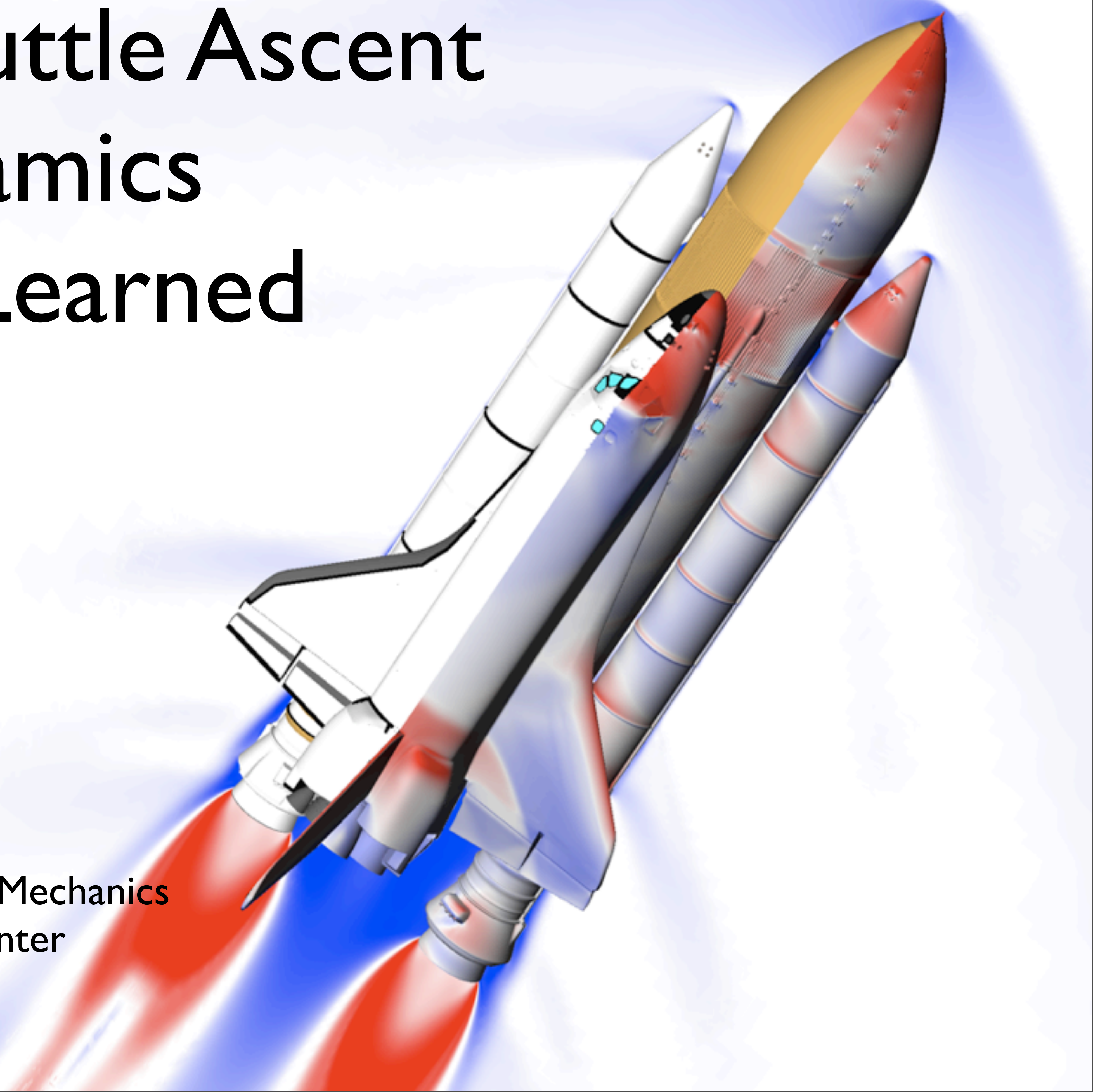
Space Shuttle Ascent Aerodynamics Lessons Learned



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Outline

CCDev Recommendations

Operational Aerodynamic Data Base (OADB) Development

- Pre STS-1
- Post STS-1
- Post Challenger Accident
  - Initial ascent CFD development
- Post Columbia Accident
  - Refined models, redesigns and debris assessments

Ascent Aerodynamics Lessons Learned

While many Shuttle lessons learned are configuration dependent, many are applicable to other launch vehicles.

Read the previous lessons learned

- "Shuttle Performance: Lessons Learned," NASA Conference Publication 2283. Part 1 & 2, March 8-10, 1983. (STS-1 thru STS-5). Over **739 pages** related to entry and ascent aerodynamics.
- Robert "Bob" Ryan/MSFC retired & I-Shih Chang/Aerospace papers.

Requirements

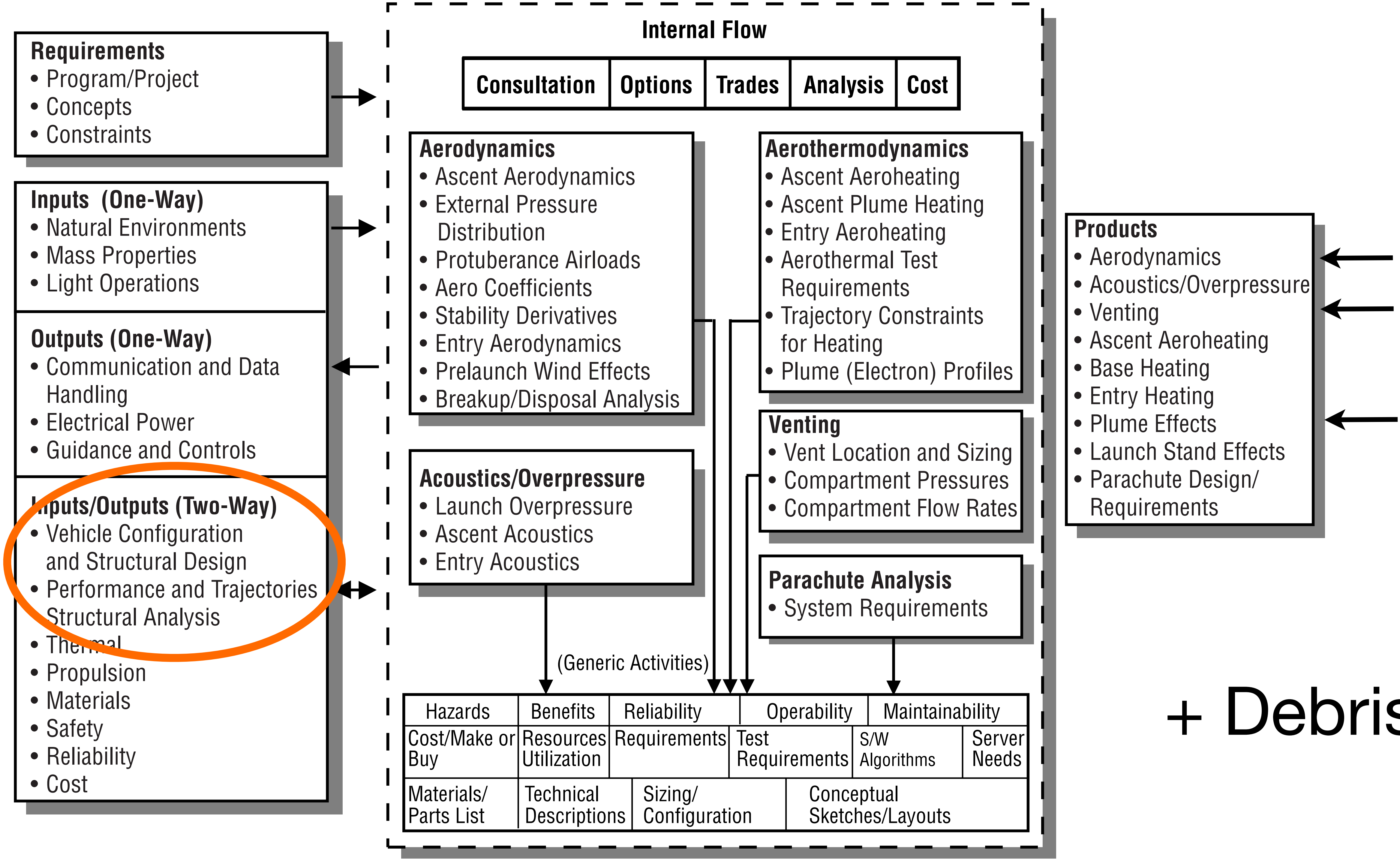
- Aerodynamic databases are typically derived requirements.
  - The details of the database are a function of the vehicle geometry, flight environments, structural and thermal limits etc. and are typically unique for a given configuration.

Building aerodynamic databases

- Databases must be comprehensive, covering all flight environments and all operational phases.
- Focus on high loads and on nonlinear regions and controls (plumes).
- **Abort assessments often require more resources than nominal flight.**

Ascent Aerodynamics & Induced Environments

Humphries, W. R. et al , “Information Flow in the Launch Vehicle Design/Analysis Process,” NASA TM-1999-209877



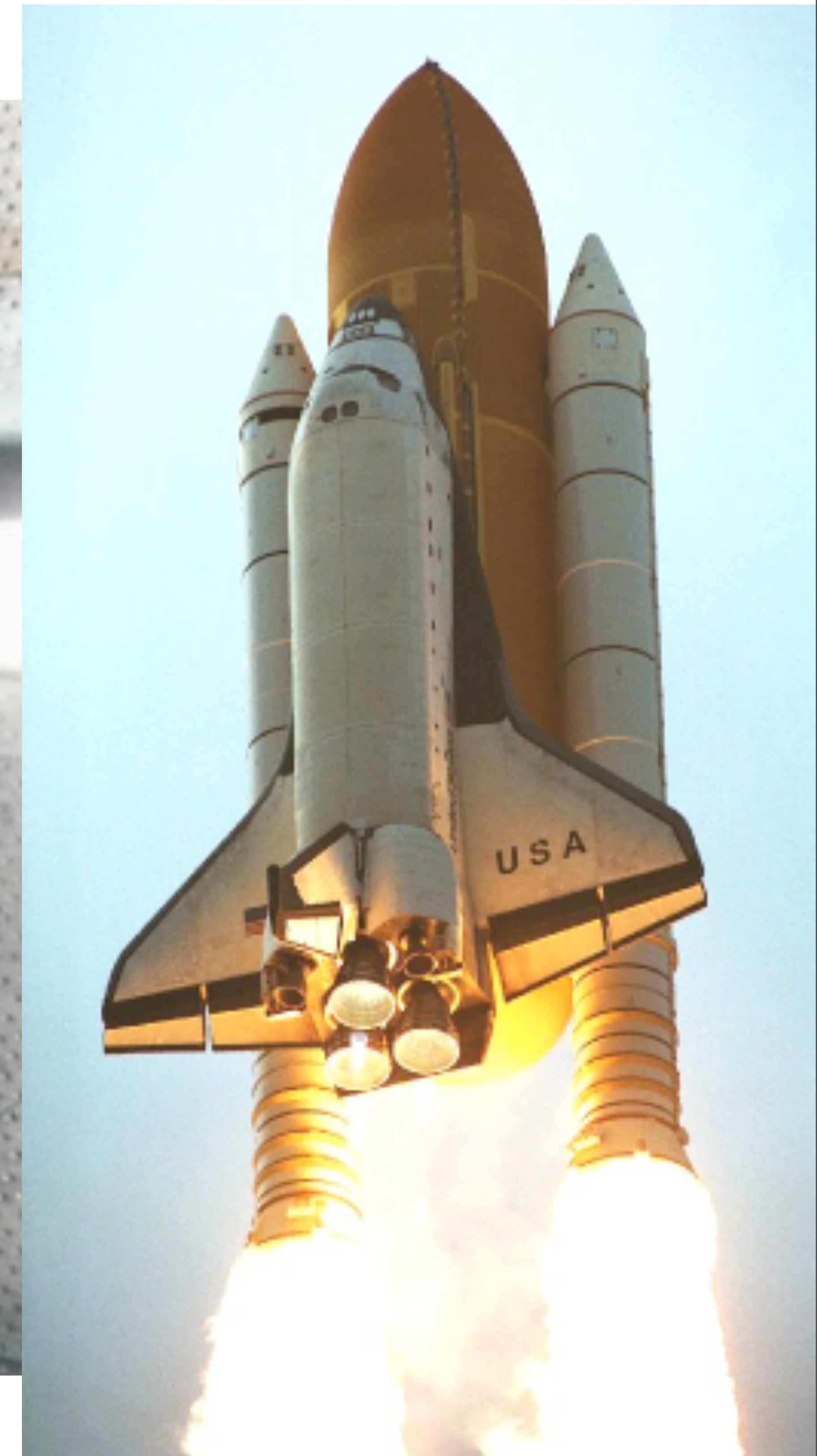
+ Debris

Figure 5. WBS 2.3, Aerodynamics and induced environments design process flow.

Aerodynamic Tools

Modeling & Simulation

Ground Test



Flight Test

Lessons learned

Verification and validation are key elements of a credible database.

- Know your tool limitations.
- Anchor models to wind tunnel and/or flight data.
  - Or check wind tunnel with CFD.
- Verify analytical models independently.
- Document model development and all assumptions.
- **NASA should consider collecting and providing historical program data to CCDev companies for a validation purposes. We should also consider gathering data where it doesn't exist. e.g. parachute loads, high Re wake environments...**

Pay attention to flight instrumentation

- Instrument key areas to validate models.
- An accurate air data system is required to develop accurate post flight reconstructions.
- Track the flight data and look for problems near the edge of the envelope.

Work with your customers and providers

- Establish data exchange standards and make certain that you know how your data is being used and the pedigree of the data that you receive.

Testing and analysis lessons learned

Geometry is a first order effect

- Fly what you test, test what you fly.
- As-built geometry, asymmetries, protuberance, TPS, etc.
- Apollo, Shuttle, X-43, etc.

Be prepared to analyze and reanalyze (test and retest)

- Early in the design process flight design and structures will want comprehensive environments.
- Budget for reassessment of design changes including the final configuration.

Respect the physics

- Unsteadiness, separated flow, hysteresis, etc.
- Look out for highly localized maxima. Transonic buffet.

Design within your test and modeling capabilities

- The consequences are higher costs and risks.

CFD + Wind Tunnel = Aero Data Base

When did modeling vs. testing arguments start?

First Annual report, NACA 1915, Page 13.

- Of the many problems engaging general attention, the following are considered of immediate importance ...
  A. Stability as determined by mathematical Investigations. The reduction to practical form of the analytical methods of determining the stability of aeroplanes from design data, without necessarily requiring wind tunnel tests or full sized tests of the same.

We should really strive to combine the strengths of both techniques to get an optimal database in terms of accuracy and cost.

- Know the limitations of your tools.
  - Wind tunnel scaling vs. CFD modeling limitations
- Efficiency matters
  - Wind tunnel productivity/CFD code optimization

CFD Observations

CFD is a skill

- Typically solution quality is a function of user experience and attention to details.
  - Turbulence models, grid quality, numerics, etc.
  - Be wary of steady state simulations of unsteady flows.
  - AIAA CFD Drag Prediction Workshop.

Verification and Validation are key to building credible solutions

- Iterative, spatial, temporal iterative convergence
- Independent checks are key part of verification
- Validation adds to the overall workload, but builds credibility with customers.

References

Shuttle Lesson Learned

- "Shuttle Performance: Lessons Learned," NASA Conference Publication 2283. Part 1 & 2, March 8-10, 1983. (STS-1 thru STS-5)
- J.C. Blair, Robert S. Ryan, & L.A. Schutzenhofer, "Lessons Learned in Engineering," NASA CR-2011-216468, June 2011.
- Robert S. Ryan, "A History of Aerospace Problems, Their Solutions, Their Lessons," NASA TP-3653, September 1996.
- Marvin Sellers. "Advances in AEDC's lifetime pressure-sensitive paint program," AIAA paper 2005-7638.

Others

- "Standard for Models and Simulations," NASA-STD-7009, July 2008.
- I-Shih Chang, "Investigation of Space Launch Vehicle Catastrophic Failures," Journal of Spacecraft and Rockets, Vol.3,No.2,March-April 1996.
- 1st AIAA CFD Drag Prediction Workshop, June 9-10, 2001.

The Space Shuttle was an ambitious engineering undertaking.

- It was the first orbital vehicle designed to be reusable and to land on a runway
  - Originally intended to be fully reusable but cost and technological hurdles forced a change to a partially reusable system.
- First NASA launch vehicle to include aerodynamic uncertainties
- Designers had worked on Mercury, Gemini and Apollo in the previous 10 years.
- LO_2+LH_2 and Solid Rocket Booster parallel burn first stage
  - Overpressure, cryoingestion.
- Flew 135 missions from 1981-2011, two catastrophic losses.

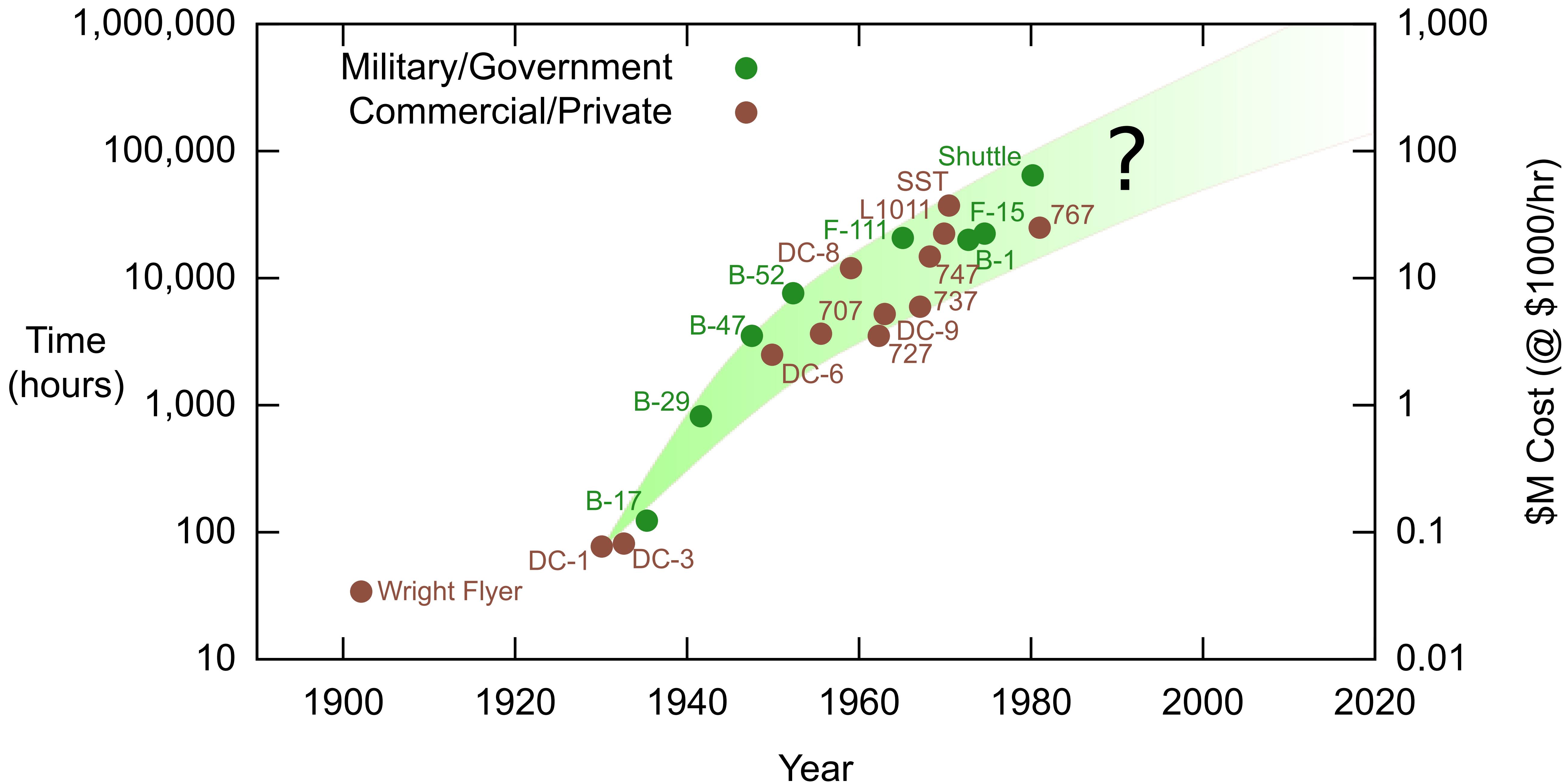
The Shuttle aerodynamic database was based on a large number of wind tunnel tests, with limited modeling & simulation.

Over 100 wind tunnel models were built during Phase C/D and over 56,000 hours of wind tunnel testing was done, 46,000 by the prime contractor.

Aerodynamics,
Aerothermodynamics,
Structural loads,
Structural dynamics,
Stage separation,
Aborts.

Configuration	Wind tunnel (hrs)
Orbiter	24,900
Mated	17,200
SCA	3,900
JSC/MSFC	10,000
Total	56,000

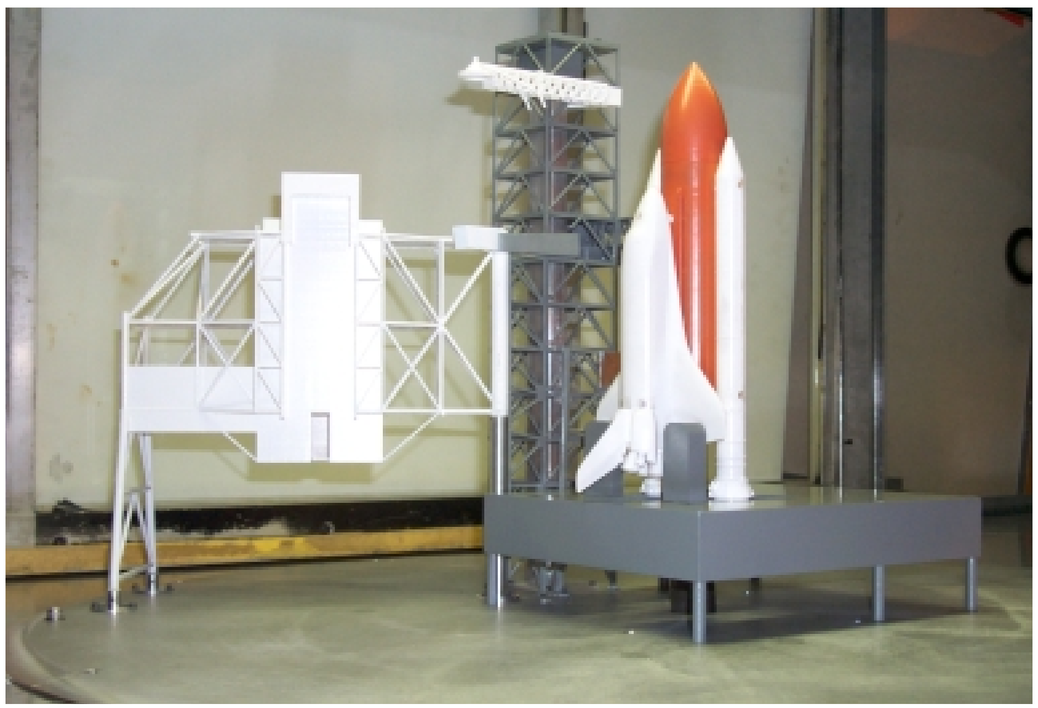
While modeling contributed to the database development, wind tunnel testing dominated aerodynamic database development before 1980.



Data from NASA SP-440 & online sources

Overall the STS-1 prelaunch environment predictions were very good and demonstrated sound engineering practices.

During my career at JSC we reviewed and re-evaluated many of these environments and found relatively few areas to update.



IA-346 Ground Winds Test, 2002.

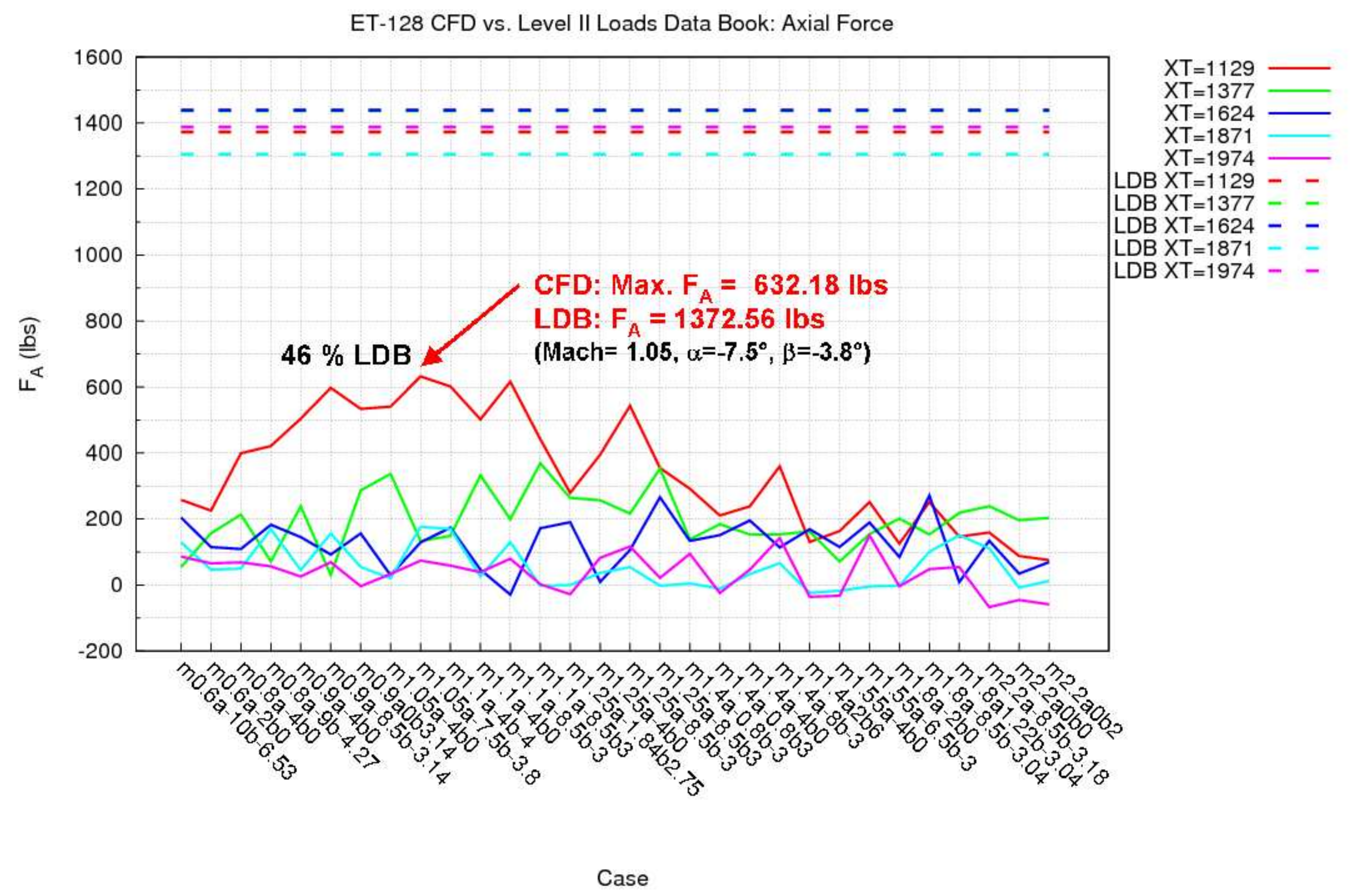


Figure 20: **ET-128 DCR CFD vs. LDB: Total Axial Force on LO_2 Feedline Bracket/yoke.**

STS-50 pressure distributions and wing loads, 1994.

Transonic Vertical Tail Airloads, 1996.

Discrete and distributed protuberance airloads, 2004.

ET venting models, roll maneuver environment 2006 and many others.

The STS-1 problem areas were all related to testing or physical modeling limitations.

- Ignition Over Pressure (IOP) effects were more severe than predicted.
- Launch pad and vehicle generated debris damaged Orbiter tiles.
- Base pressure underestimate resulted in lofted trajectory
- Non-equilibrium effects nose up pitching moment.*

* Weilmuenster, K. James, Gnoffo, Peter A., and Green, Francis A., “Navier-Stokes Simulations of Orbiter Aerodynamic Characteristics including Pitch Trim and Bodyflap,” Journal of Spacecraft and Rockets, Vol. 31, No. 3, May-June 1994.

Post STS-1 engineers used flight data to update environments and modify the launch platform.

- IOP testing was redone with a splitter plate. A new scaling relationship was developed and the water spray was redirected toward the “source” of the SRB IOP. Water troughs were installed in the SRB exhaust ducts.
- Base pressures were updated with flight data.
  - Overall pressures could not be updated due to the limited flight measurements.
- Entry aerodynamics updated to account for non-equilibrium effects, entry CFD continued to work issue.
- Launch pad & the External Tank were modified to reduce debris potential.

Post Challenger/51-L Shuttle Problems

January 28,1986 No analytical capability to predict ascent aerodynamics

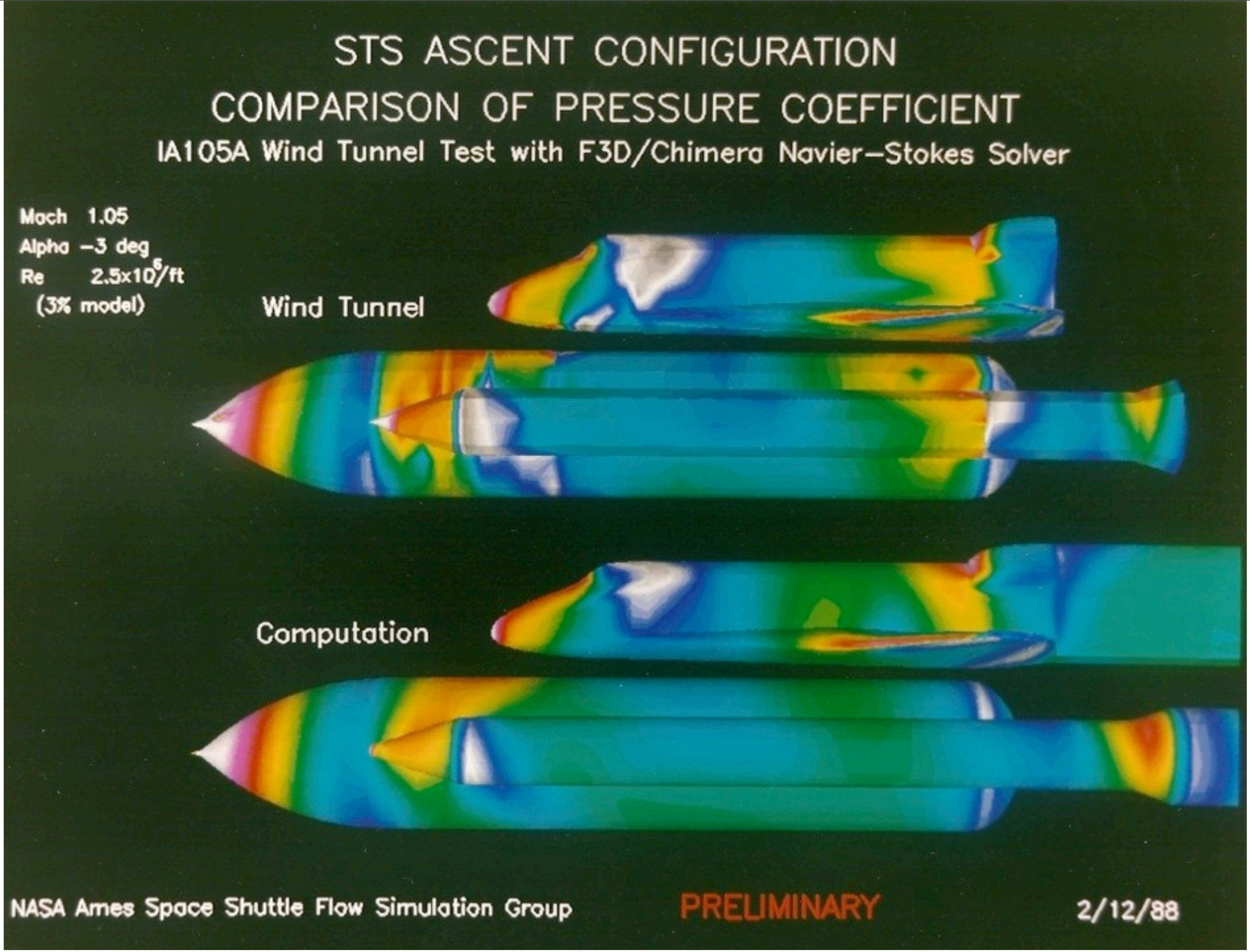
Fall of 1986 Joseph Steger & Pieter Buning/NASA ARC proposed development of an overset capability to simulate the Shuttle ascent configuration.

- Initial development of OVERFLOW CFD code.

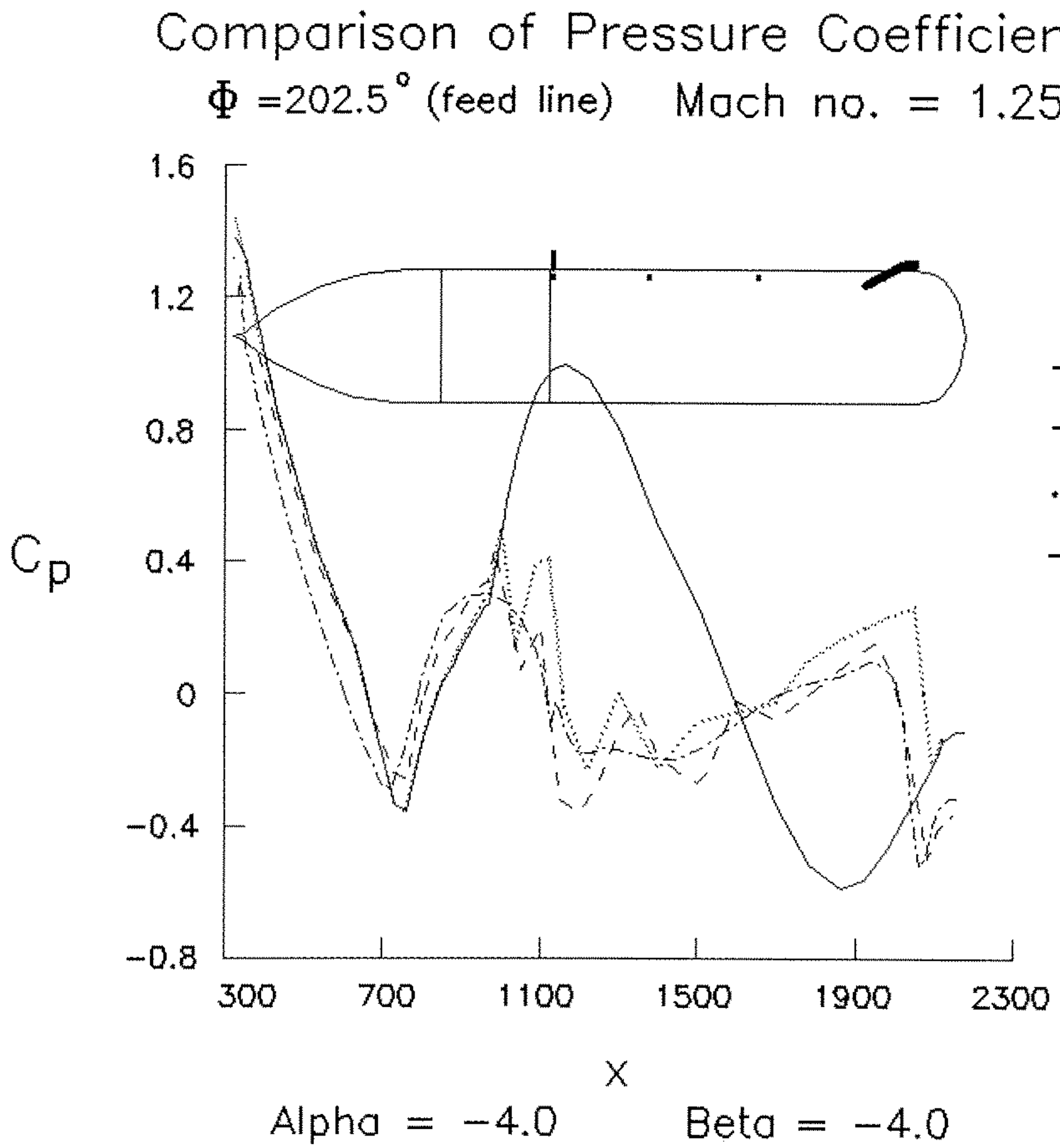
Initially focused on fast-separation abort and STS-1 trajectory lofting base pressure issues.

Payload bay door loads and many more..

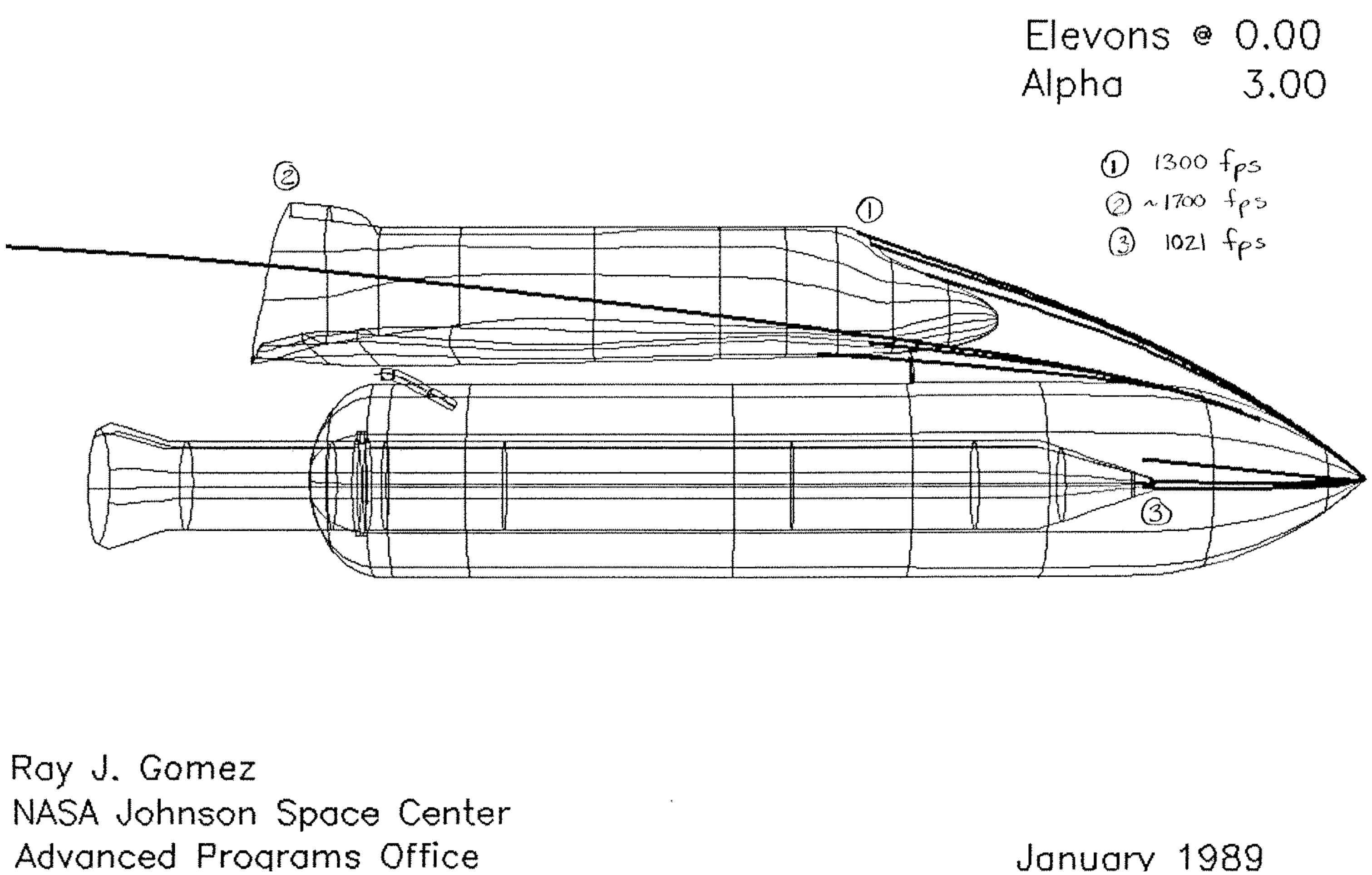
Reference: F.W. Martin, Jr., and J.P. Slotnick, "Flow Computations for the Space Shuttle in Ascent Mode Using Thin-Layer Navier-Stokes Equations," **Applied Computational Aerodynamics**, P.A. Henne, ed., AIAA, 1990, pp. 863-886.


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

Early ascent CFD uses included resolving IVBC-3 pressure database issues and early debris transport.



STS-27R Debris Transport



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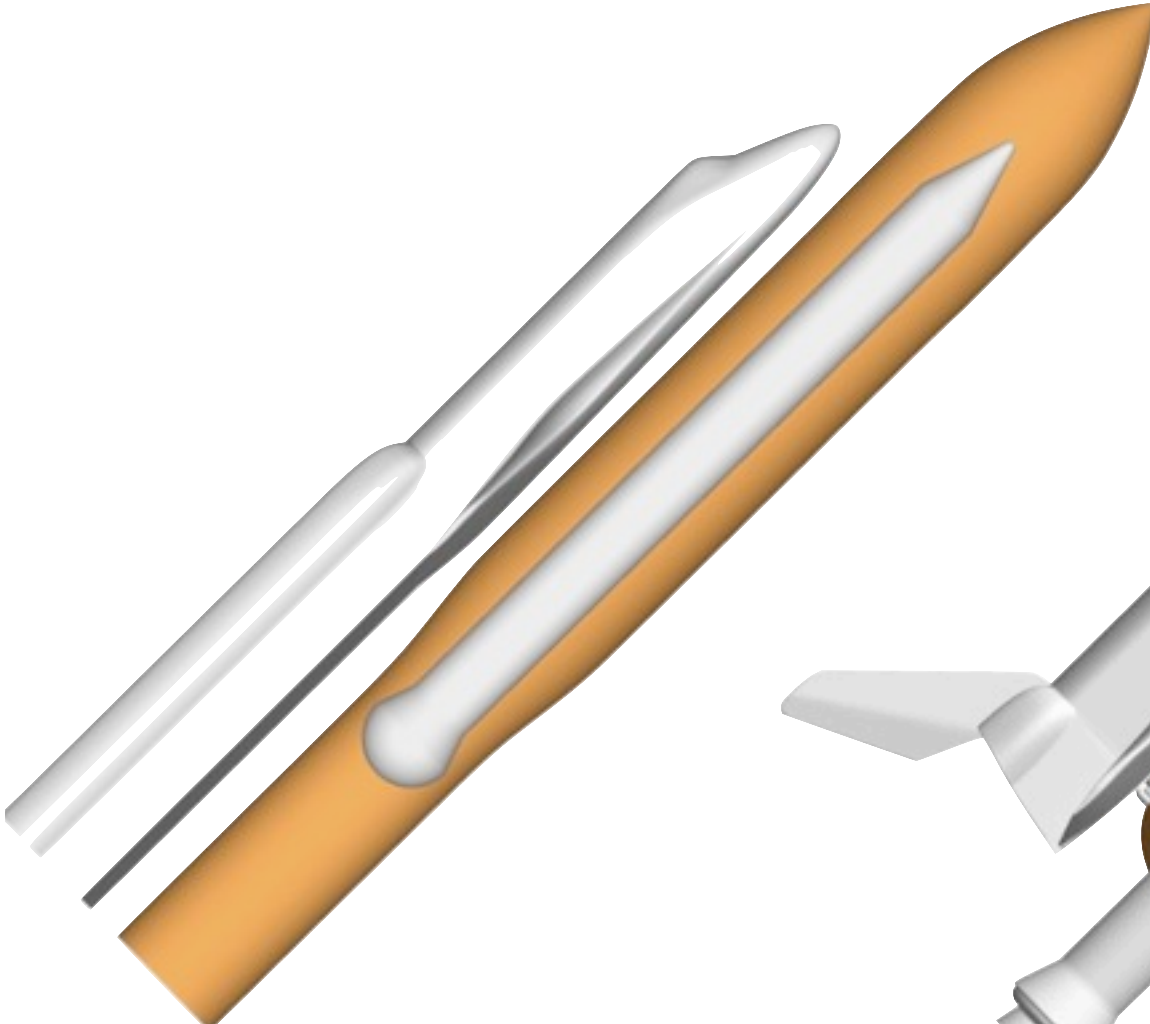
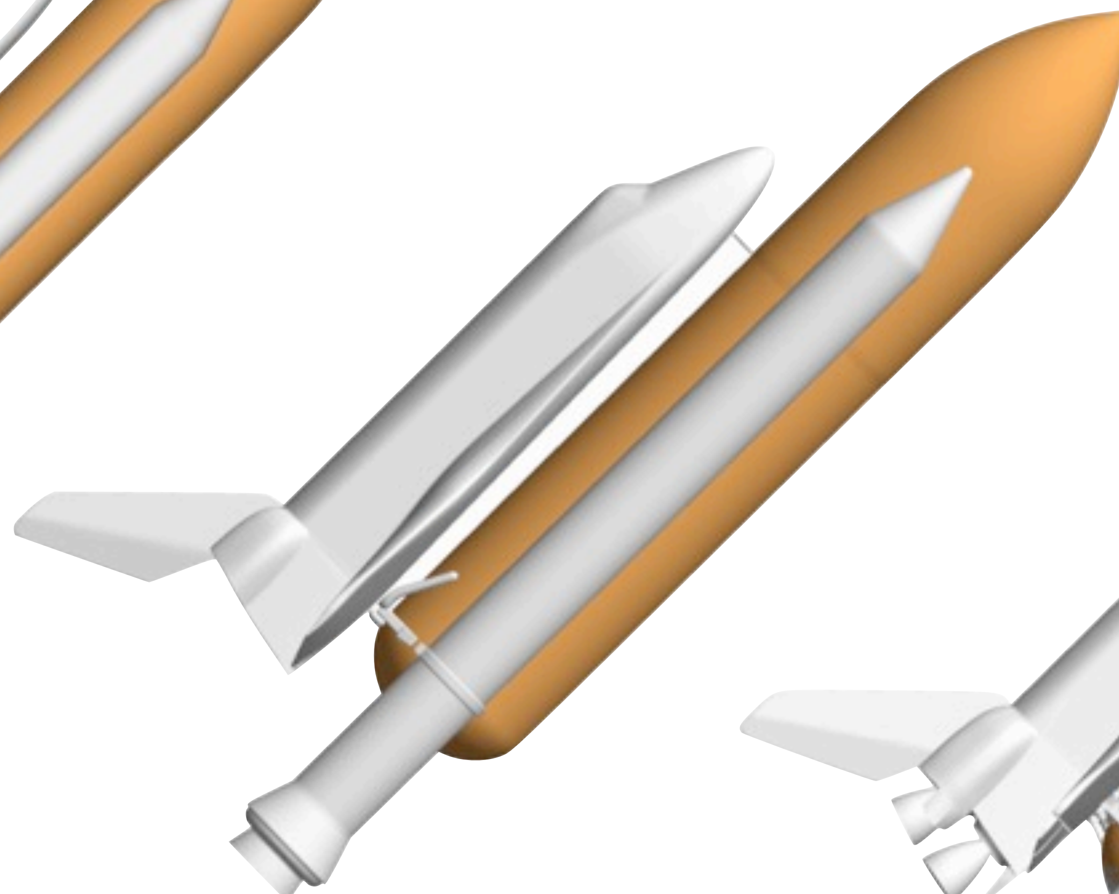
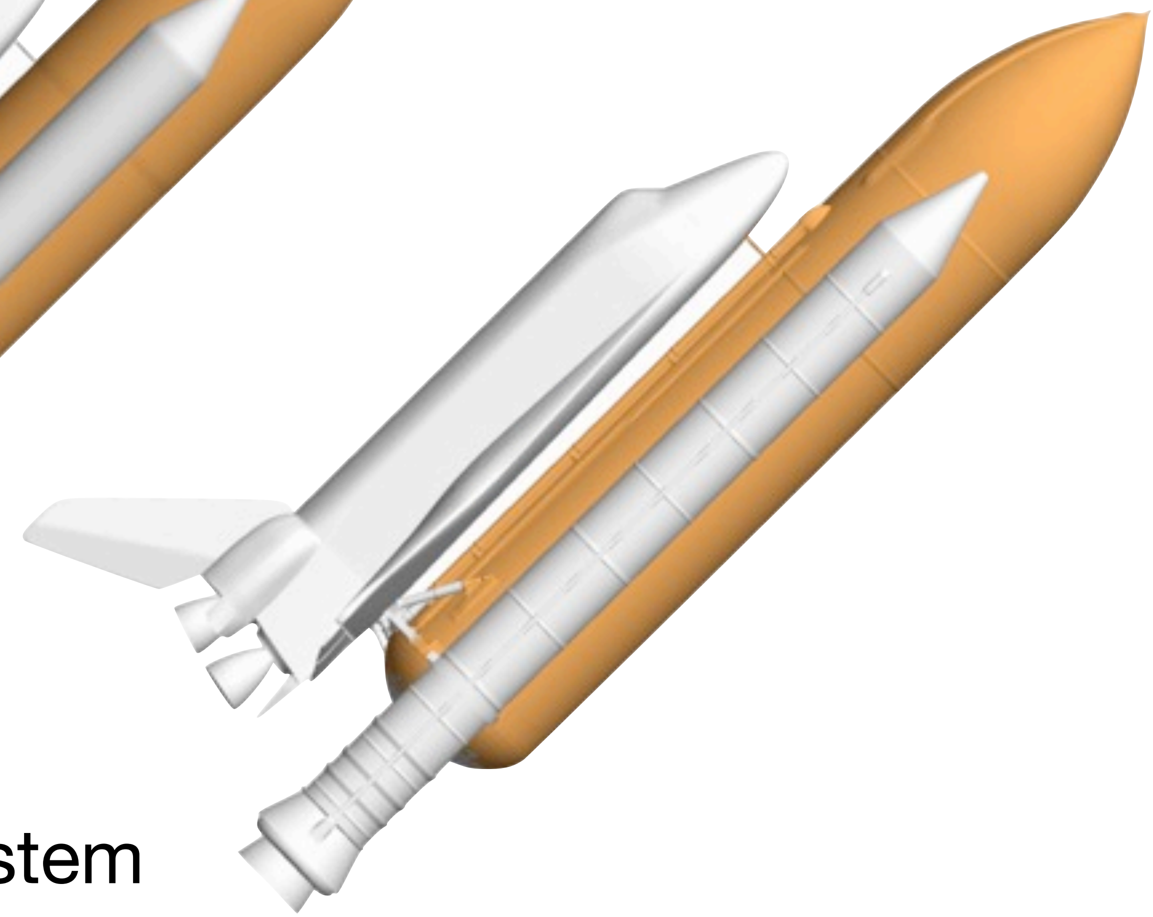
SSLV Grid System Evolution



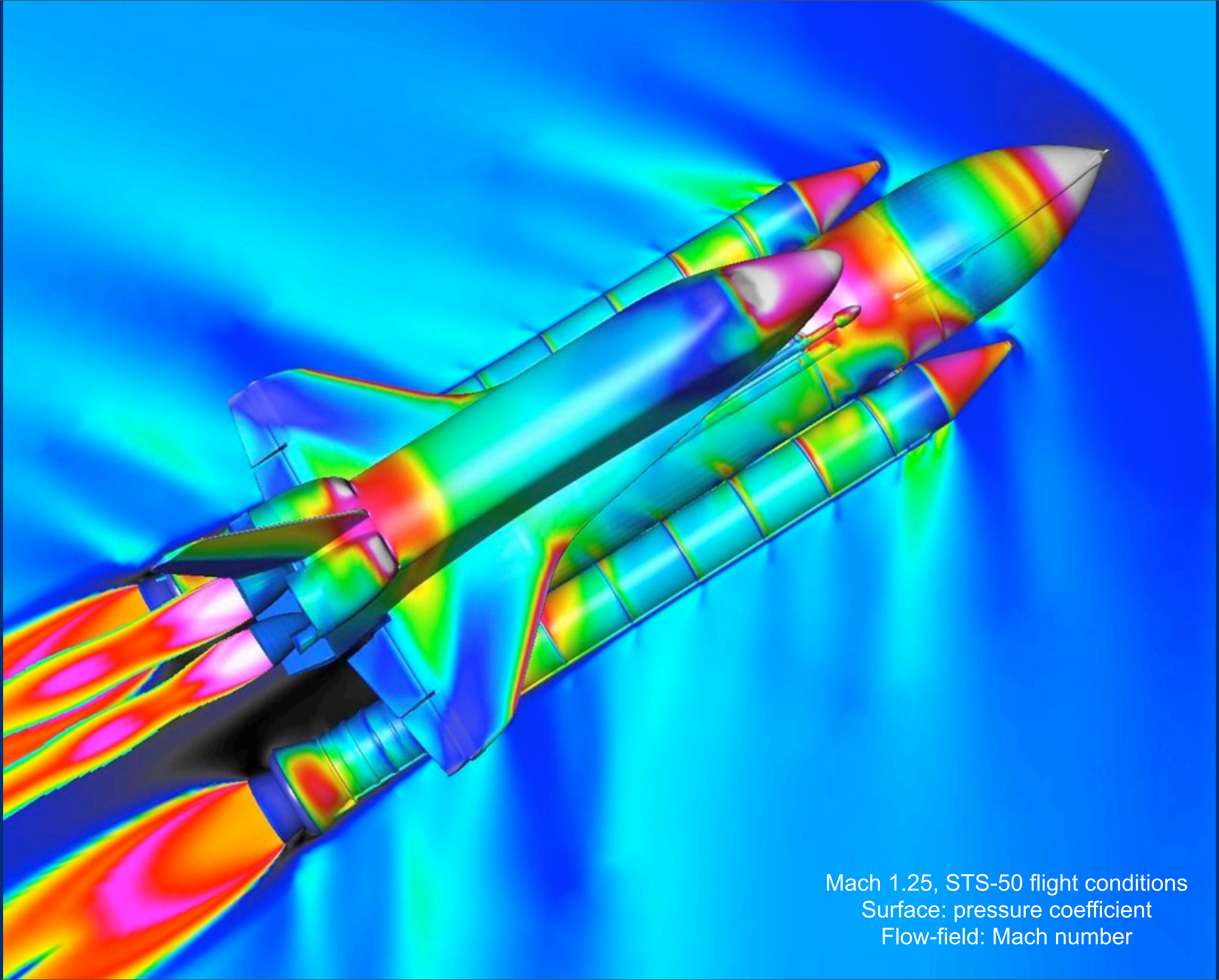




Mid 80’s grid system
3 Grids
10k surface points
0.3 million volume points

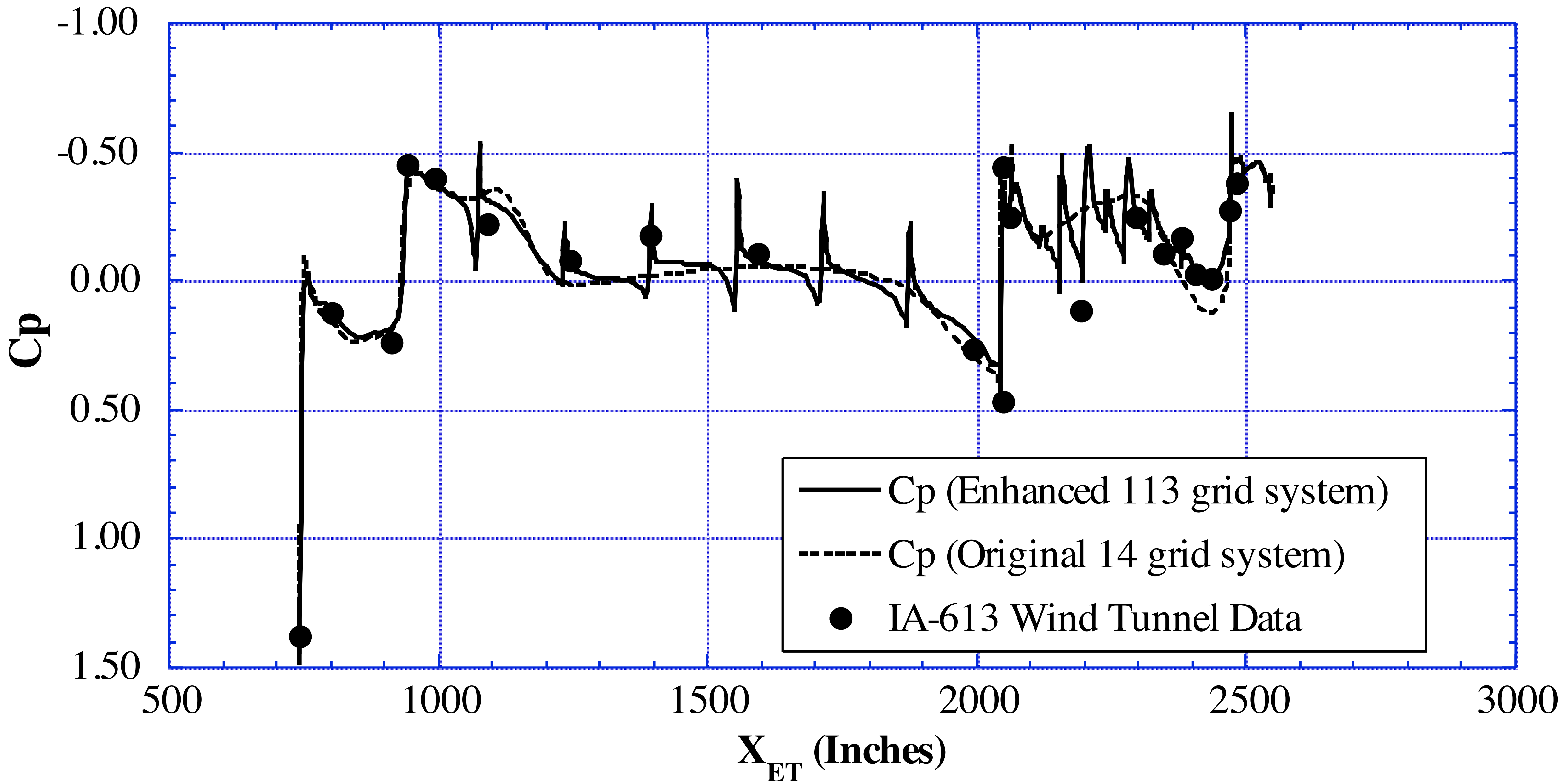
Late 80’s grid system
14 Grids
35k surface points
1.6 million volume points

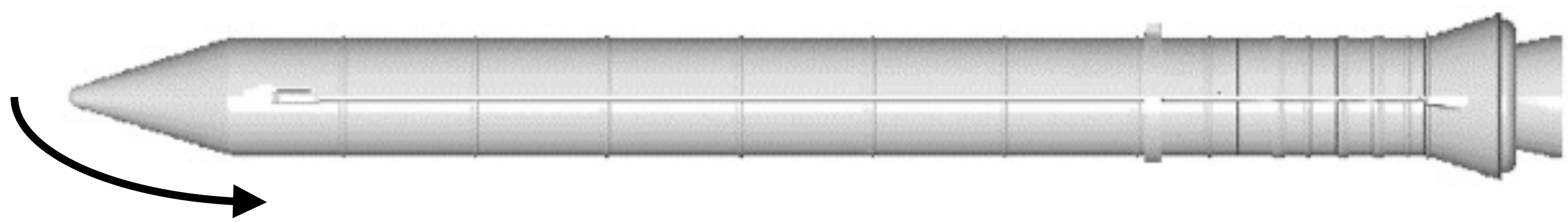
Early 90’s grid system
113 Grids
268k surface points
16.4 million volume points



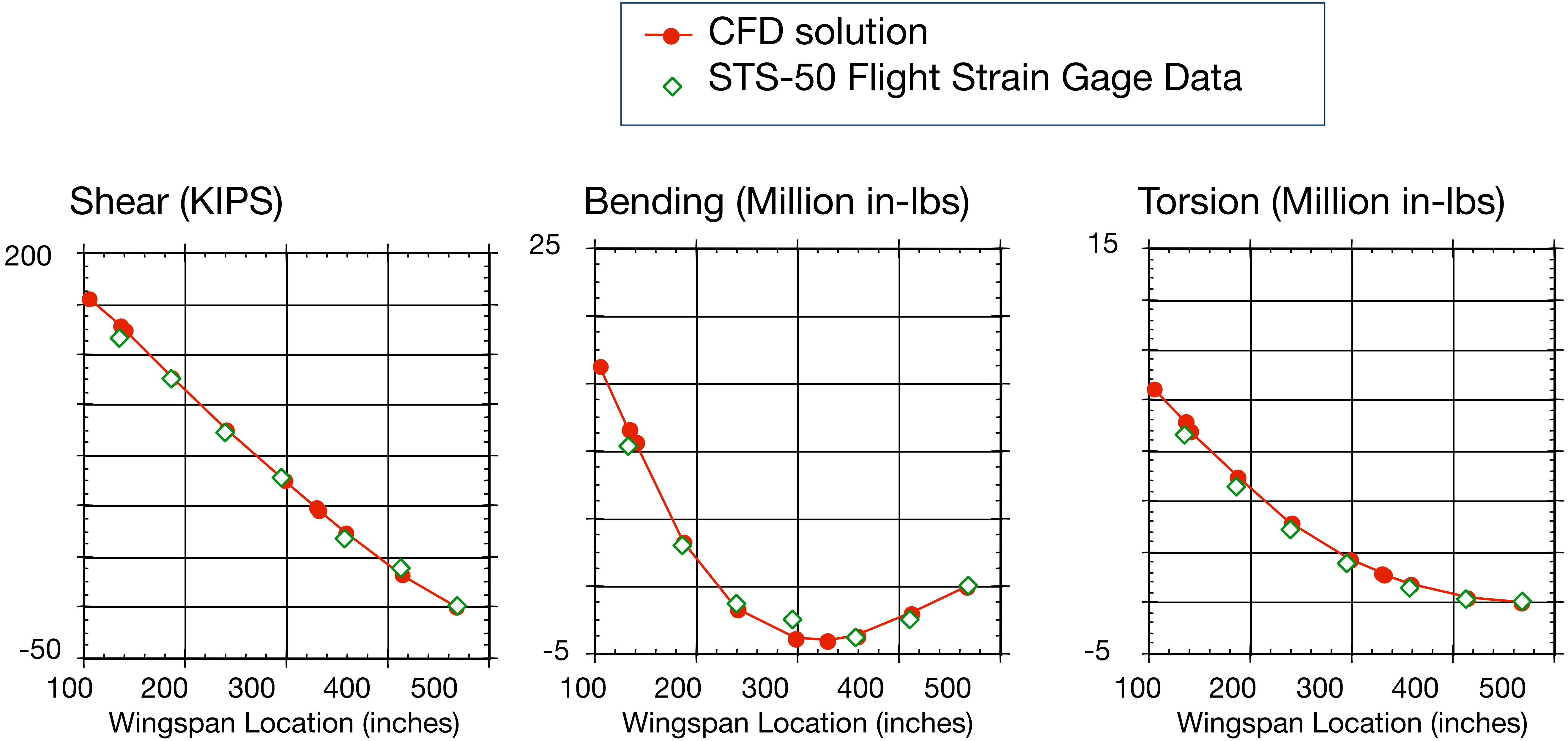
Mach 1.25, STS-50 flight conditions
Surface: pressure coefficient
Flow-field: Mach number

Solid Rocket Booster Surface Pressures
Φ = 0°, Mach 1.25, WT Re, AIAA-94-1859

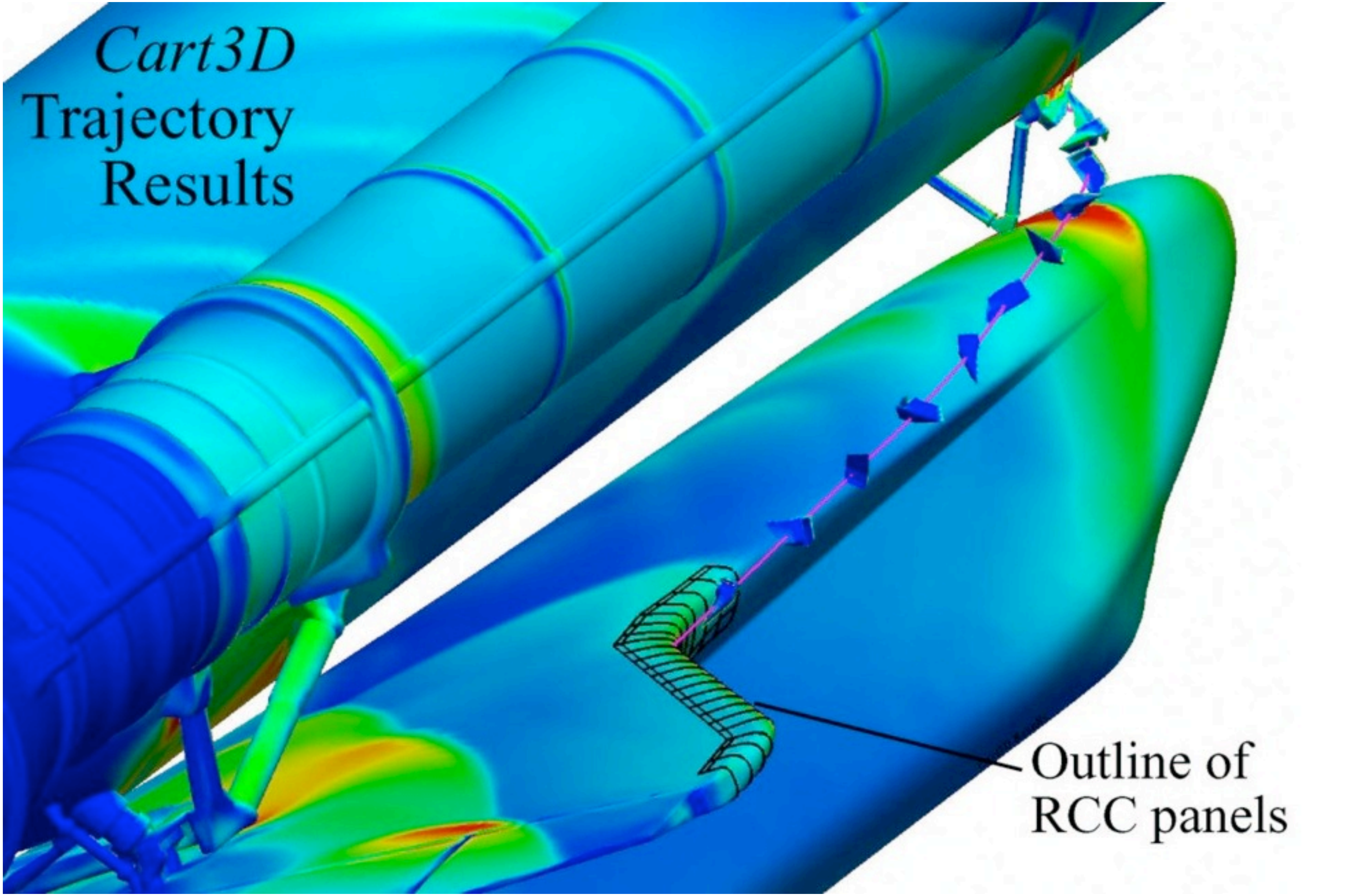




Flight Orbiter Wing Loads (Left Wing)
Mach 1.25, Flight Re (Slotnick, Kandula, Buning, AIAA-94-1860)



STS-107 Debris AIAA 2005-1223



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

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

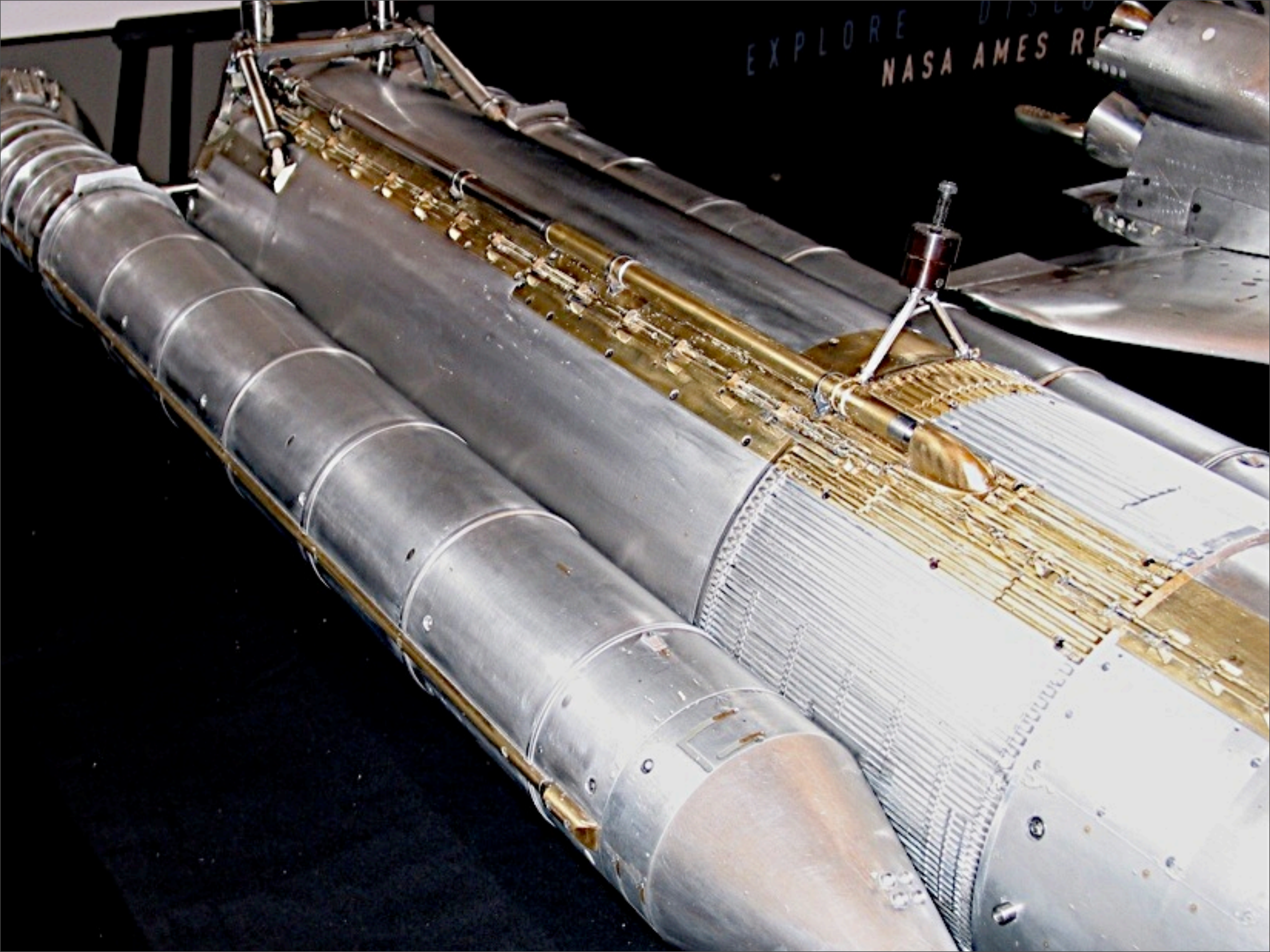
Debris liberation, **transport** and capability assessments.

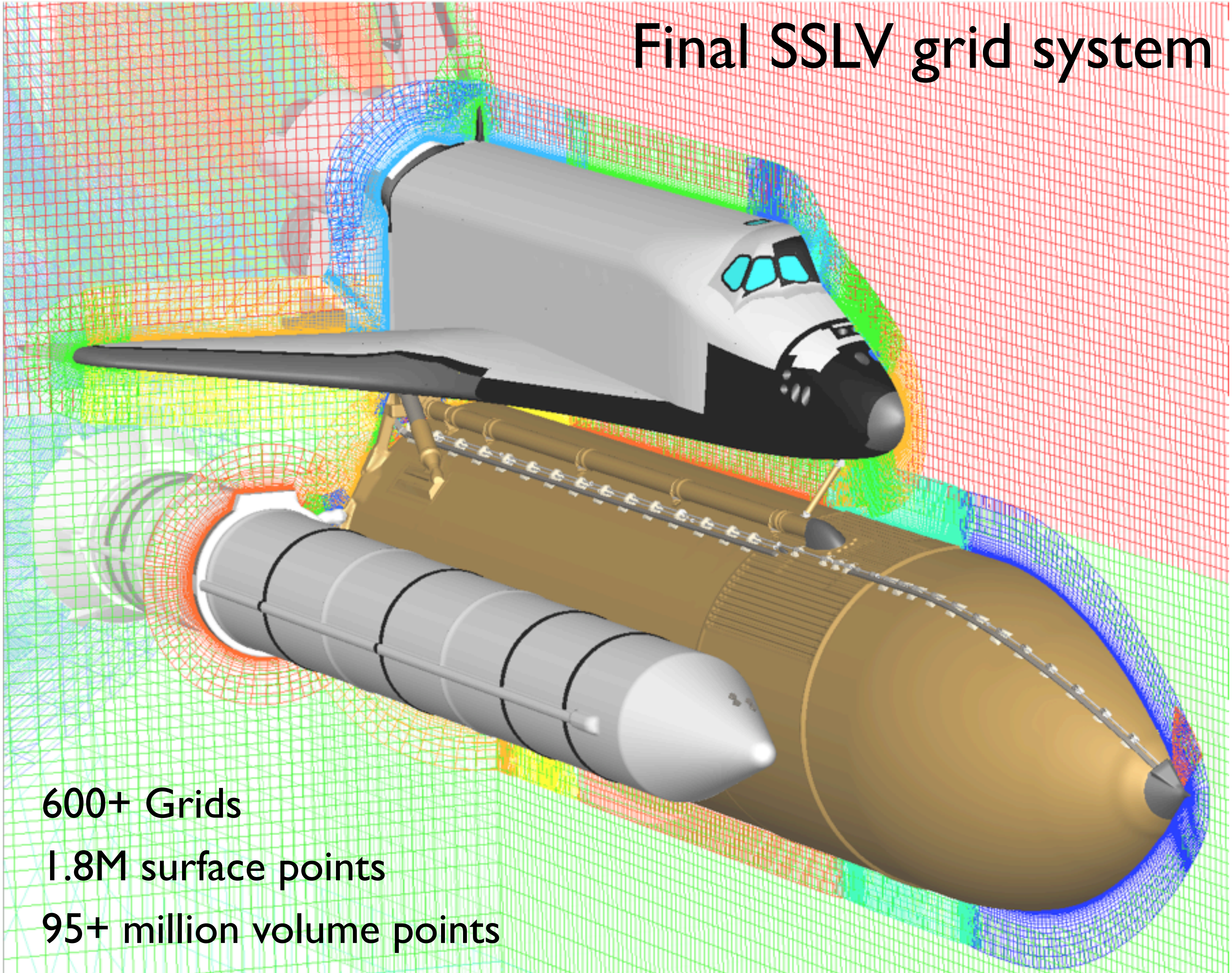
Bipod redesign assessments.

Greatly increased emphasis on verification & validation.

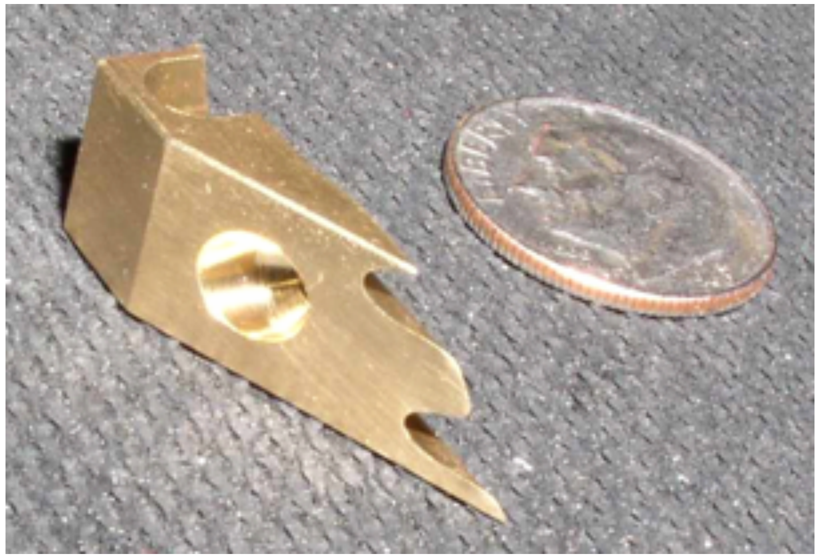
STS-114 and subsequent missions

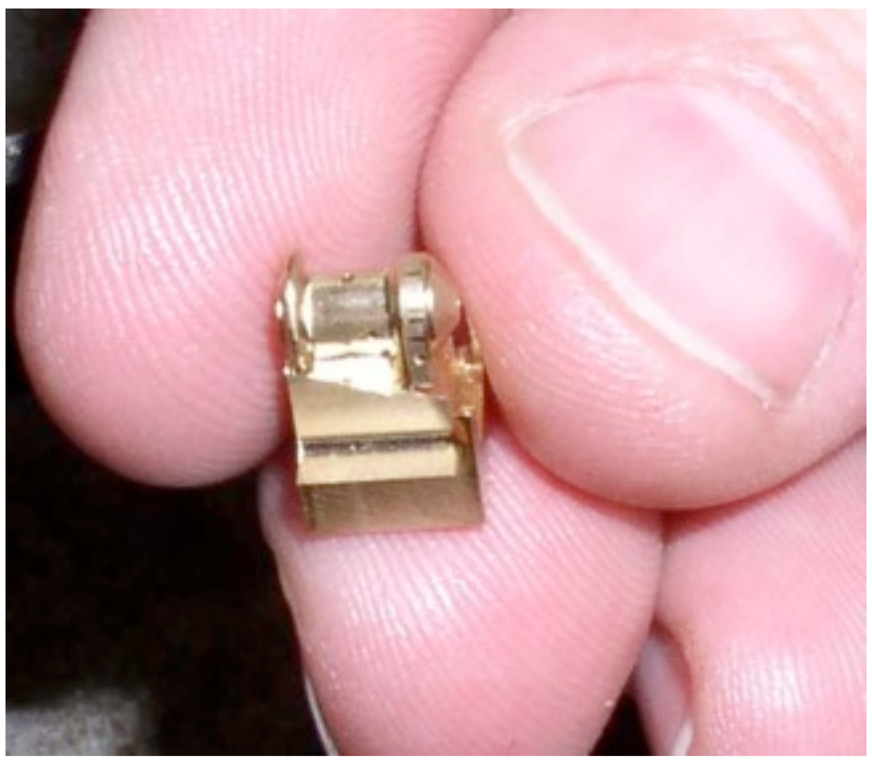
- PAL ramp foam loss, additional redesign work.
- Prelaunch, inflight and postflight debris transport assessments.

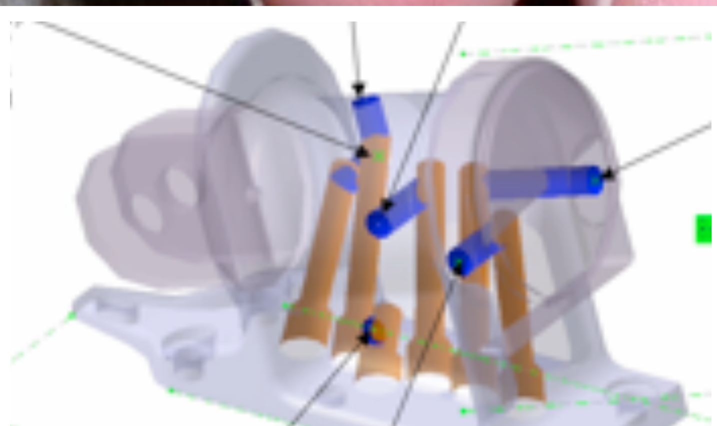

NASA AMES RE

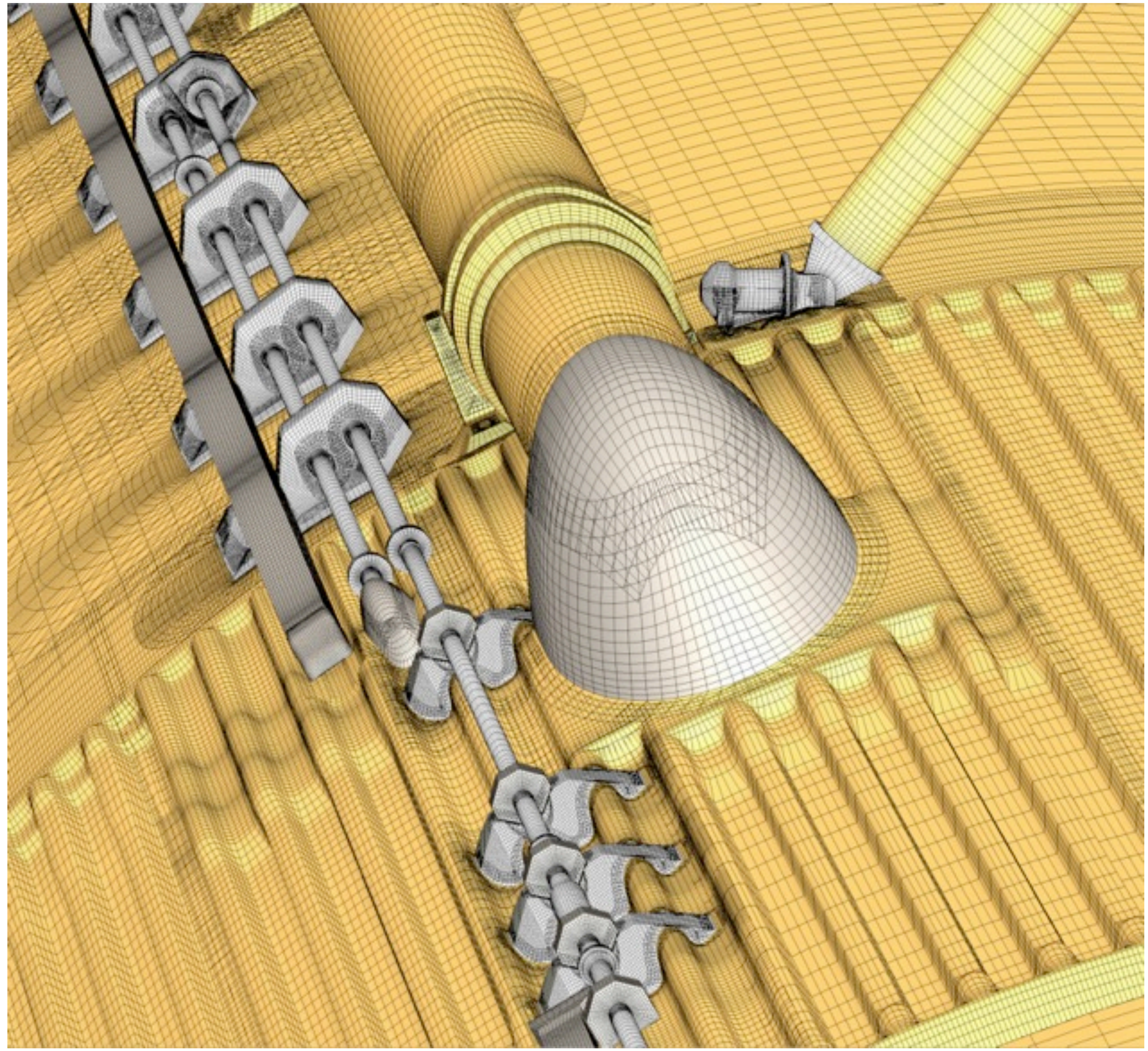

Final SSLV grid system
600+ Grids
1.8M surface points
95+ million volume points

Wind tunnel validation and CFD extrapolation

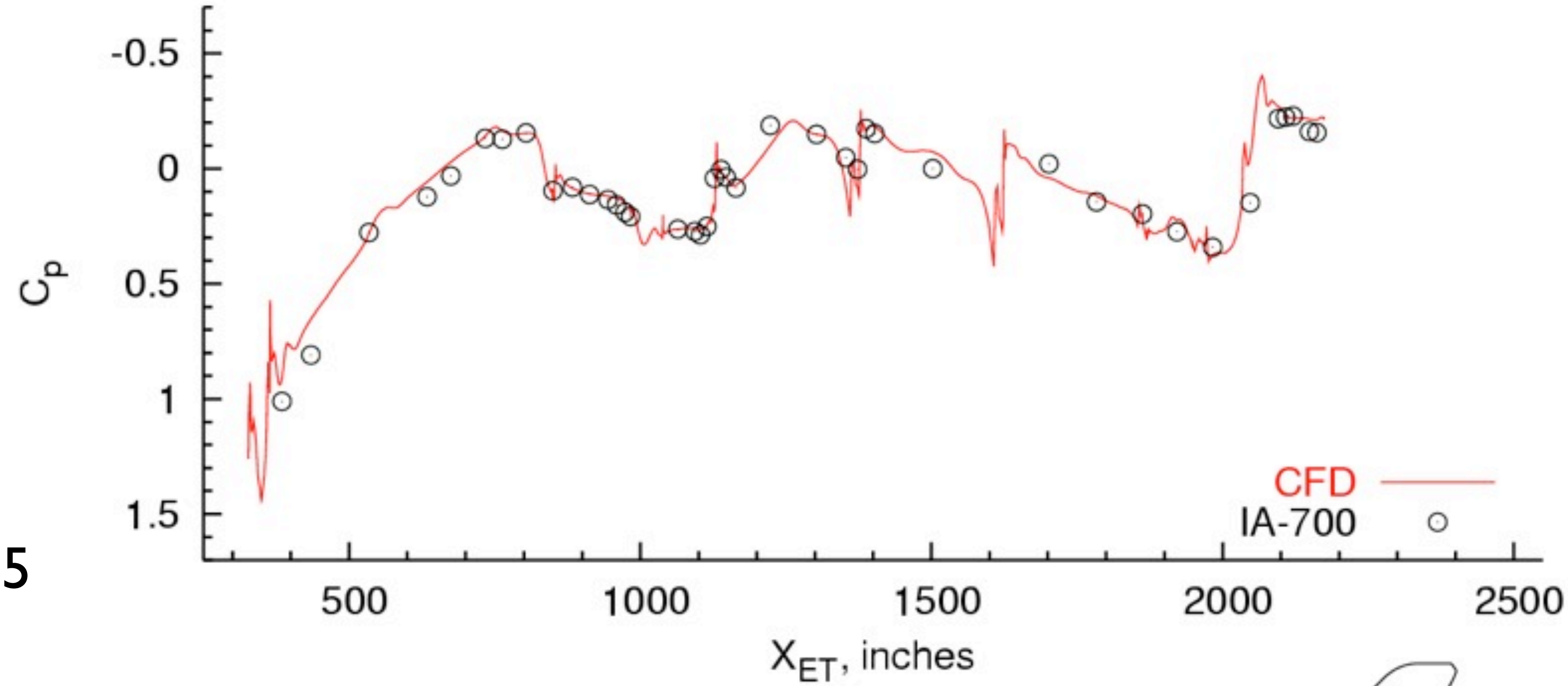




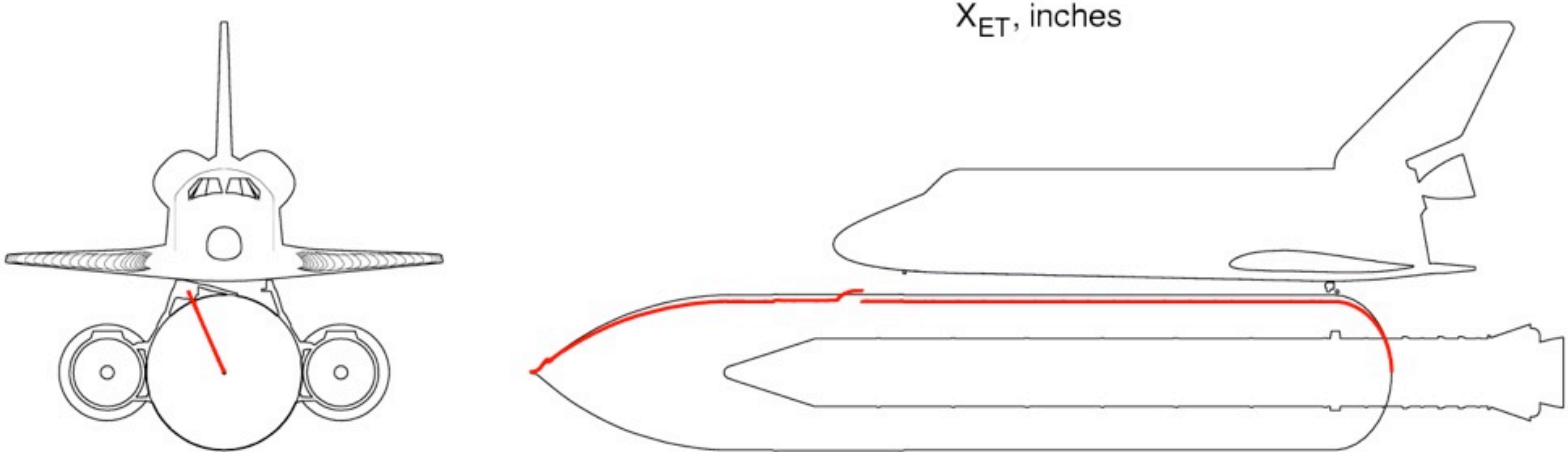




Detailed comparisons along the LO_2 feedline were key to understanding protuberance airloads.

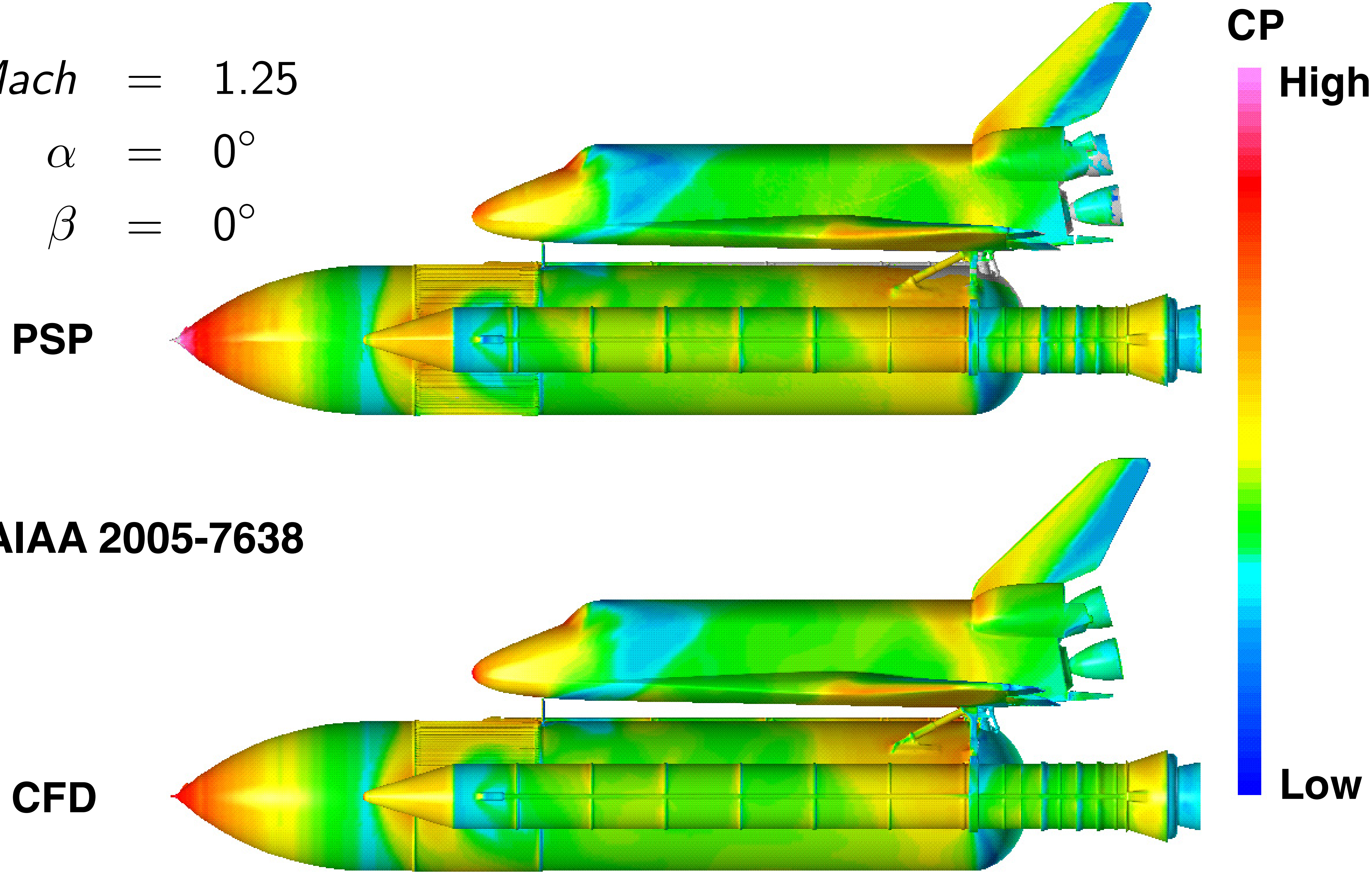


JSC 2005-62925

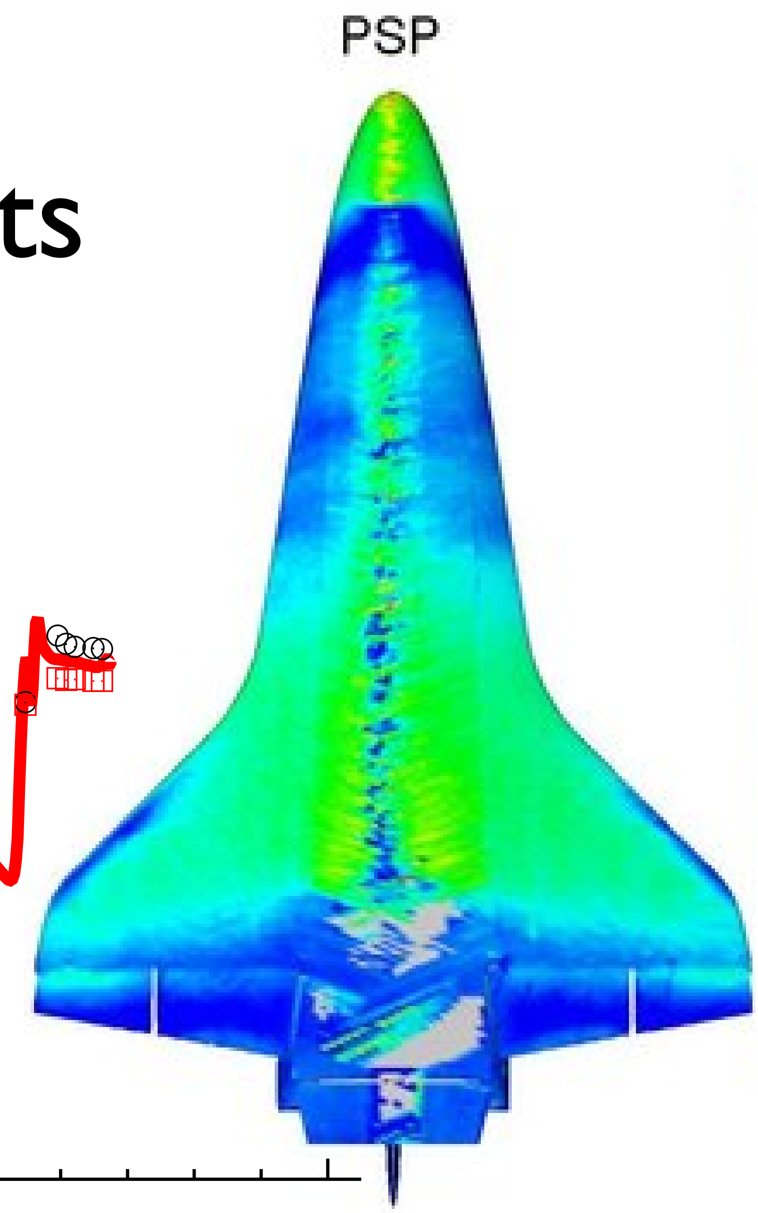


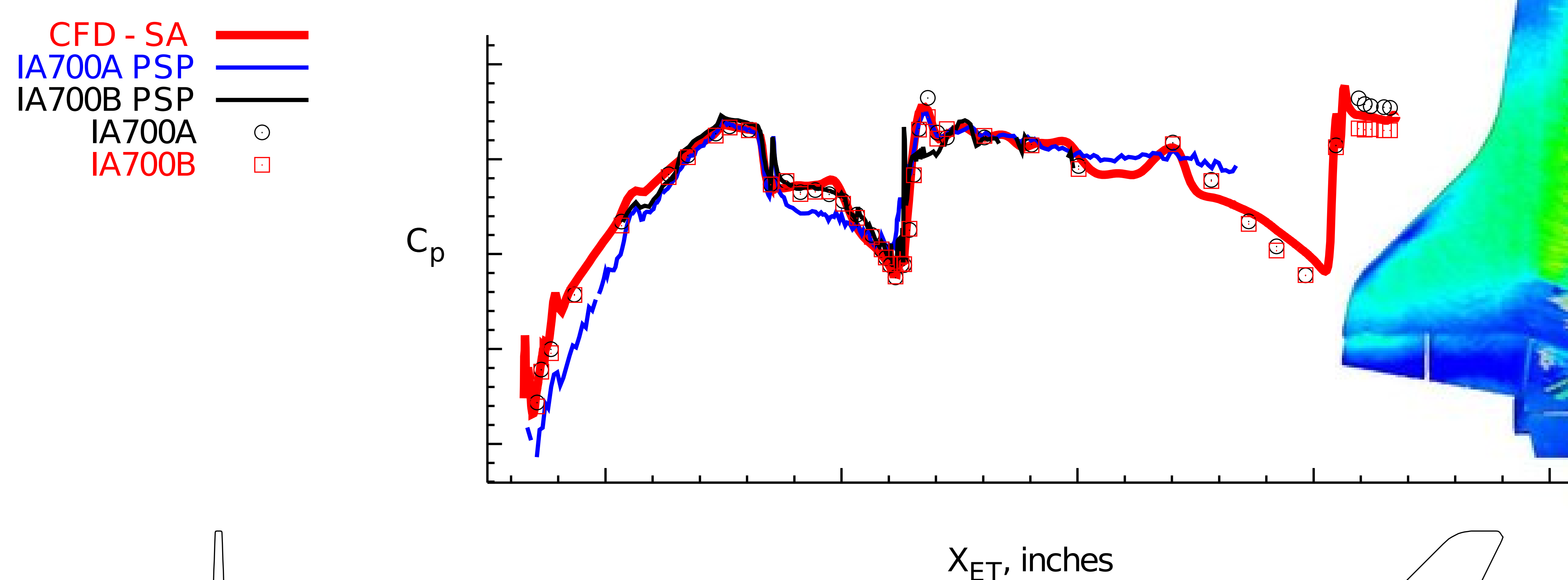
Pressure Sensitive Paint provided key validation data that supported the use of CFD models.

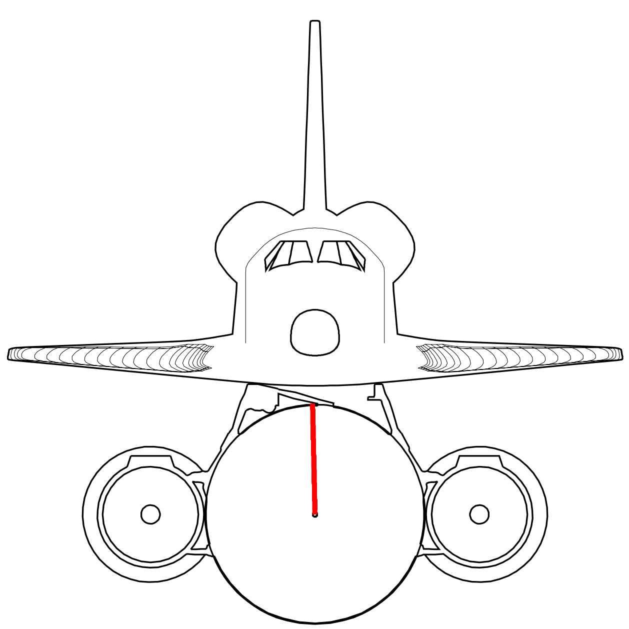
$$Mach = 1.25$$
$$\alpha = 0^\circ$$
$$\beta = 0^\circ$$

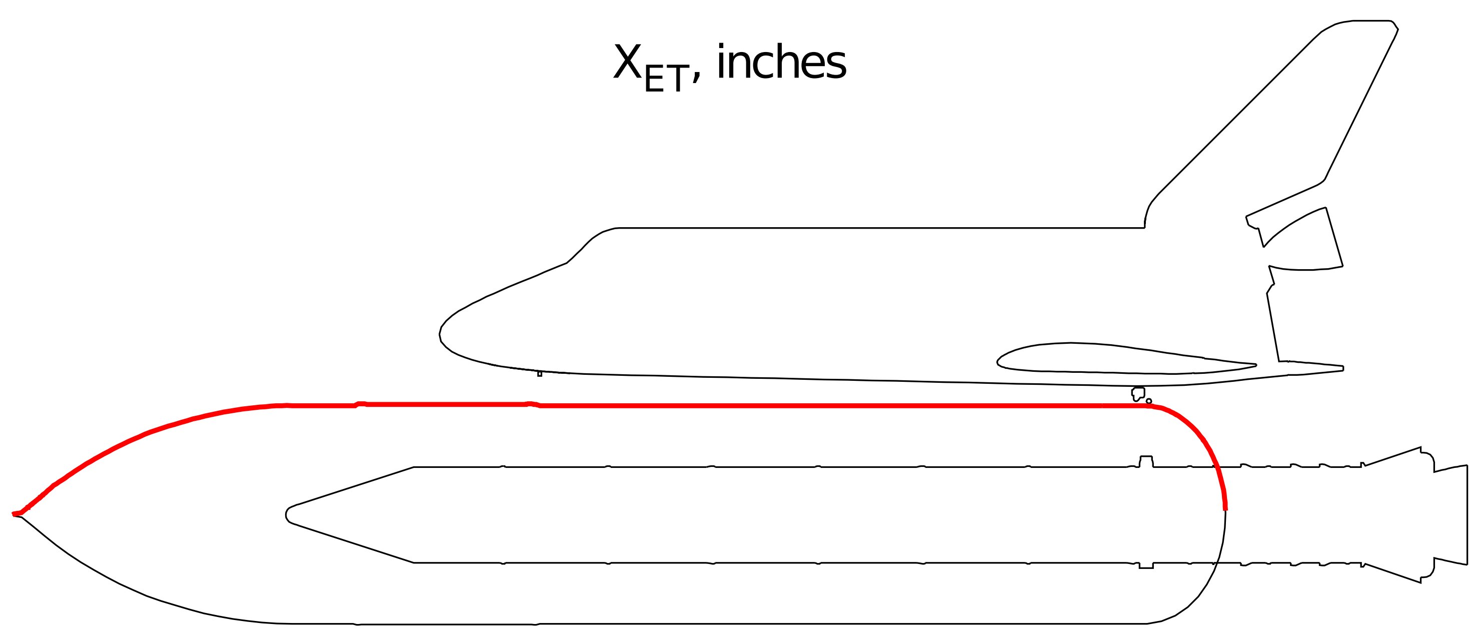


PSP requires good visibility and illumination to achieve the best results

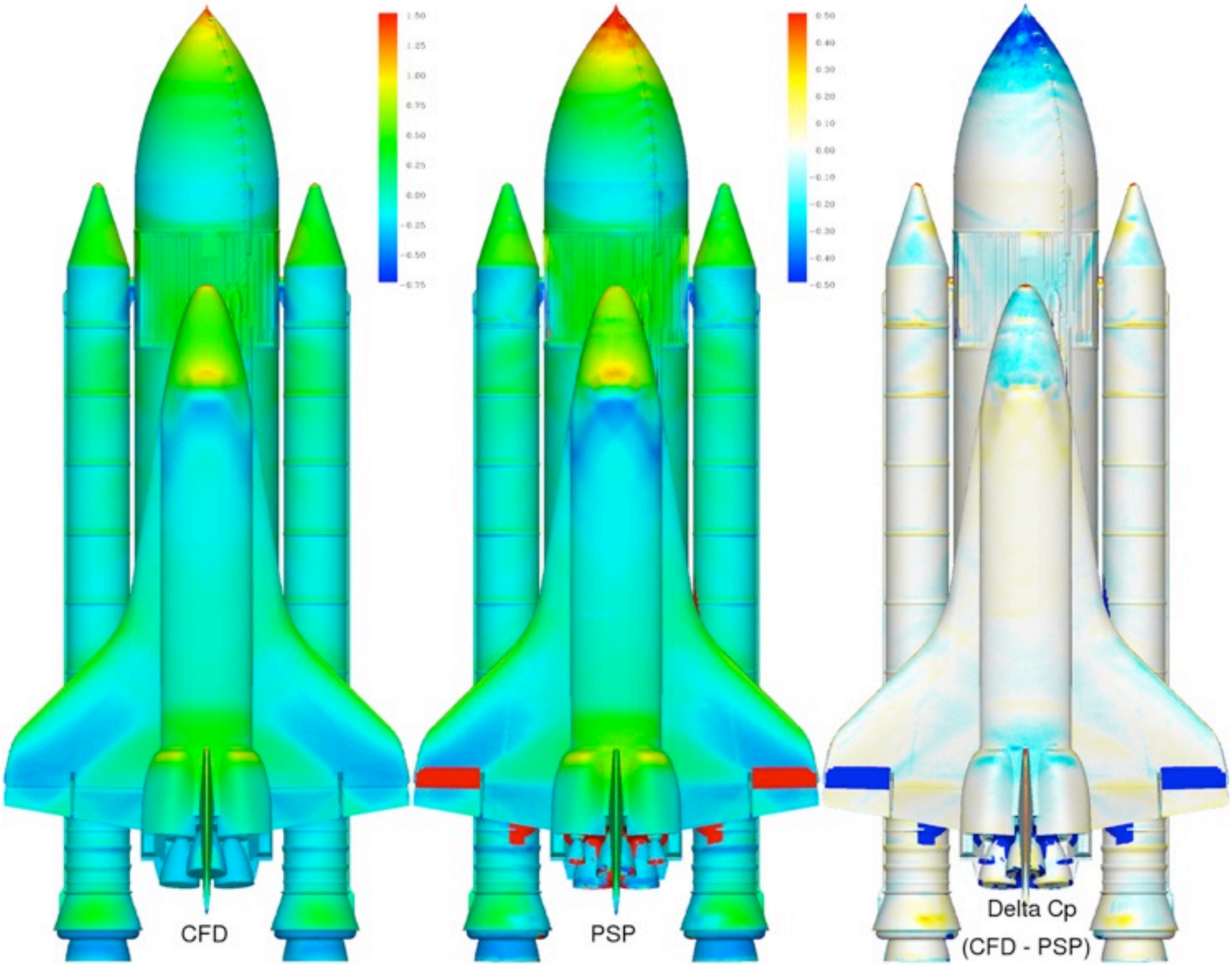








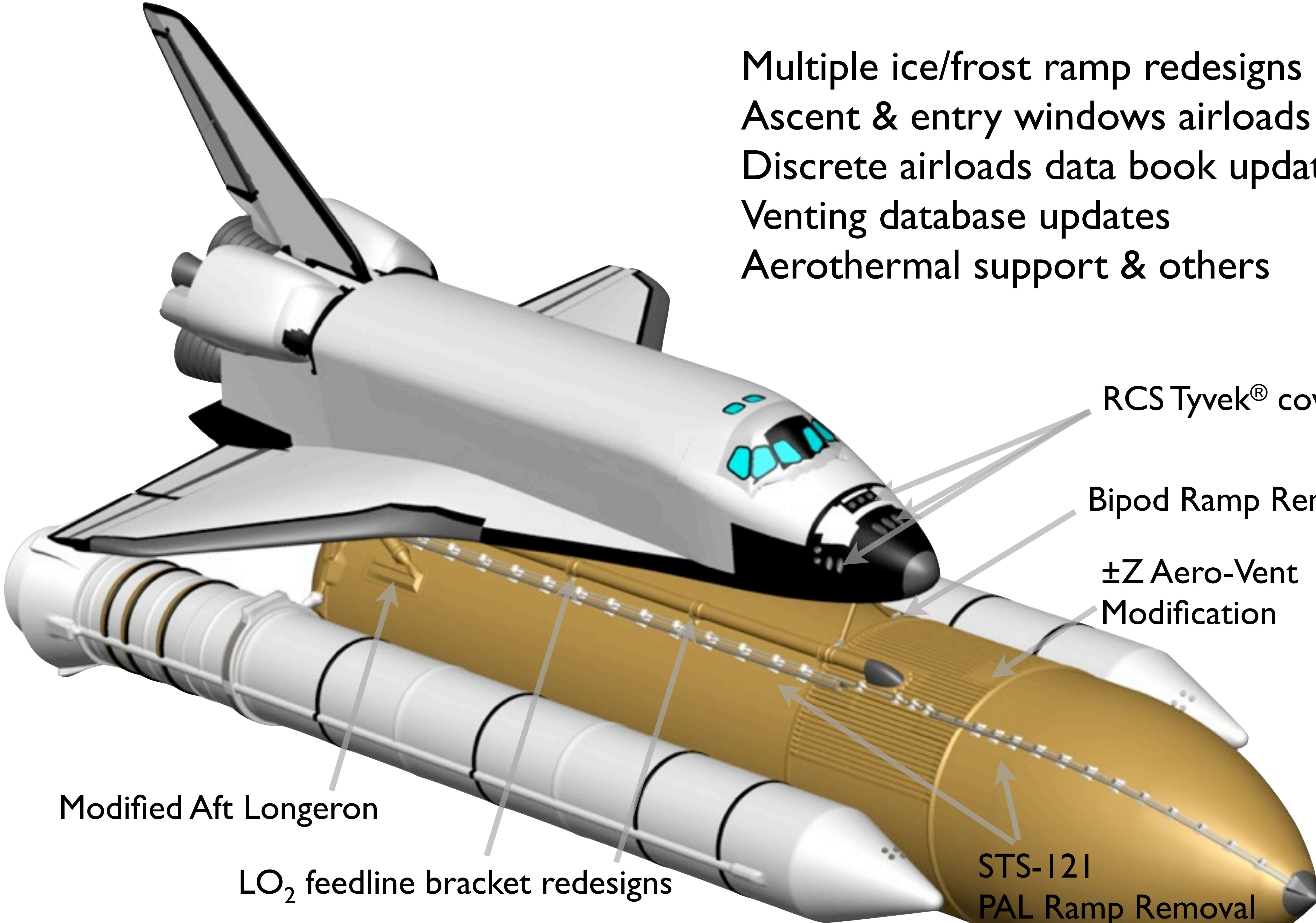
Difference plots are a more effective way of presentation comparison data.



Reynaldo J. Gomez III NASA/JSC/EG3

After validation had been established 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



Lessons learned over the last 20 years cover a wide range of topics with several common themes.

- Geometry is a first order effect
- Debris modeling and risk assessments
- Uncertainties
- Plumes
- Verification and Validation
- Data Archival
- Research areas

Geometry is a first order effect

Problem

- Over the course of the Space Shuttle Program several problems resulted from leaving out key geometry or boundary conditions. Only ET baselined CAD models.
  - Ground winds including surrounding buildings
  - Transonic wind tunnel wall effects
  - IA-700 - previous tests were based on an older External Tank configuration and was based on the Inner Mold Line (IML)
    - Detailed CFD geometry improved our validation comparisons
- External Tank shrinks 4-6 inches at cryo temperatures, SRBs are 0.9 inch longer when firing.
- Foam protuberances are built to relatively loose tolerance +/- 5°, etc.

Lesson

- Carefully consider all geometry that could affect the results.
- Keep a systems integration perspective in mind and avoid being overly focused on a single subsystem.

Ascent and Entry Debris

Problems

- Debris from various sources has been an issue since STS-1.
- STS-27R debris damage grounded the fleet until the source was identified.
- Foam debris was the root cause of the loss of STS-107.
- Internal debris flow control valve.

Corrective Action

- Documented all potential debris sources - 434 ascent, 225 ground
- Assessed critical debris sources by liberation potential and damage risk.
- Redesigned or modified processes to reduce or eliminate debris.
- Probabilistically assessed debris sources that could not be eliminated.

Lesson

- **Debris is an environment that should be assessed and documented.**
- Assess debris as a deterministic environment. If it is an issue, change the design to eliminate the debris at the source or modify the impacted hardware to be impact tolerant.
- The Space Shuttle Orbiter was susceptible to debris due to its location and hardware design requirements. Other configurations may not be.

Problem: Uncertainties

The Space Shuttle was the first aerodynamic database that included preflight uncertainties.

- Uncertainties supplied for aerodynamic coefficients.
  - Normal distributions with 3σ boundaries were assumed but difficult to justify.
  - Recent projects have used uniform distributions.
- No clear way to implement uncertainties for distributed pressures.
  - Provide design trajectory pressures to loads organizations.
- Protuberance airloads were based on bounding conservative assumptions.
  - No uncertainties were documented.
- No uncertainties updates were made using CFD during the entire program.
- **Where are the CFD error bars?**
  - **Quantification of model form error and as-built geometric variations remains a research area.**

Problem: Plume environments and modeling issues

- **Ignition Over Pressure (IOP)**
  - STS-1 support struts on RCS oxidizer tank buckled
  - STS-124 flame trench damage, over 3,500 20 lb_m bricks lost
- **Base pressure**
  - Plume testing approximately 10x more expensive than plume off
- **Booster Separation Motor (BSM) debris**
- **Return To Launch Site Reaction Control System jet interaction**
- **On orbit issues**
  - Hubble servicing mission
  - VRCS reduced effectiveness
  - “Zero thrust” vents
- Plume induced separation (Saturn V)
- MPCV Launch Abort System nonlinear aerodynamics

Historically base flowfield environment predictions have been one of the most challenging parts of launch vehicle environment development.

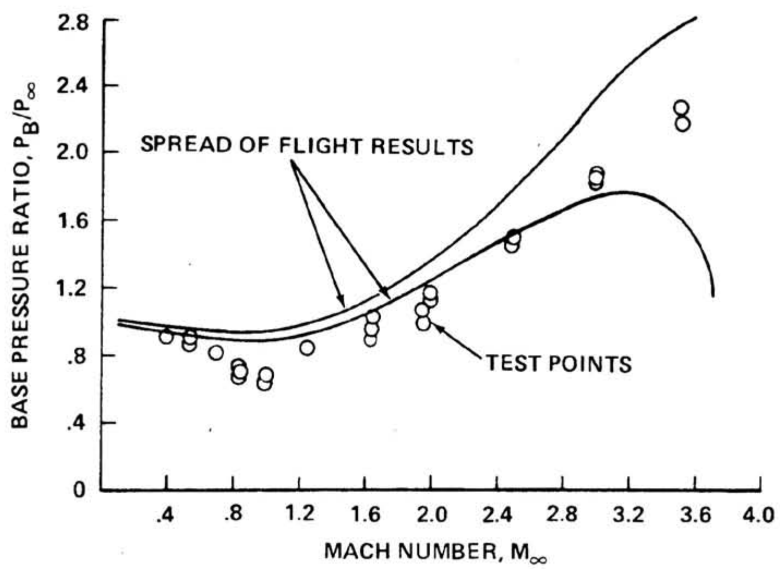


Figure 2.- Comparison of Saturn V test and flight data.

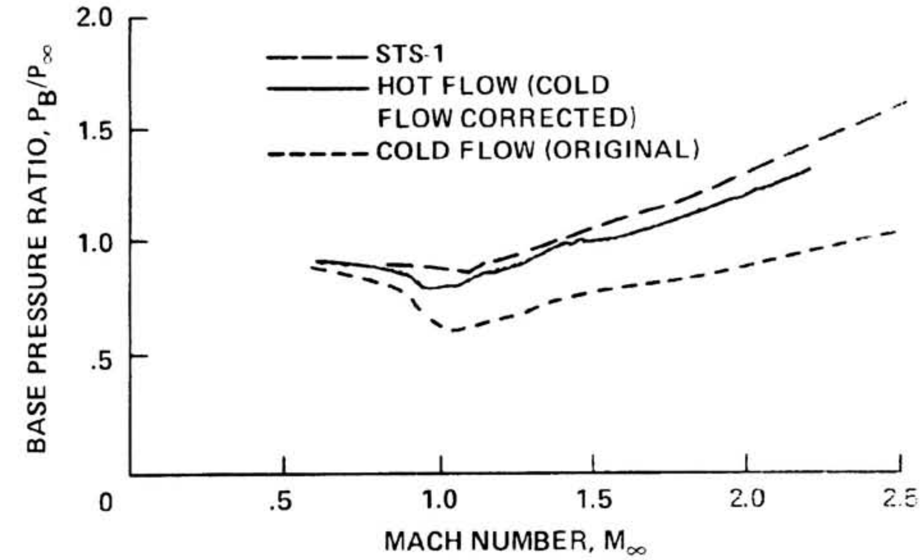
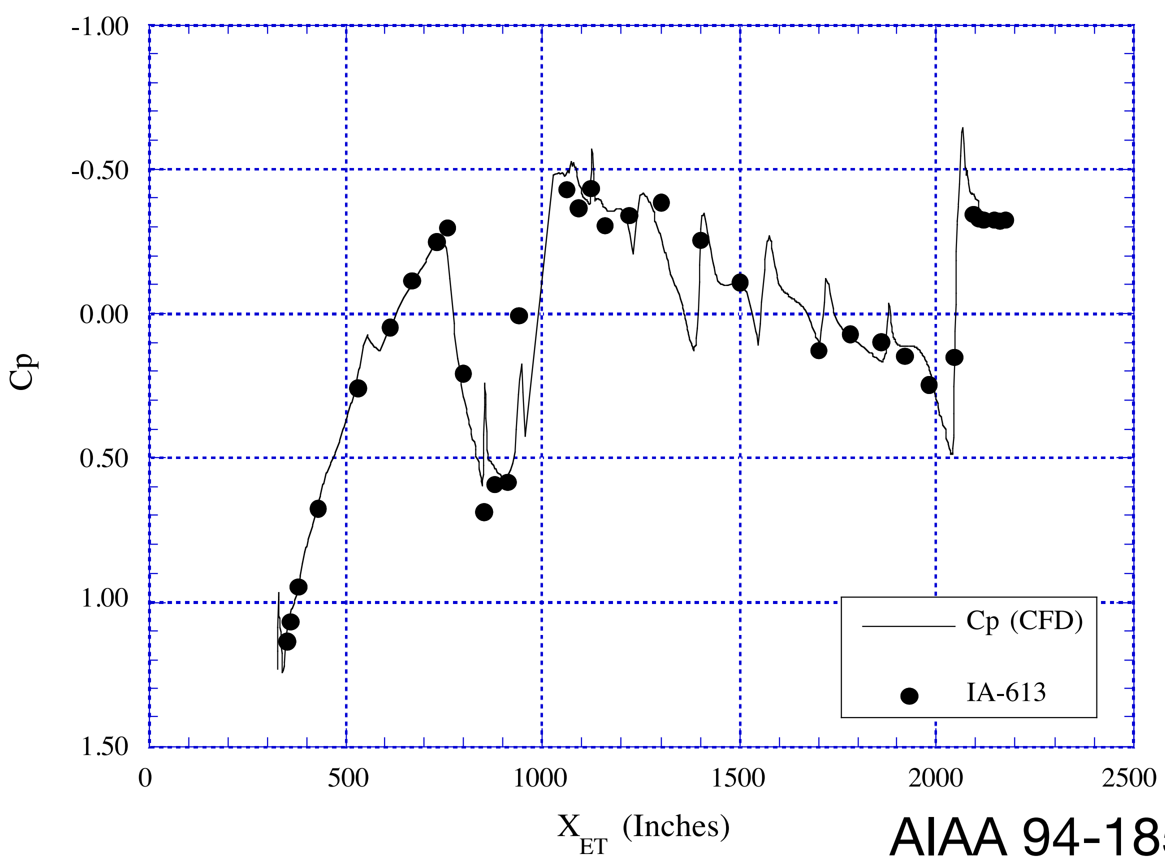


Figure 15.- STS-1 SRB base pressure compared to cold- and hot-flow predictions.

CFD matches wind tunnel w/o plumes.



(f) $\Phi = 270.0°$

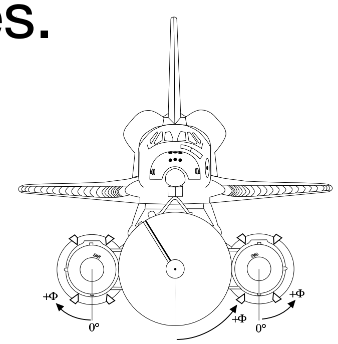
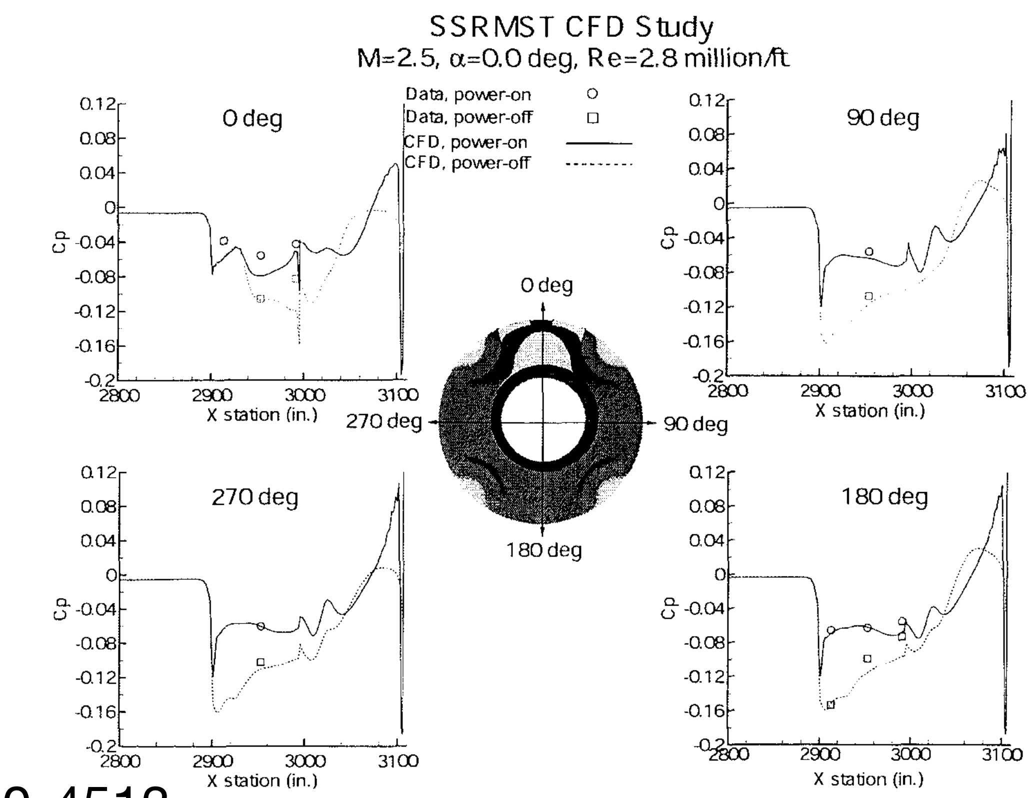


Figure 6 Instrumentation Φ angle definition

AIAA 94-1859

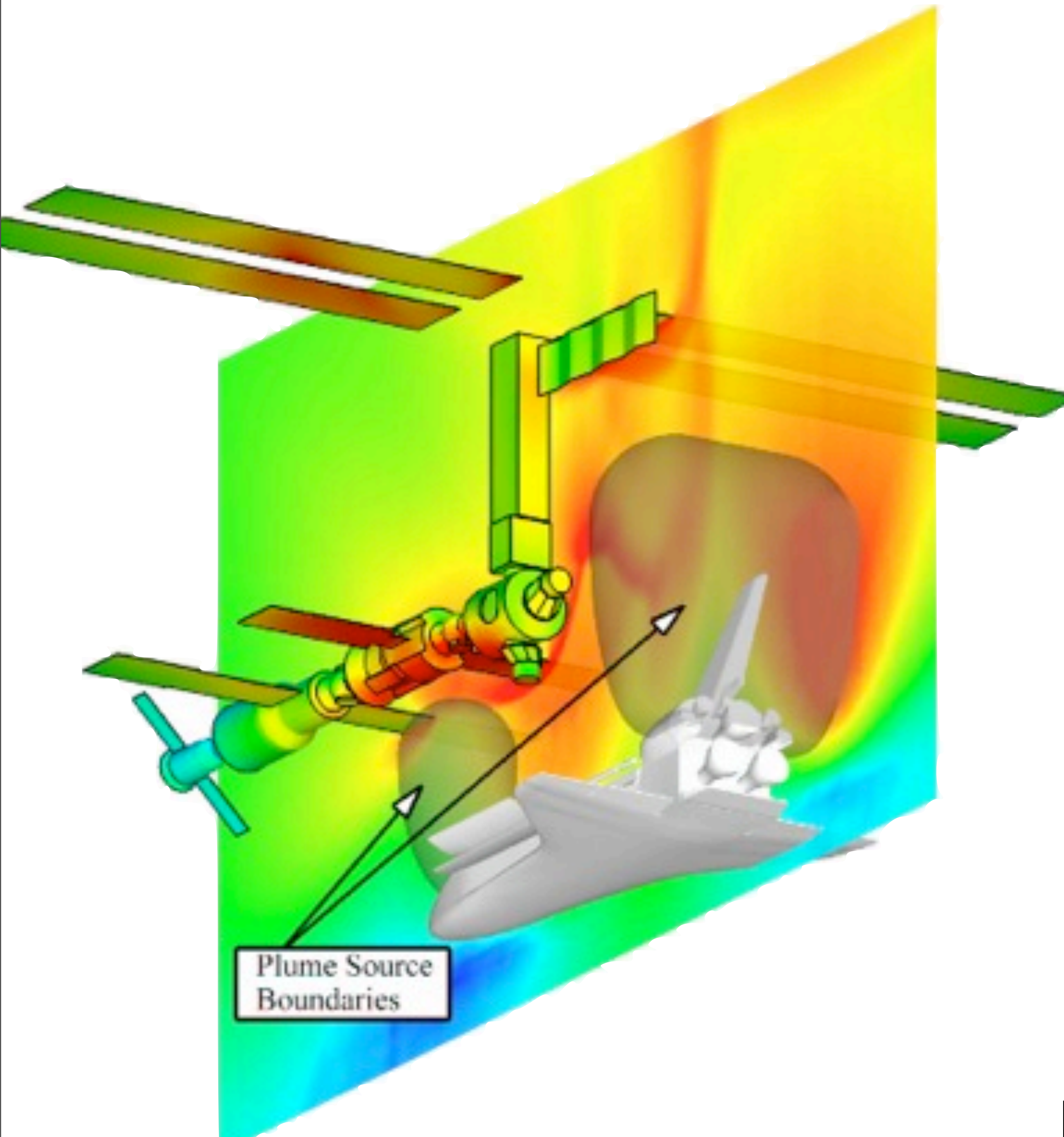
CFD matches wind tunnel with plumes.

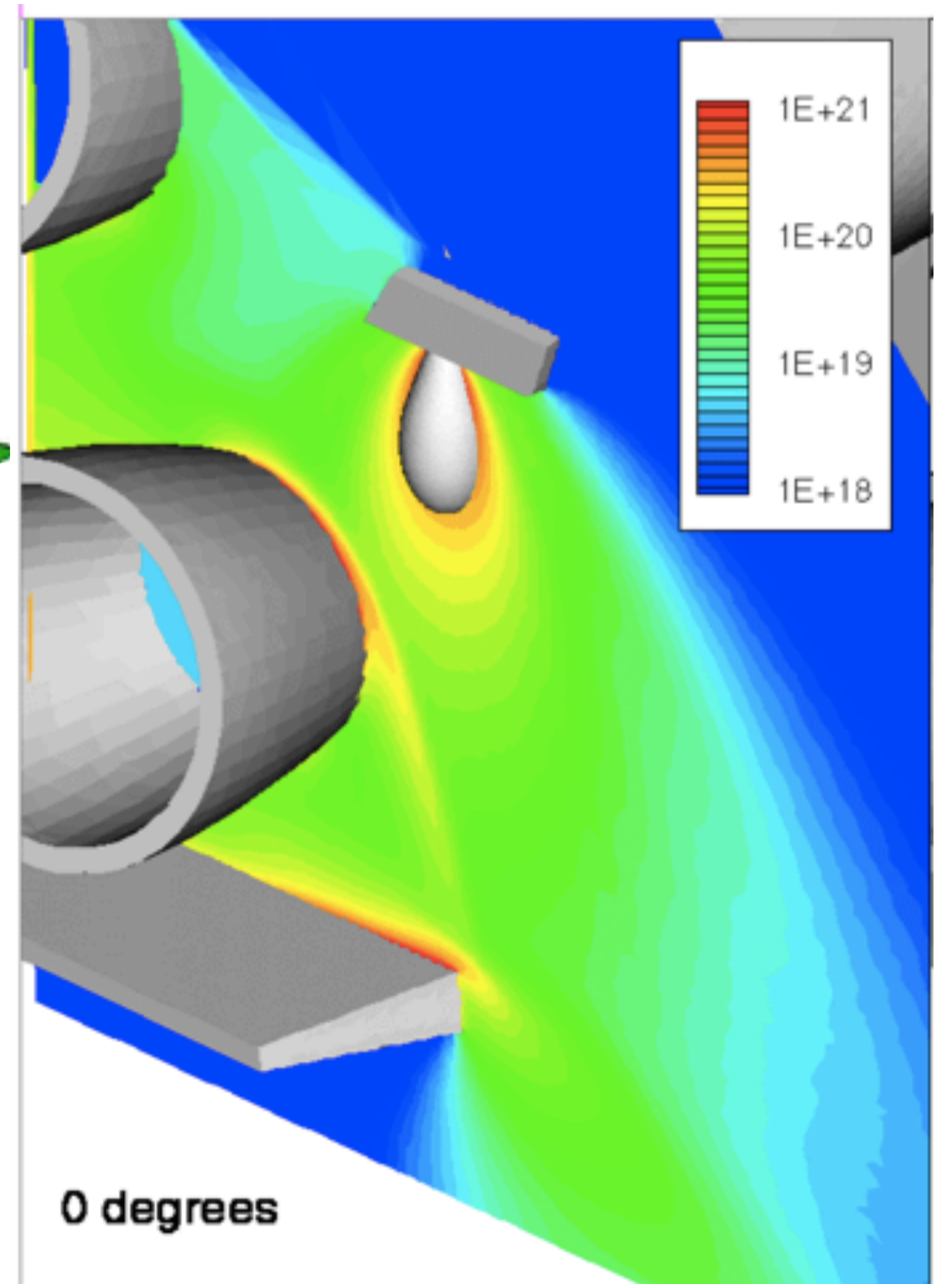


AIAA-2000-4513

Figure 5a. Power-On and Power-Off Pressure Distributions at Mach 2.5, alpha = 0 deg

Rarefied Plume Applications





Cant Angle (degrees)	Net Thrust (lbs)
0	12.879
15	16.773
20	17.461
25	17.829
30	18.105
35	18.224
40	18.193

DAC Code
Rarefied Direct Simulation
Monte Carlo (DSMC)

R5D & L5D Impinge on Body Flap
Canting outboard improves Net
Thrust

Plumes: Lessons learned

Base pressure prediction is an area that could use additional research

- More realistic plume calculations with hybrid RANS/LES schemes, plume chemistry, accelerating flow fields?

Currently Ignition Over Pressure predictions can be made without multiphase effects (Cetin Kiris/ARC, Jeff West/ MSFC)

- Multiphase effects of water deluge are a research area

Plumes interact with surrounding geometry, even in rarefied environments.

- Include geometry that is near plumes.

Protuberances

Problem

- Protuberances cause locally elevated environments that require detailed analysis and can substantially increase engineering workloads.
- All elements did not have the same understanding of protuberance airloads.
  - Was the load created by integrating Cp or p?
  - Is the protuberance vented, sealed or solid?

Corrective actions

- Checked hand calculations with CFD. Generally found the the databook was conservative, found a few cases that missed interactions.
- Extensive wind tunnel and ground testing to understand foam and ice liberation modes.

Protuberances: Corrective Actions (continued)

Corrective Actions

- USA/JSC/MSFC worked to improve aerothermal testing and analysis.
- Worked with elements to insure consistent understanding of airloads application.

Lesson

- Minimize protuberances where possible.
- Use bounding engineering techniques to characterize airloads, check conservatism and interactions with CFD.
    - Engineering level techniques for estimating static airloads are straightforward and generally conservative. Dynamic and aerothermal environments are much more challenging to characterize.
- Document protuberance airloads assumptions and make certain that all elements are aware of how to apply them.
- Shuttle had conservative airloads on most protuberances and bounding loads on running loads. Consistent treatment should be considered.

Data Archival

Standardizing wind tunnel data with the Chrysler Dataman contract was an important start.

- Shuttle Wind tunnel data Access Tool (SWAT)
- After STS-107 EG3 developed website to provide simple consistent access to all Shuttle wind tunnel data and reports.

1999 Powerpoint files won’t open in recent versions of MS Office

- ASCII, Adobe PDF or paper has the best chance of standing the test of time.

Early CAD models did not stand the test of time.

- In-house modelers in the 70’s did not have keep up with modern standards.
- Continuously migrate geometry to new systems as they emerge.

Key CFD limitations/research areas

Uncertainty estimates

- Where are the CFD error bars? How do estimate model form uncertainties/as-built geometry uncertainties?

Massively separated flow prediction behind bluff bodies

- Key issue for capsules

Strong shock wave boundary layer interactions

- Heating, abort systems, plumes,...
- Heating predictions within a factor of 2x near protuberances and cavities is challenging.

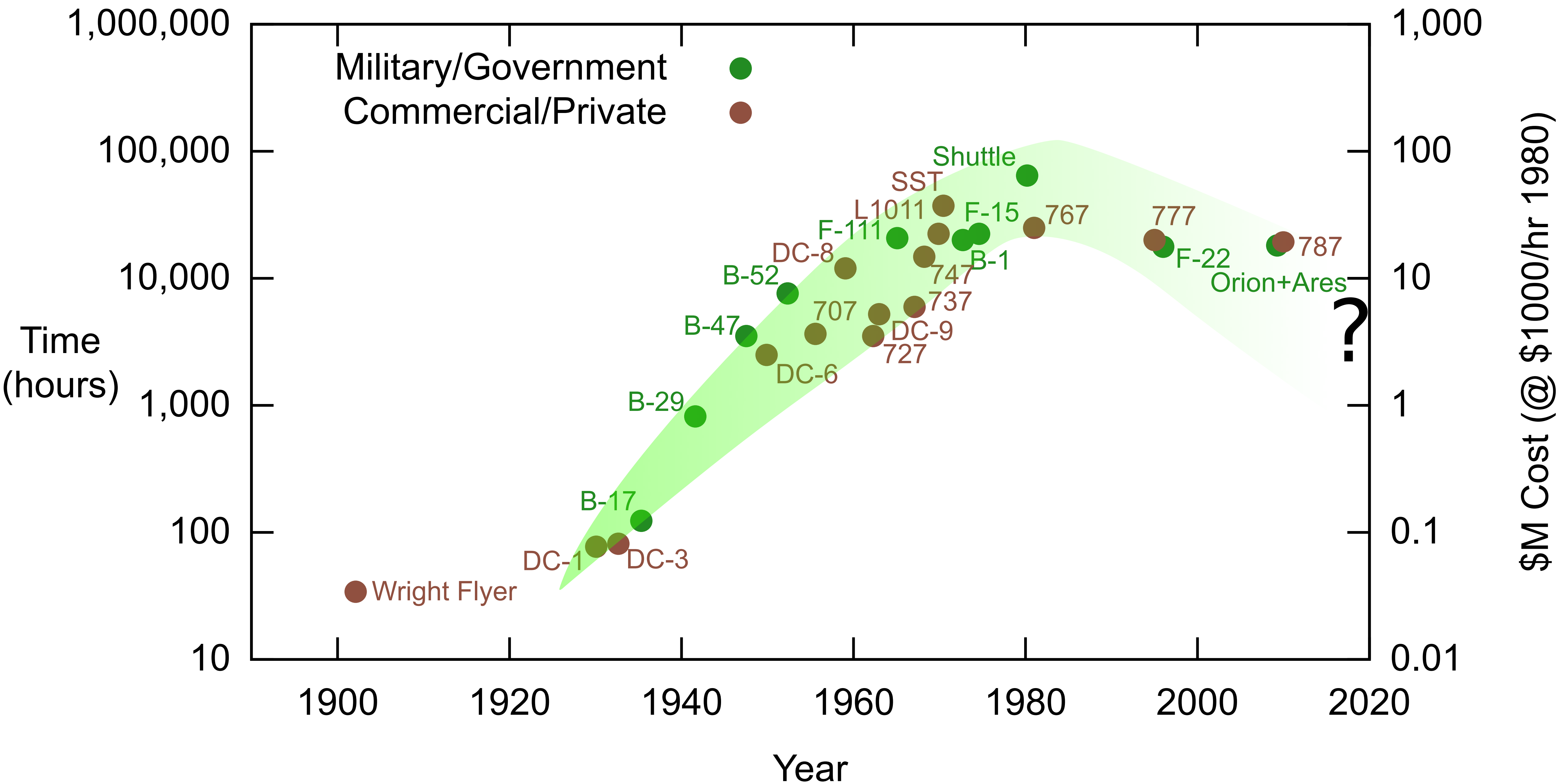
Boundary layer transition prediction

- Empirical techniques exist but transition location can be very sensitive to small perturbations.

Analytical launch vehicle acoustic predictions

- Cavity acoustic predictions have been gradually getting better as codes move towards LES simulations, but populating a database for a relatively complex vehicle is beyond our current capabilities.

Faster computers and improved modeling and simulation capabilities have reduced wind tunnel testing costs. Major programs still need considerable wind tunnel budgets, since CFD cannot produce all of the data that is required.



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

Recommendations from a reviewer's perspective

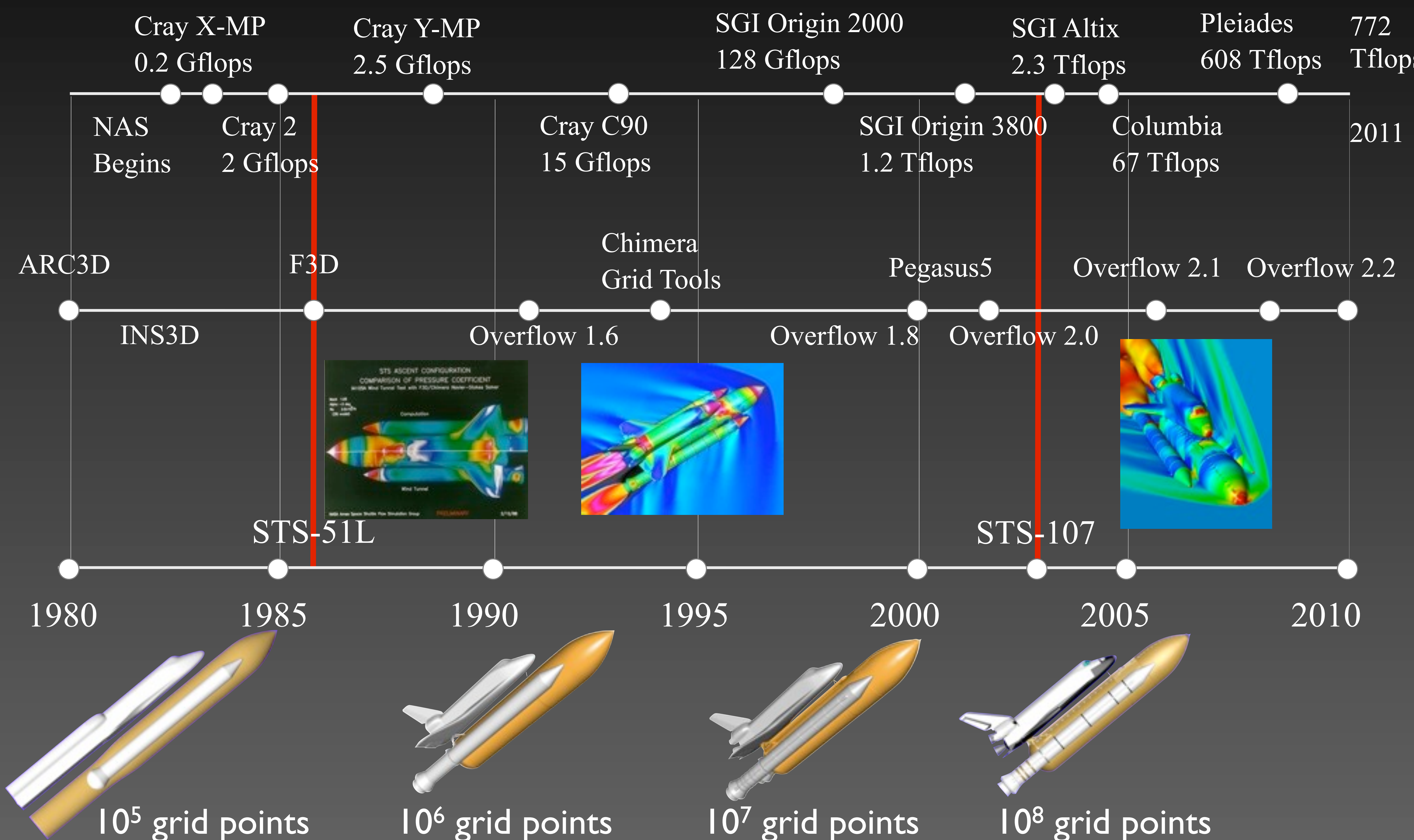
Provide objective evidence that demonstrates that the induced environments have been adequately characterized.

- Complete coverage of all flight regimes and envelopes.
- Verification and Validation data to support the use of CFD and other modeling tools.
- Independent verification of data.
- Rationale for uncertainty estimates.

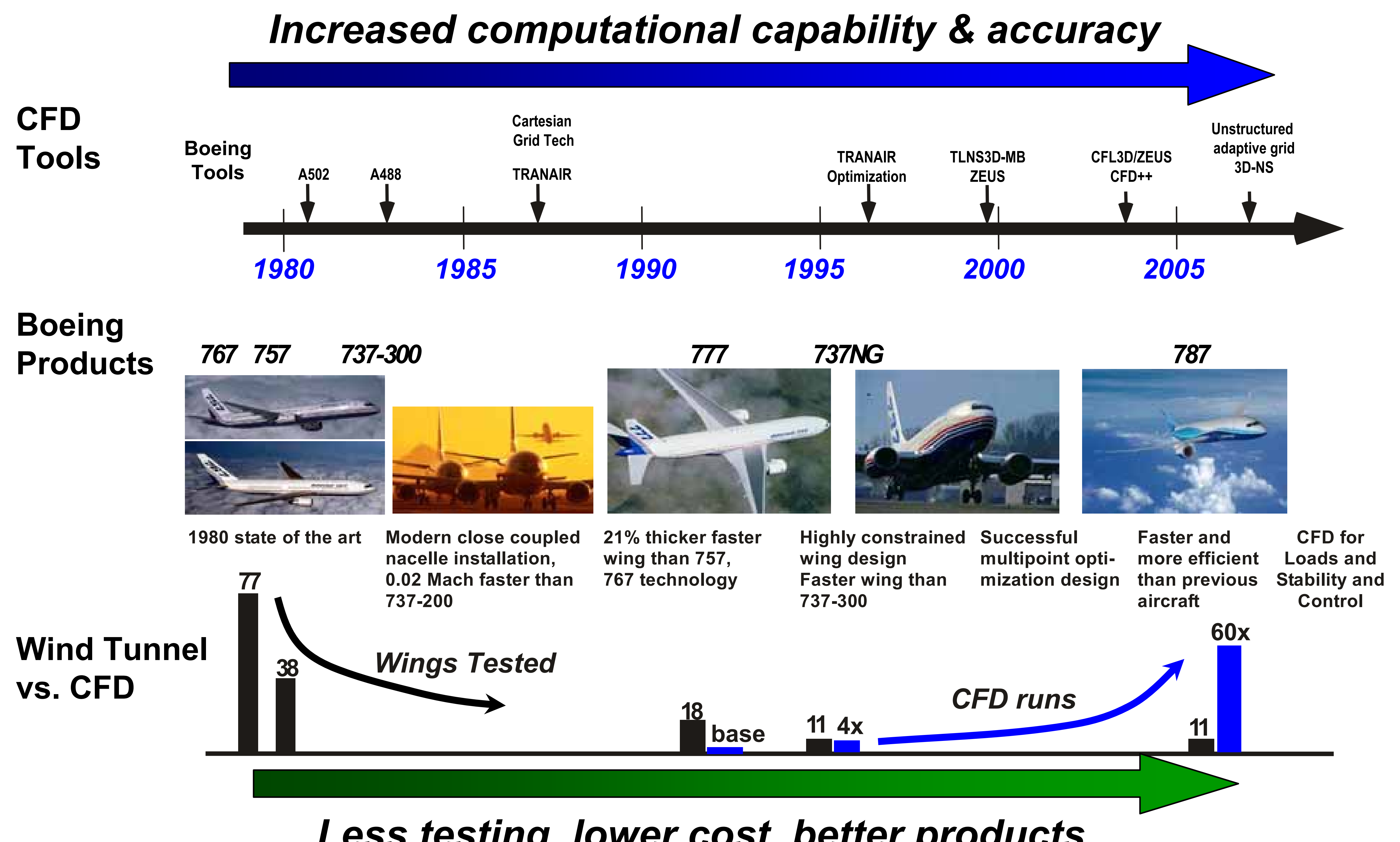
Flying with a crew requires working to a higher standard.

Back Up Charts

Timeline of Computing & Overset Space Shuttle Applications



Modeling and simulation can reduce cost and result in improved designs.



Douglas Ball/Boeing, IDC HPC User Forum, October 2008.