Aerodynamic Prediction
Best Practices and Lessons Learned

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Outline

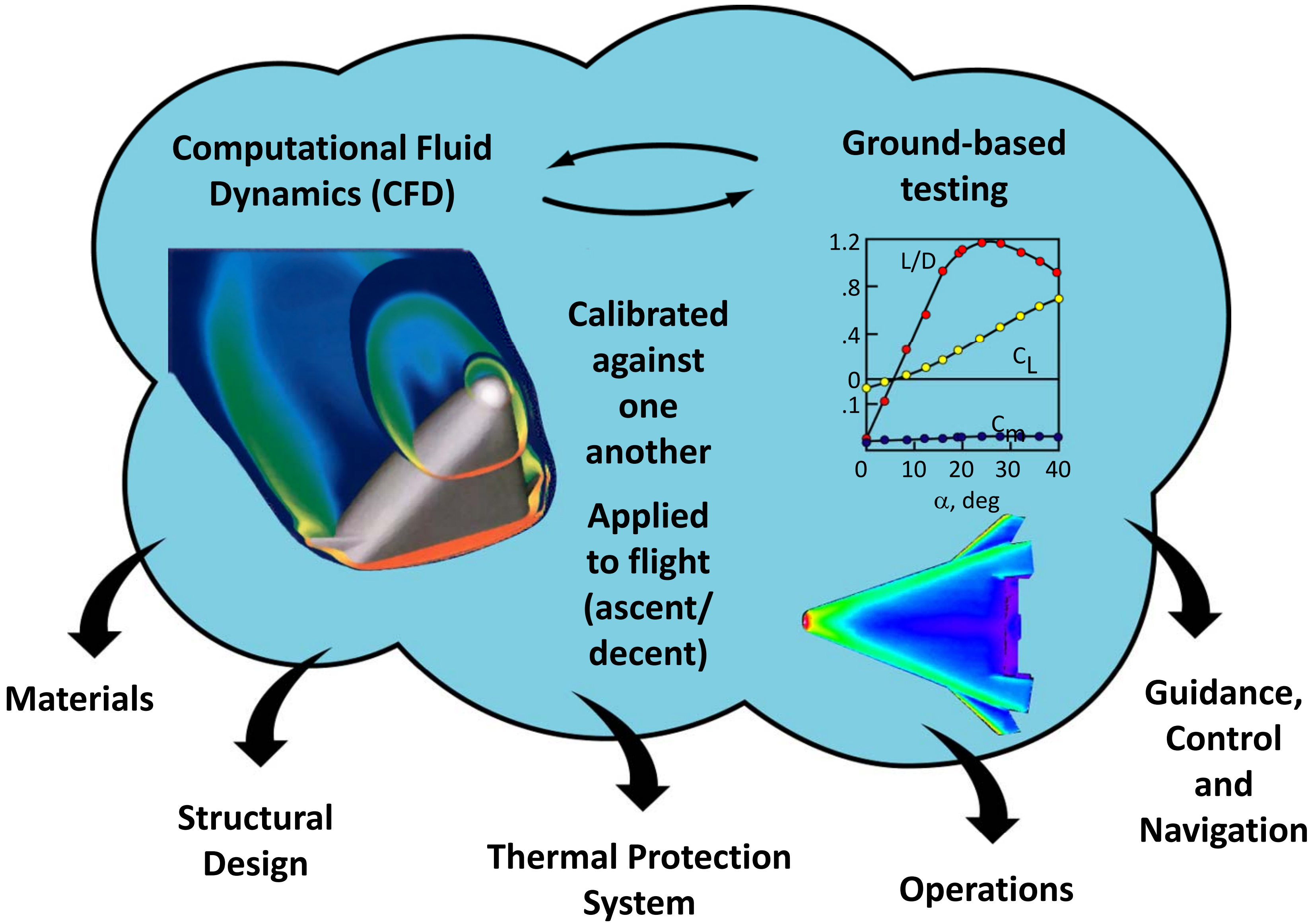
- **Background**
- **Examples of known and unknown risks and their consequences**
  - **Ares I-X, not funding wind tunnel test to clarify tower strike probability**
  - ***CTV/X-38, assuming it would fly like X-24***
  - **X-33, detailed aerodynamics conducted after OML freeze**
  - **Pegasus XL, no experimental aerodynamics**
  - ***X-43, insufficient aerodynamics***
- **Process for Aerodynamics from concept to flight**
  - **Details**
  - **Experiment and CFD applications**
- **Flight test is the ultimate end-to-end check**
- **Summary of Lessons learned**
- **Final Comments**

Background

- **Not having the right information at the right time for analysis, design, simulation and decision points will result in Risk for Design Analysis Cycle (DAC) of a Flight Program**

- **For the purposes of this talk, Aerodynamics is inclusive of:**
  - **Aerodynamic coefficients, both static and dynamic as well as control effectiveness**
  - **Aeroheating coefficients**
  - **Surface pressure coefficients and integrated line loads**
  - **Fluid Dynamics; boundary layer transition and separation, vortex flows, shock/shock and shock/boundary layer interactions, etc.**

Aerodynamics Affects Everything Else



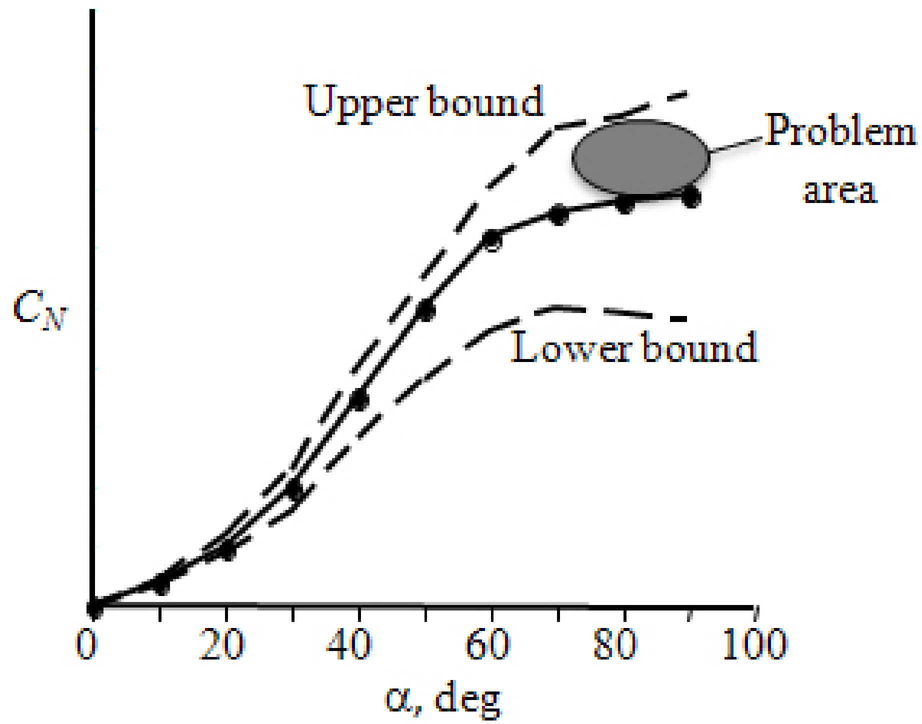
Example 1—Not Having the Right Information at the Right Time

Not funding lift-off testing

- **Ares I semi-empirical Lift-off data from the early databook, approved in 2008, was used for Ares I-X and resulted in possible tower strikes in lift-off simulations**
- **Once problem identified, Aero Panel could not just arbitrarily change the data simply because the results were bad**
- **Without other information available, Ares I-X decided to add a “flyaway” maneuver at lift-off to fly the vehicle away from the tower.**
- **“Flyaway” maneuver added risk to launch and damaged the pad with exhaust gasses**

Ares I Aerodynamic Databook Information

- **Original, semi-empirical Ares I Lift-off data from the approved Databook was "constructed" using other vehicle data, engineering methods and judgment with associated uncertainty bounds appropriate for this engineering approach**
  - **There was a lot of discussion of "appropriate"**
- **This was reasonable but when compared after experimental data obtained later it turned out to be very conservative**

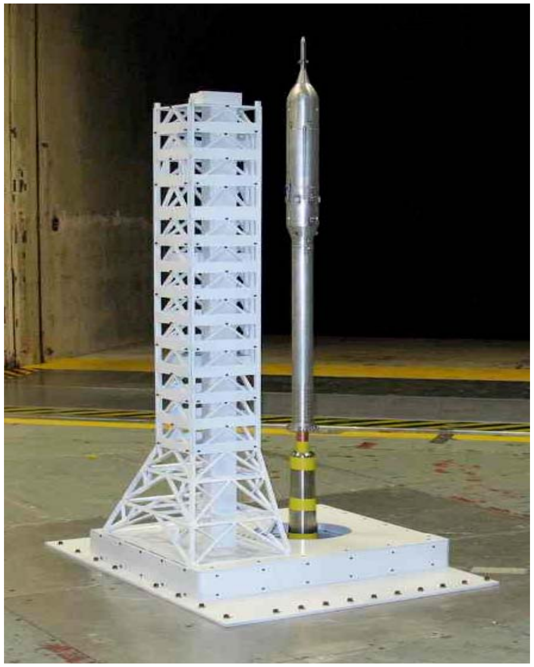


Ares I-X Lift-off Flyaway Maneuver

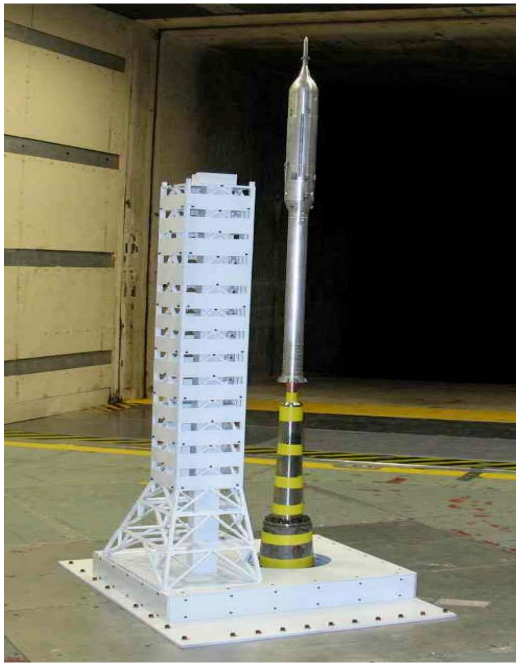
Obtaining Experimental Lift-off Data for Ares I

- Follow-on wind tunnel results indicated that original data was very conservative at all wind azimuths and various tower clearance heights
- Tower strikes were not really an issue for design crosswinds

X/L= 0



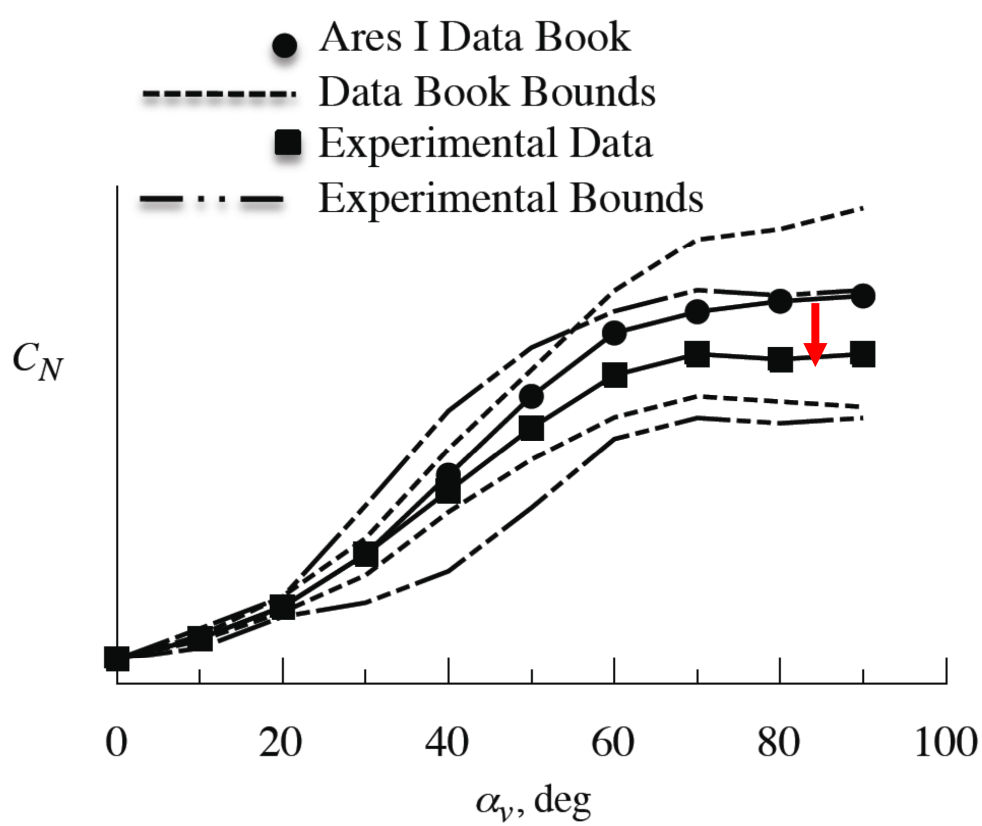
X/L= 0.22



X/L= 0.40

Final Ares I Lift-off Data

- **Original semi-empirical estimate was not "incorrect" but mean experimental data was lower by about 15-percent in the problem area**
  - **Tower effects further reduced the mean by up to 40-percent**
- **Credible experimental results also allowed a reduction in uncertainty bounds at high-AOA but did increase uncertainty in the mid-AOA range**

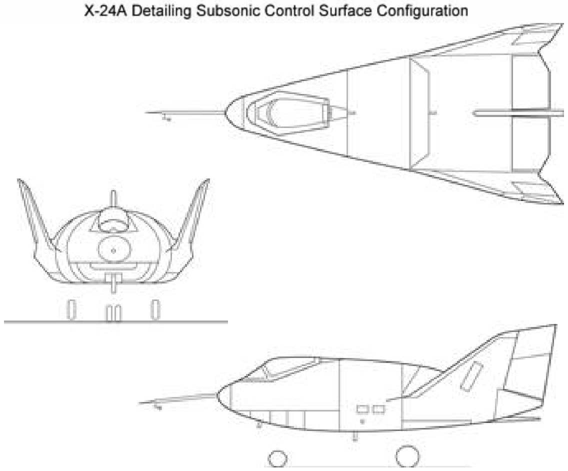


Lesson Learned

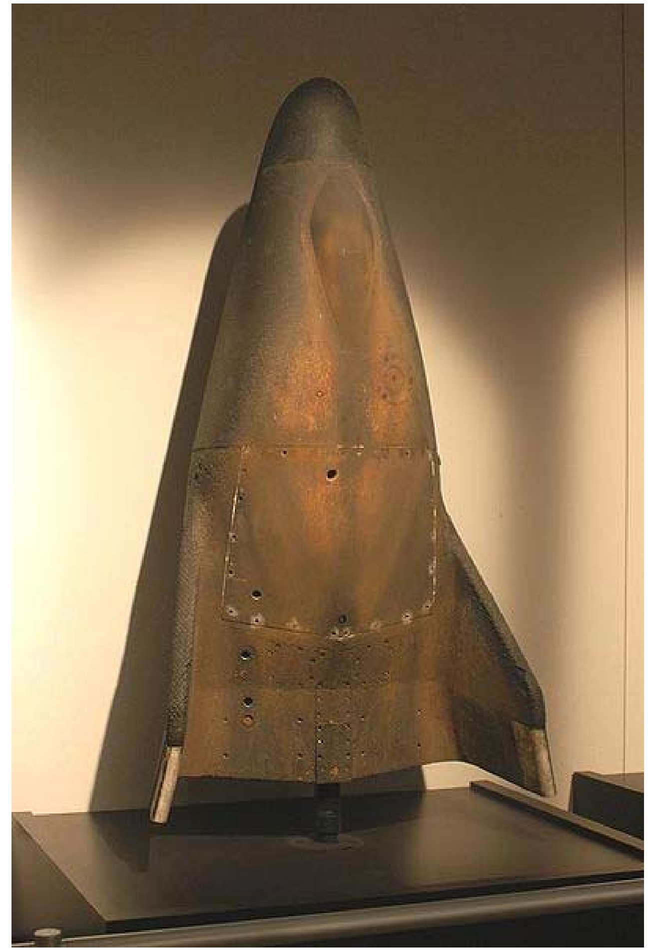
- **A decision for Ares I-X had been made with information that was not as accurate as needed and resulted in an unnecessary maneuver that was not acceptable for regular Ares I operations**
- **This situation occurred because wind tunnel test was deemed too costly and too time consuming for the Ares I-X Flight Project**
- **This example, along with others to be mentioned, drive home the point of having the right information at the right time**

Example 2—Assuming Two Similar Configurations Have Same Aero

CTV/X-38 was initially to be the X-24 OML



X-24A flown Mach 2 to landing



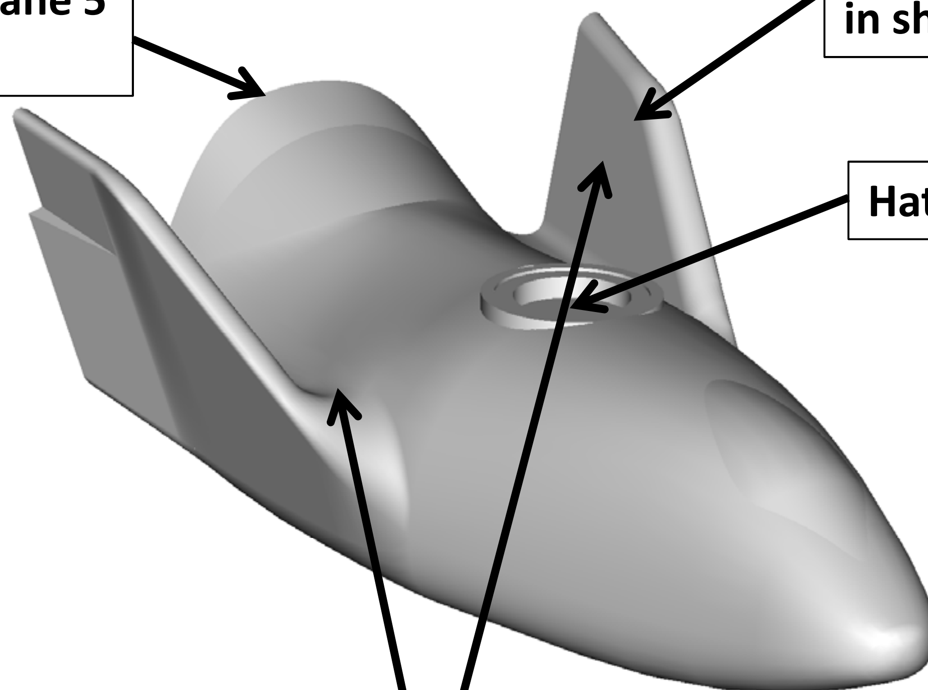
X-23A Precision Reentry Including Maneuvering reEntry (PRIME) flown Mach 25 to Mach 2

CTV/X-38 OML Modified to Launch on Ariane V

Flare to mate with Ariane 5 and no center fin

Shortened fins to fit in shroud

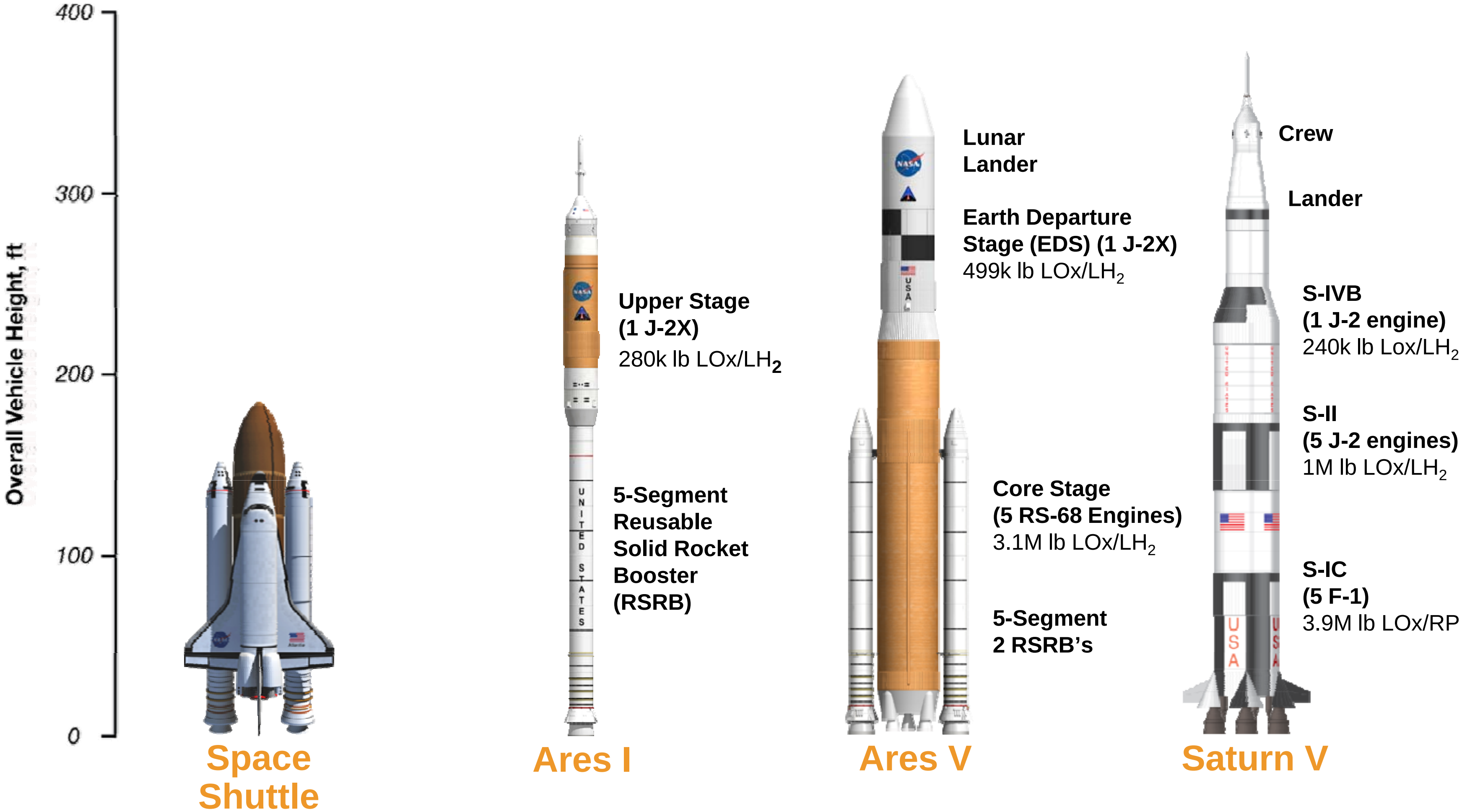
Hatch to mate with ISS



OML changes resulted in flow separation in channel and fins and would have rendered CTV/X-38 configuration unflyable and discovered through extensive wind tunnel work by Pel Phillips in UPWT

Shuttle and Saturn Provided Information for Ares I and V

Note that from DAC-1 to 605-054 to A106 Ares I was not the same configuration



Lesson Learned: If it is not the same OML, it is a new configuration and do not assume that it will have the same characteristics!

Example 3, OML of X-33 Frozen Before Detailed Aero Assessment

- In optimization phase after OML frozen wind tunnel and CFD results indicated trim problems near Mach One
- Change in fins and aftbody contour recommended using both experiment and CFD but program was terminated with failure of LH2 tank

Dryden Flight Research Center ED97-43938-3
X-33 Reusable Launch Vehicle (Artist concept courtesy of Lockheed Martin)

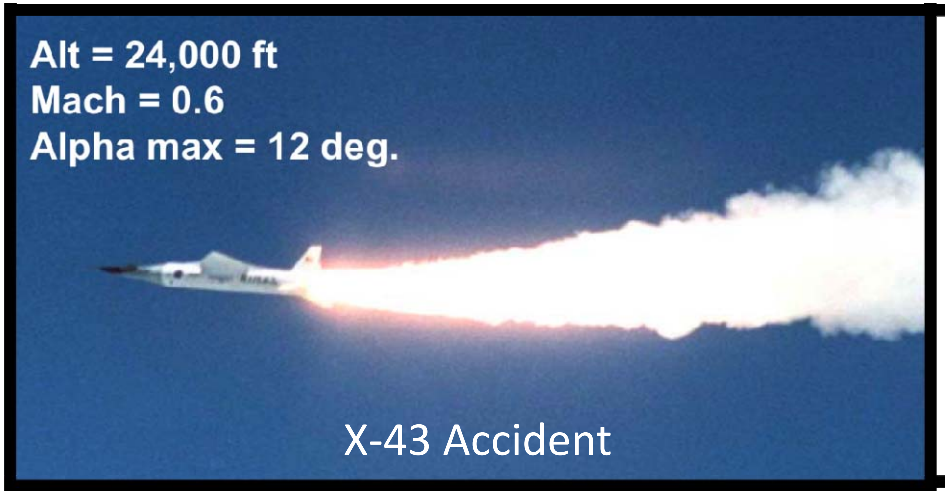
Lesson Learned: If pitching moment is not zero everywhere the rest does not matter

Example 4, Pegasus XL Developed without Wind Tunnel Testing

- **Accident due, in part, to**
  - **Configuration aerodynamics developed without wind tunnel testing and the configuration changed from Standard to XL**
  - **Limited auto pilot design with no positive control of sideslip**
  - **Standard really was not flying very well**
- **Recovery consisted of**
  - **Wind tunnel tests, which showed errors in original aero**
  - **Improved auto pilot**
  - **Better estimate of sideslip**

Lessons Learned: Do not bet everything on computations, look out for configuration changes and assess flight characteristics

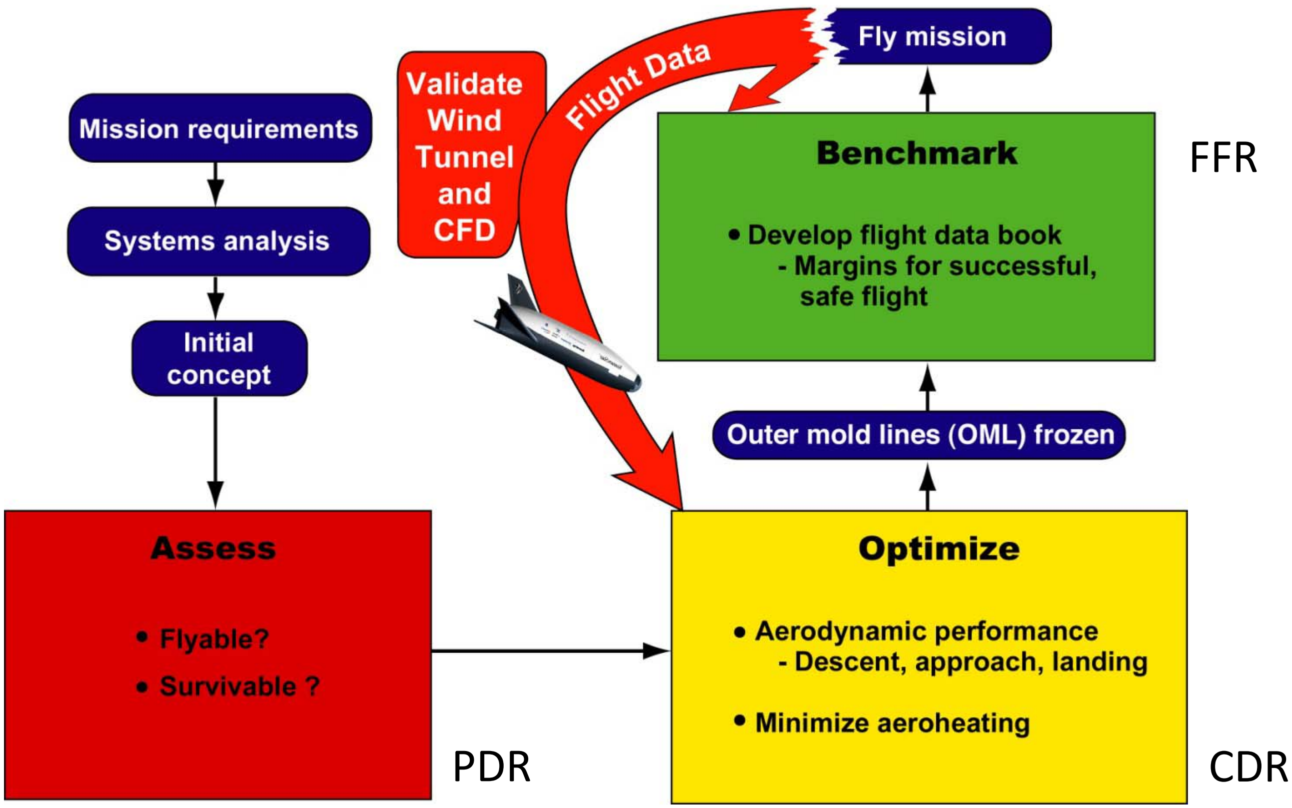
Example 5—X-43 Accident from Many Errors



- **Accident due, in part, to**
  - **Launching at higher q's**
  - **Aileron control effectiveness larger than expected and led to vehicle oscillations**
  - **Fin hinge moments exceeded**
  - **Caused by analysis mistakes, an OML change after the Aerodynamics was obtained and insufficient test points**
- **Recovery consisted of**
  - **Proper wind tunnel testing and analysis**
  - **Proper oversight and engagement of review panels**

Lessons Learned: Do not skimp on wind tunnel data, fly what you tested and review panels should be engaged early

A Process for Aerodynamics from Concept to Flight



Requires

- Trajectory Definition
- Performance Analysis
- Controls
- Atmospheric Model
- Databases
- GN&C Algorithms
- Structural Analysis
- Uncertainty Analysis
- End-to-End Simulation
- Allowable Risk

This must happen before every flight. It may go fast if next flight is similar but it must happen every time. If you skip parts, you can find yourself in trouble!!

Assessment

- **Based on mission requirement and conceptual analysis, concepts are generated and must be assessed for viability**
  - Limited wind tunnel testing
  - Engineering methods and CFD
    - With current capability these are becoming one
  - Information for all other discipline teams
  - Will it succeed?
- **Generally concluded with a PDR and authority to proceed to critical design phase**
- **CTV/X-38 configuration change in this phase rendered the concept unflyable**
  - If it is not the same configuration it is a new configuration and you must start from scratch

Optimization

- **Detailed determination of Aerodynamics of the vehicle with experimental and CFD testing/analysis**
  - **Databases for GN&C**
  - **Surface pressures and line loads for Structural Analysis and Bending**
  - **Heating for TPS determination and sizing**
  - **OML frozen**
- **Completed with CDR and approval to build hardware**

- **X-33 OML frozen but, as was found later, could not be trimmed at all flight conditions**

Benchmark

- **Final information leading to FRR and flight**
  - **Aerodynamics for as built OML**
  - **Final databases for simulation and analysis**
  - **As built vibration testing for final input to GN&C**
- **Ares I-X vibration testing was successful and verified projections**

- **Pegasus XL flown on zero experimental Aerodynamics**
- **X-43 actually had some serious Aerodynamic shortcomings that the FRR board missed.**
  - **Review panels must be engaged early to have best results**
  - **This applies at PDR and CDR as was shown in the Ares I-X design cycle**

Fly

- **Review panels engaged early**
  - This is very important and should start at PDR and follow all the way through the project
  - Fire-hosing a panel for a week is not the way to get a good result
- **There cannot be too much instrumentation on the first couple of flight articles**
  - This is often the first thing to go as budgets and schedules get squeezed
- **Once flying, REALLY LOOK at how well it is flying**
  - Do not just say it worked if it went somewhere
  - Delta II best practices in CFD did not identify an unsteady aerodynamic problem but it was critical examination of HOW it was flying that led to the work for a solution

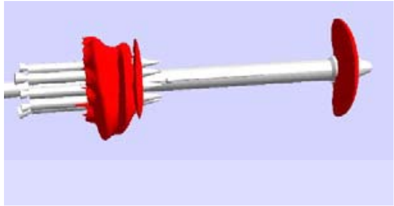
Flight: Delta II Heavy Unsteady Flow Caused Large Engine Deflections

Government/Industry team developed the solution

Main engine deflections larger than predicted for 3 successful flights--MER-B, SIRTF, and MESSENGER

- Standard analyses with usual best practices, did not detect an unsteady flow problem
- Unsteady problem was originating under solid rocket booster cluster
- Problem detected, quantified, and corrected with a coordinated wind tunnel, CFD, and GN&C approach
- This coordinated approach used as the model for the Ares aero team

National Transonic Facility



Red regions highlight supersonic flow near Mach 1

Lesson Learned: Really look at how a vehicle is flying and even best practices at the time may not catch everything

How to Make this Process Really Work

- **Integration of Experiment and CFD**
  - **What Experiment can do**
  - **What CFD can do**
- **Validate Tools**
- **Understand the fluid mechanics of your data**
- **Integration of Data Providers and Users as well as Vehicle System Designers**

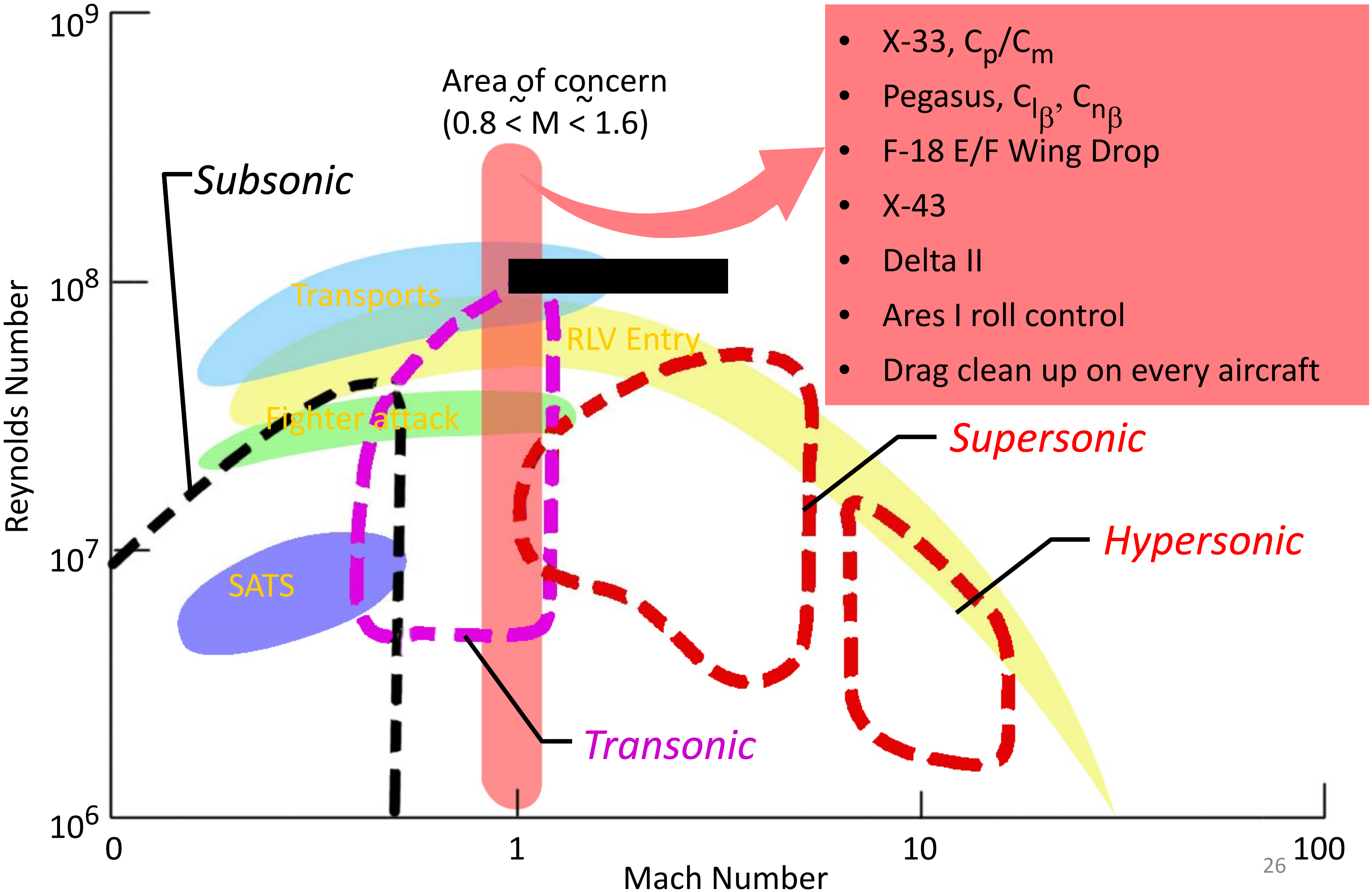
Integration of Experiment and CFD

- **Must have both as CFD is not there yet!!**
- **If both give similar answers you have some hope that it is right**
  - **It took a long time to get this right for Ares I but in the end it was invaluable**
- **Plan testing and CFD for maximum impact**
  - **Design of experiment can work**
- **Plan for UQ up front**
  - **UQ is a real problem because when the simulation fails, what is the rationale for changing the bounds?**

What Experiment Can Do

- **Physics is correct whereas CFD models physics**
  - Issues with installation, Reynolds number, power simulation effects but the gas is right and the turbulence is right if tripping employed
- **Vast array of test points required for simulation databases that CFD simply cannot obtain**
  - Model attitudes, configurations and conditions
  - Low speed for take-off and landing
- **Surface pressures for CFD calibration**
  - This is a must for CFD to provide credible line loads for structural analysis for the case of asymmetries in model geometry
- **Use multiple facilities with proper overlap/duplication of points where possible**
- **Plan proper repeat runs for uncertainty before you test**
- **Propulsion simulation very difficult on the small scale models for this class of launch vehicles**

Range of Wind Tunnels Required for Development of Flight Vehicles

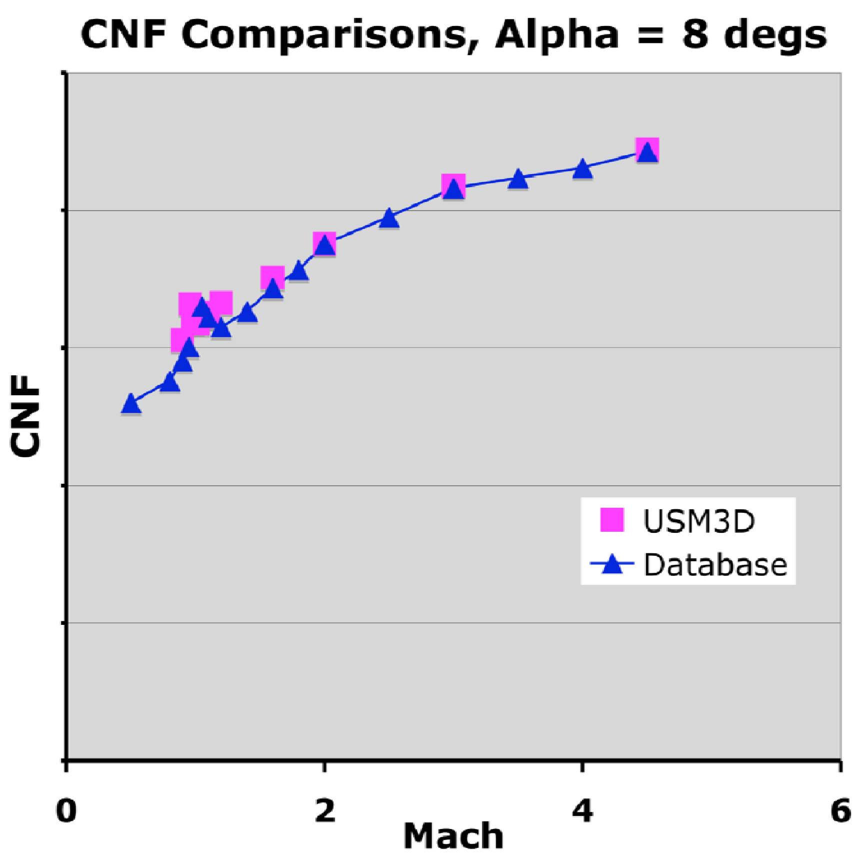


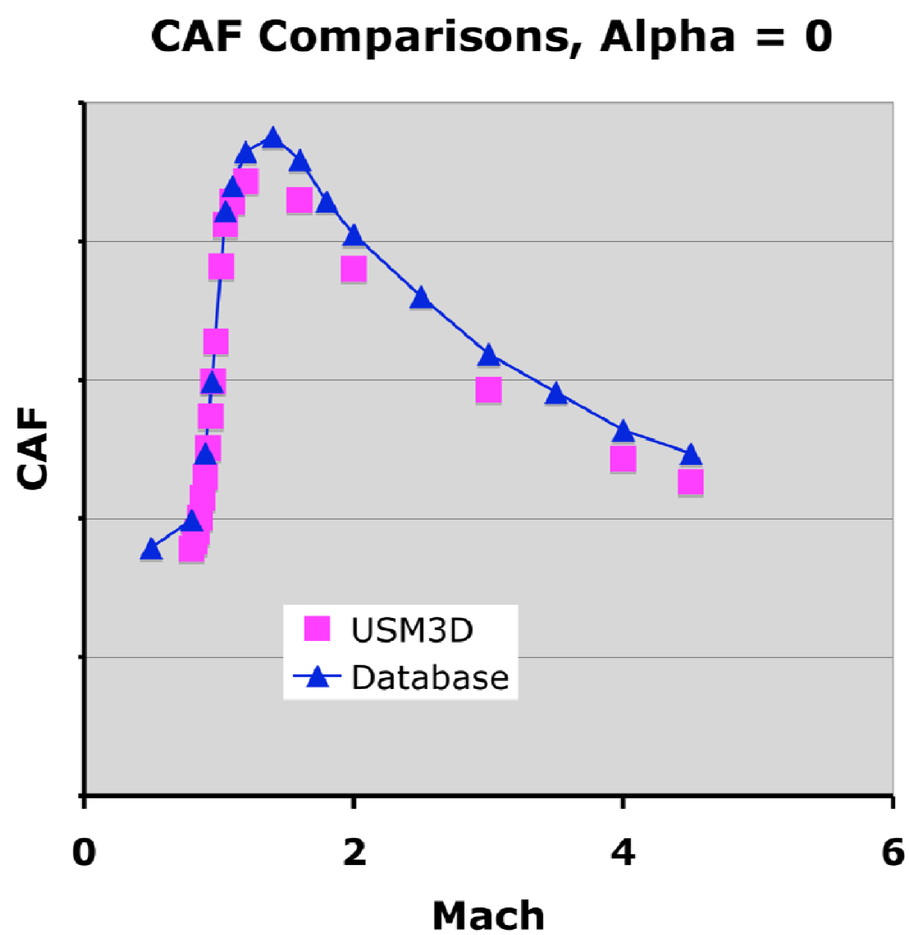
What CFD Can Do

- Once things are working small changes can be assessed as was done in Ares I
  - Compare codes against one another
  - Turbulence models
  - Grid refinement
  - Compare CFD results with experimental results wherever possible
  - For Ares I this was about a two year process between the experimental and CFD experts on the Aerodynamics Panel
- Reynolds number effects
- Detailed surface pressures for line loads and protuberance loads
  - Simply cannot put enough holes in a model with protuberances or asymmetries to get this. Must have some experiment for calibration
- Propulsion simulation
  - Combination of CFD propulsion and experiment aerodynamics showed potential roll control issues for Ares I near maximum dynamic pressure
  - Stage separation
- Great confidence that another Ares-like configuration would work but not at all confident that different configurations would not need a similar period for demonstration of capability

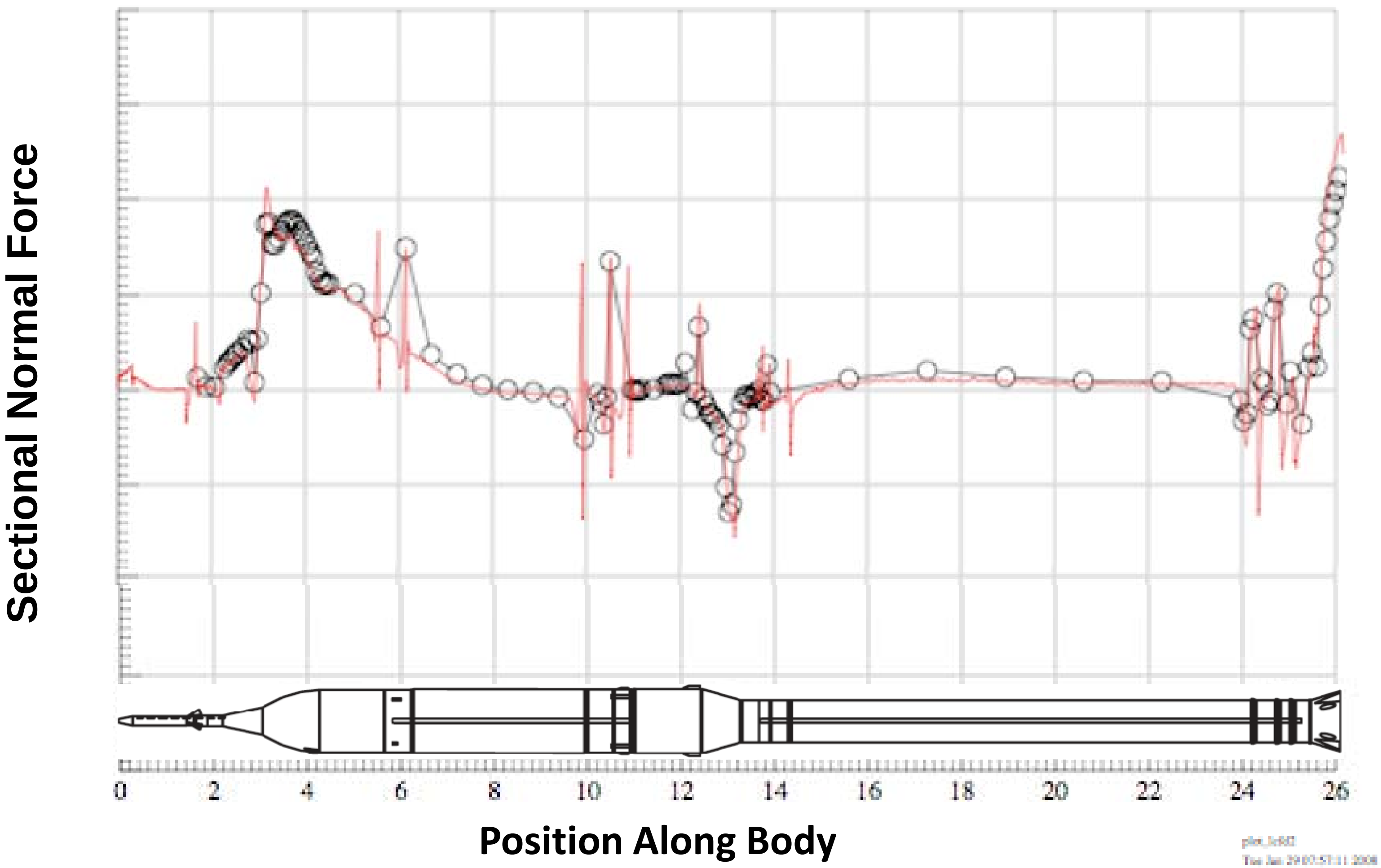
Ares I Agreement Between Experiment and CFD

Forces



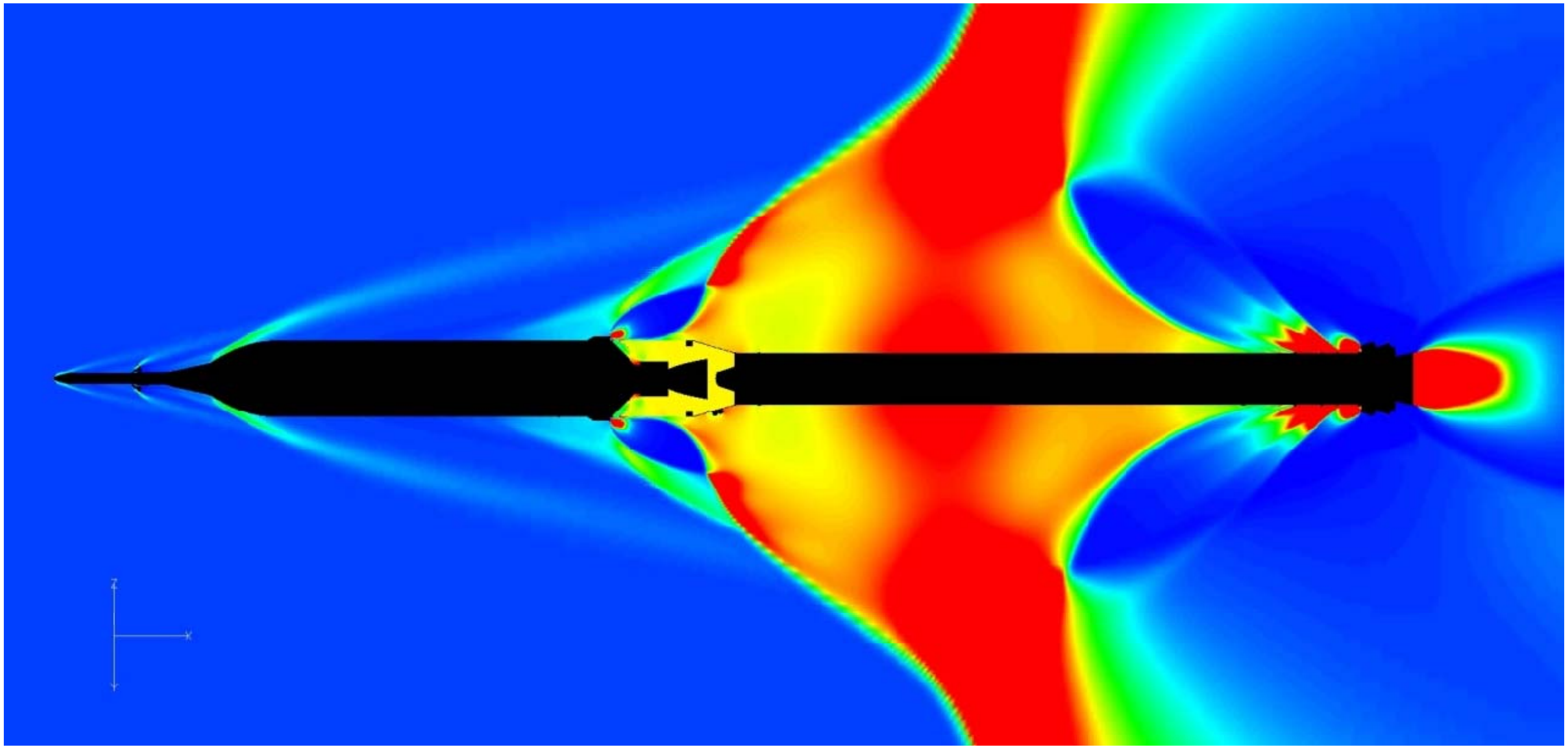


Ares I Agreement Between Experiment and CFD
Line Loads



Ares I CFD Stage Separation

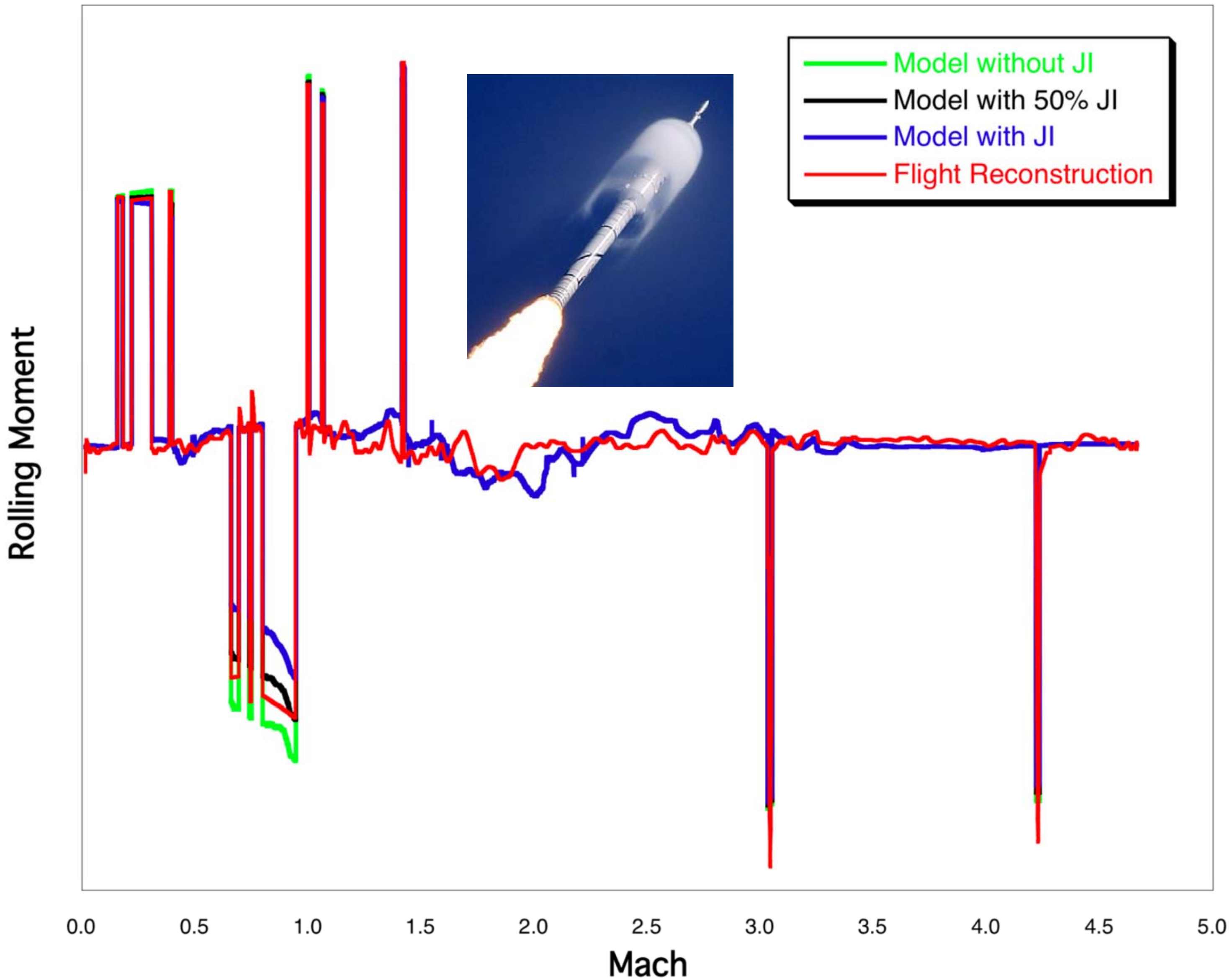
- All USMs & BDMs Firing, try this on a 1-percent model
- CFD validated against unpowered stage separation results from AEDC
- BUT there is no validation of the powered CFD results



Validate Tools

- Must close loop with the DAC process and tools or the first flight does not provide anything
- Post flight Ares I-X made the tools for this class of vehicles look good BUT this is for things that look very much like Ares I and not for everything

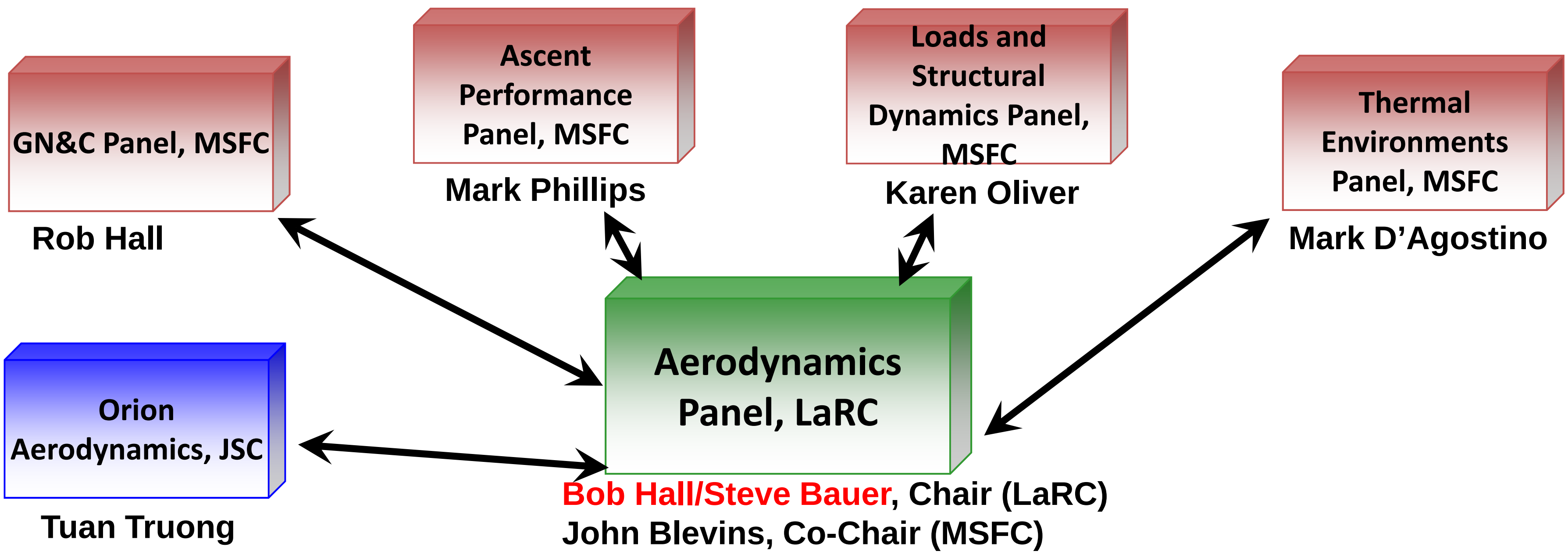
Flight: Example of Ares I-X Flight Test Results and Pre-flight Model Estimates



Understand Fluid Mechanics

- On and off body flow visualization
- Reynolds number effects
- Boundary layer transition and separation
- Shock interactions
- Control effectiveness
- This can take time but it is worth it

Developing a Flight Vehicle Is All About Integration



Other Aero Panel Members

Abdol-Hamid	Ares I CFD
Steve Bauer	Ares I–X Aero Lead
David Bennett	Ares V Database Development
Pete Covell	Engineering Integration
Michael Hemsch	Uncertainty and Quality Assurance
Scott Holland	LaRC Ares I Element Manager
Goetz Klopfer	CFD Stage Separation (Ames)
Cetin Kiris	Ares V CFD
Bandu Pamadi	Database Development
Russ Rausch	Aeroelasticity/Ground Loads
Bill Tomek	Wind Tunnel Testing Lead

Integration of Data Providers and Users

- **Who is using the data and what do they think they need**
  - Database formats
  - GN&C simulations
  - Structural analysis for strength or bending modes
- **It is critical to ensure that Aerodynamics is providing what is needed and that the user actually uses it correctly and clearly understands any limitations**
- **Level of fidelity increases at each step in the design process……or does it?**
  - If a set of data meets the requirements with proper margin you are done!
    - Do not waste resources on data you do not need
  - If a simulation fails then the user needs to be clear on what is needed so the providers can determine if the Aerodynamic data can be provided
    - Determine cost to program to obtain better data
    - Accept the risk if cost is too great or it just cannot be provided
- **Close the loop between Aerodynamics and Vehicle Systems**
  - Ares I roll control was limited at maximum dynamic pressure and changes to Systems Tunnel and LH2 Line were critical

Summary Examples and Lessons Learned

- **CTV/X-38 was not X-24 in the end and would not have flown**
  - If it is not the same configuration you better start from scratch
- **X-33 could not trim at all Mach numbers**
  - Needed configuration changes identified with combination of experiment and CFD
- **Pegasus without experimental data and not much CFD did not really fly well and the change to XL resulted in failure**
  - Experimental data is critical
  - Look at how something is flying
  - Do not believe more than is real

Summary Examples and Lessons Learned

- **X-43 booster had insufficient/incorrect aerodynamics**
  - **Experimental data is critical**
  - **Fly what you tested**
  - **Need for early panel engagement**
- **Delta II used experimental "best practices" but it was not good enough**
  - **Really examine how a vehicle is flying**
  - **Took a test in NTF to find the unsteady flow**
- **Ares I was showing the benefit of good integration**
  - **Experiment and CFD**
  - **Providers and users of Aerodynamic data**
  - **This took a couple of years of work to make it happen**
  - **Ares I-X took advantage of this, it flew successfully and provide tool validation results**

Final Comments

- **No intent to throw stones here but there are things that can happen if you do not do Aerodynamics right**
- **Aerodynamics must be integrated throughout the Design Cycle**
- **Nothing magic here but it is critical to JUST DO IT**
- **Must have the experienced staff who understand what is needed, when it is needed and where it is needed in the Design Cycle**
- **Do not think that Aerodynamics is unimportant and/or too costly to obtain. It may seem expensive but it is dirt cheap when compared to an accident.**