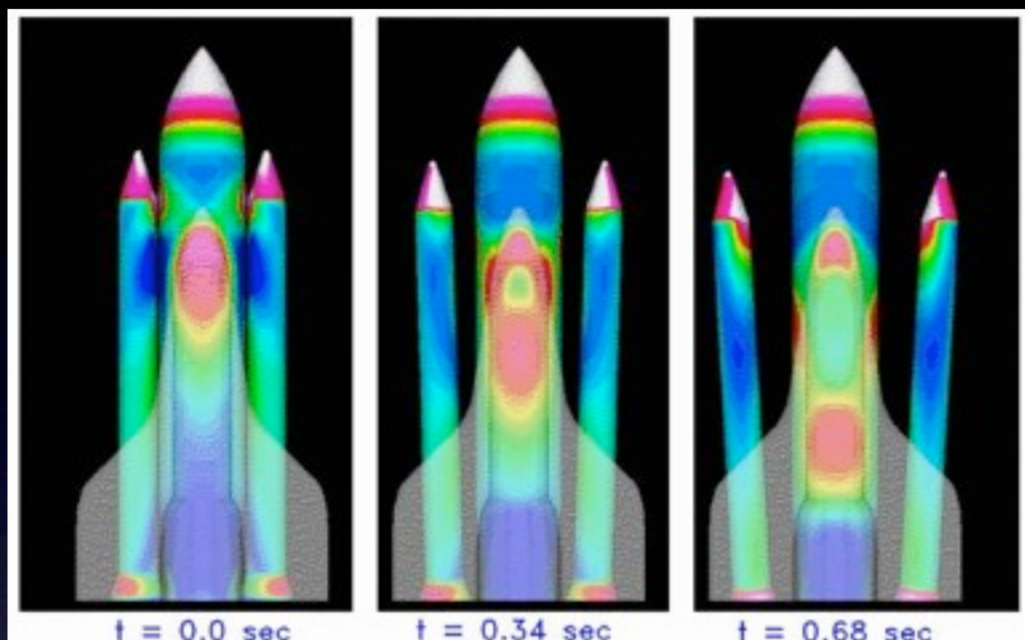
$M_\infty = 18$
$\alpha = 35°$



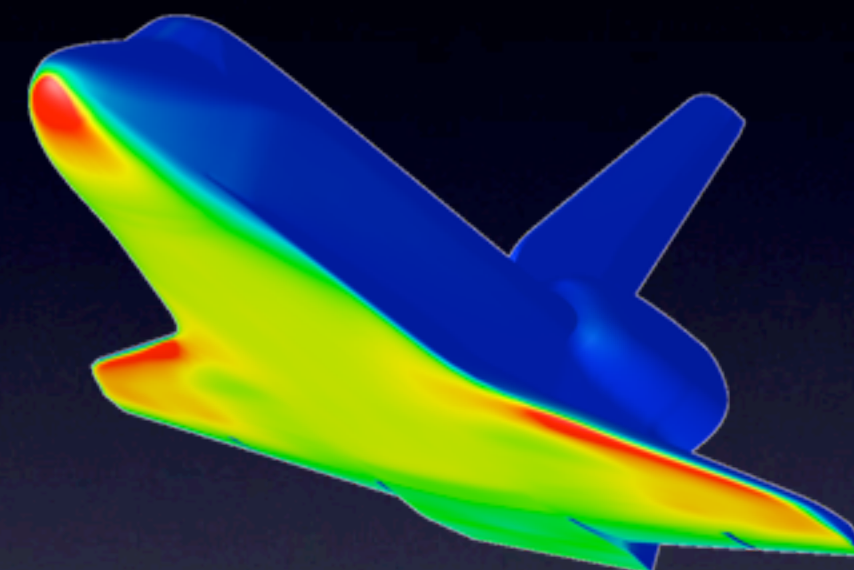


Parallel computing from prelaunch to landing

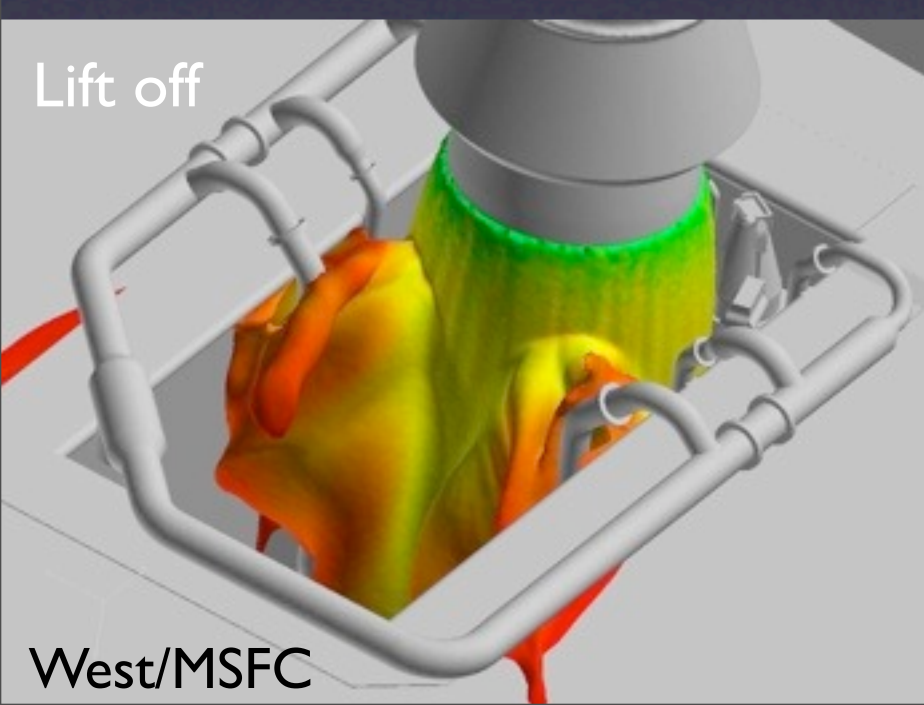
On-orbit Assessments
Hypervelocity Orbital Debris

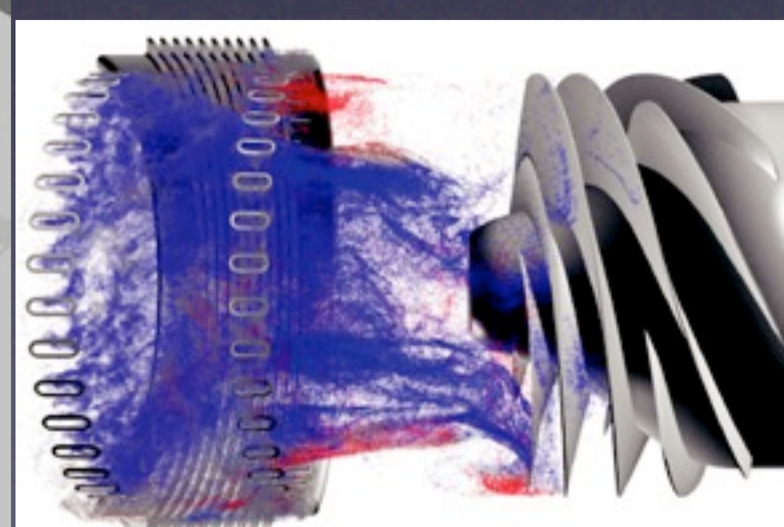


AIAA-2003-1248
Contingency Abort

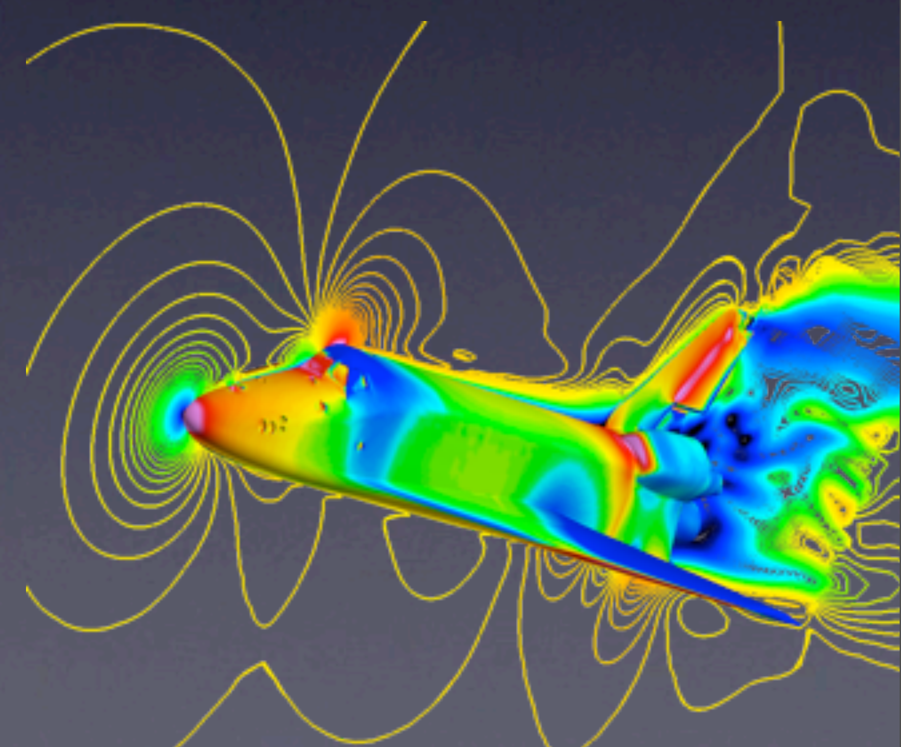


Transonic airloads
Roll maneuver



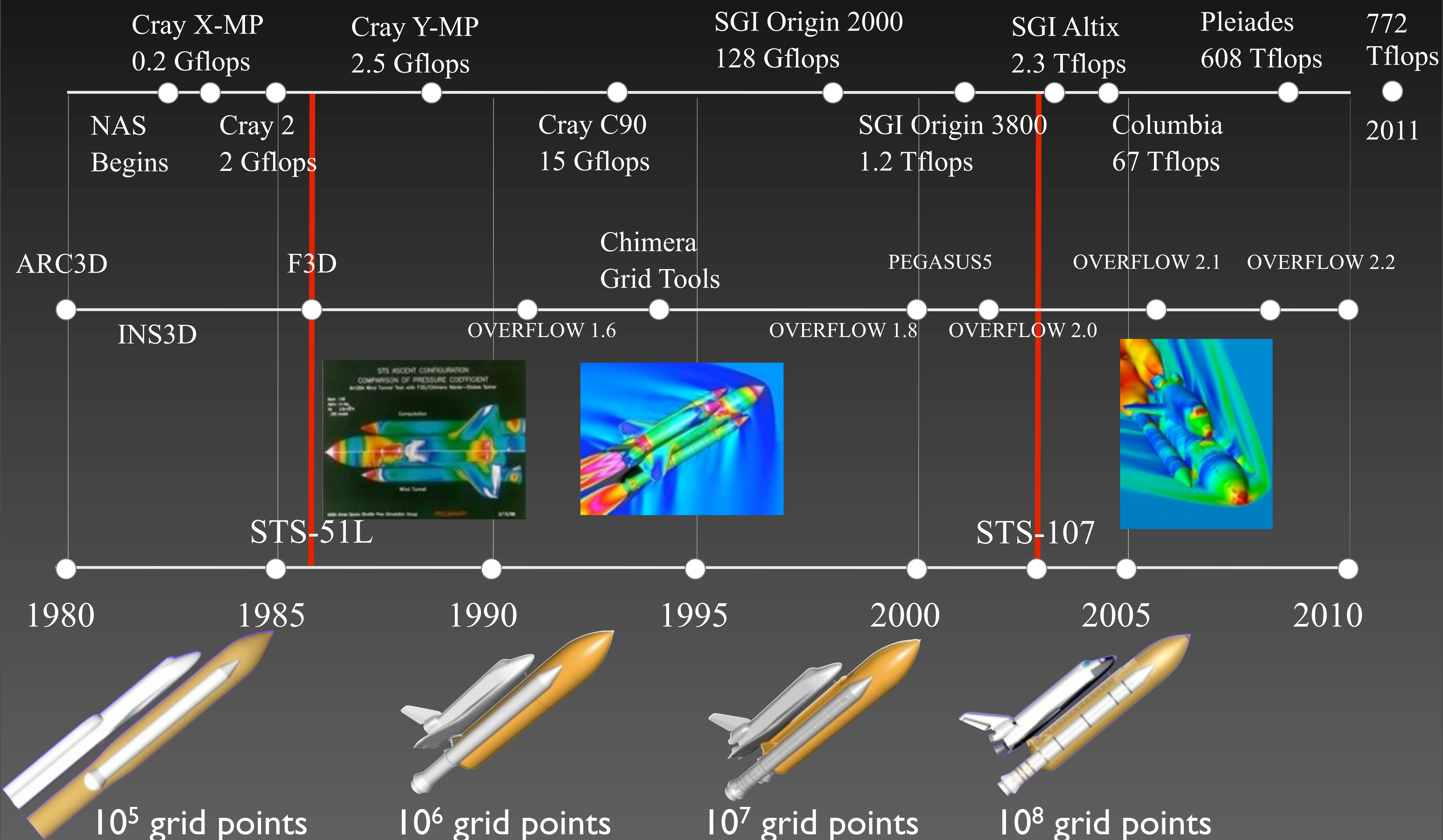


Cetin Kiris/ARC



Entry Airloads

Timeline of Computing & Overset Space Shuttle Applications

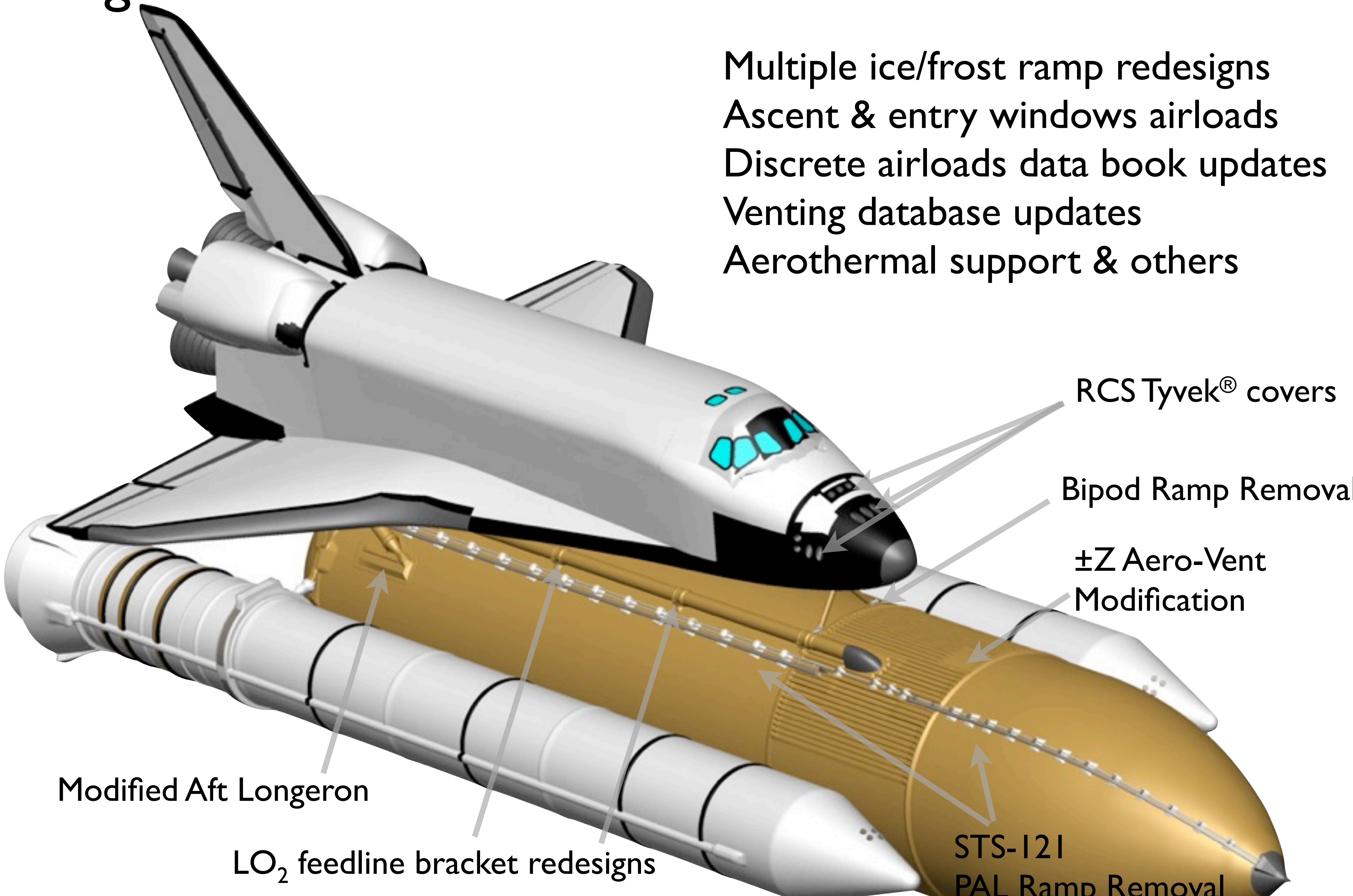


We went to the moon without CFD or parallel computers. Why do we need them now?

- Reduce number of physical tests and improve relevance when you run test
  - Nearly 100,000 hours (11 years) of Shuttle wind tunnel testing
  - Many facilities have shut down or been mothballed
- Provides flight increments/ environments that cannot be obtained from other sources.

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



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

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.