A Perspective on Computational Aerothermodynamics at NASA

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Objective

Provide an historical perspective on the growing role that Computational Aerothermodynamics (CA) has played in hypersonic vehicle design and analysis in NASA.

CELEBRATING 100 YEARS

NASA Langley Research Center 1917-2017

Introduction

- Computational aerothermodynamics (CA) is CFD with the added emphasis that high temperature gas effects on pressure, skin friction, and heat transfer are included in the numerical simulation.
- The fundamental role of computational aerothermodynamics is the simulation of aerodynamic forces and heating for external and internal high speed flows.
- Emphasis on planetary entry - issues similar for sustained hypersonic flight.

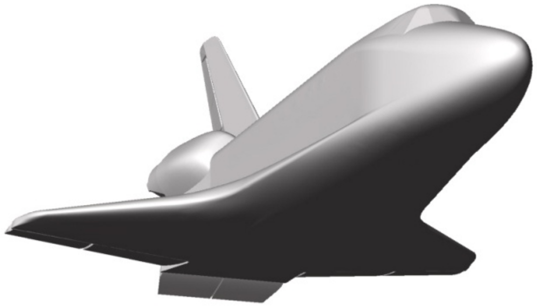
Case Studies

1. Pitching moment anomaly in STS-1
2. Static Instability in Mars Pathfinder
3. Columbia accident investigation
4. Boron Nitride Nanotube Production Rig

Code verification and validation are required for acceptance of any CFD simulation tool. The ability to resolve highly visible problems in flight data analyses have helped to advance the credibility of CA .

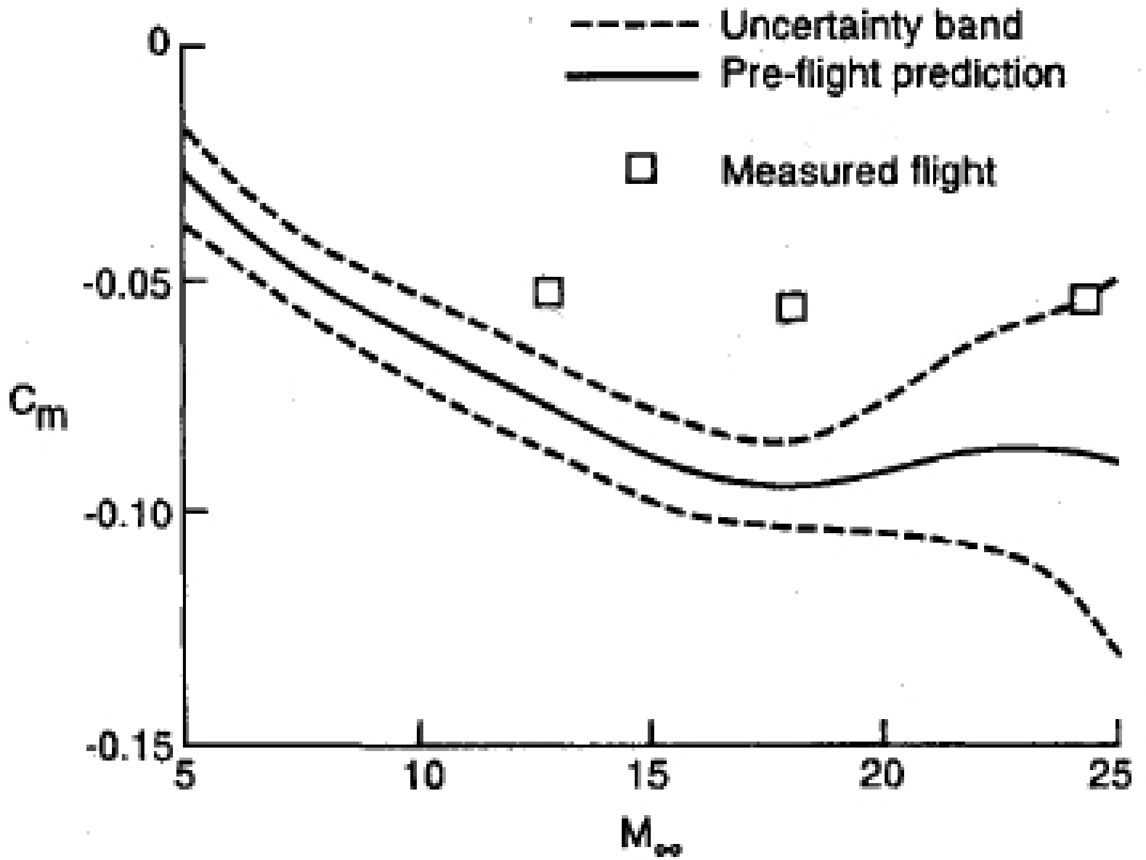
Pitching Moment Anomaly in STS-1, April 1981

• The vehicle's bodyflap had to be deflected to an angle over twice that predicted prior to the flight.



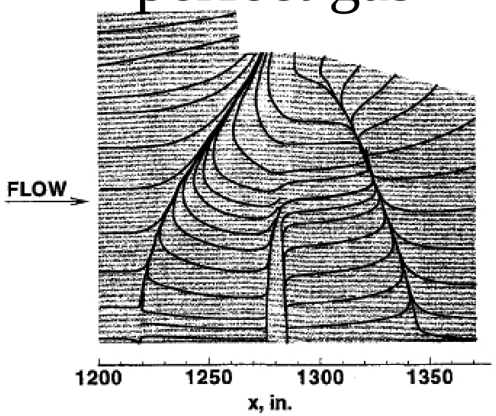
• The aerodynamic performance characteristics had been determined by extensive testing in ground-based facilities.
• The anomaly had been attributed to a number of phenomena including viscous effects, diminished bodyflap effectiveness, Mach number effects, and high-temperature-gas effects.
• Mid 80's analyses could not capture all flow physics or geometric complexity.
• Weilmuenster et. al., "Navier-Stokes Simulations of Orbiter Aerodynamic Characteristics including Pitch Trim and Bodyflap", JSR, Vol 31, No. 3, 1994.

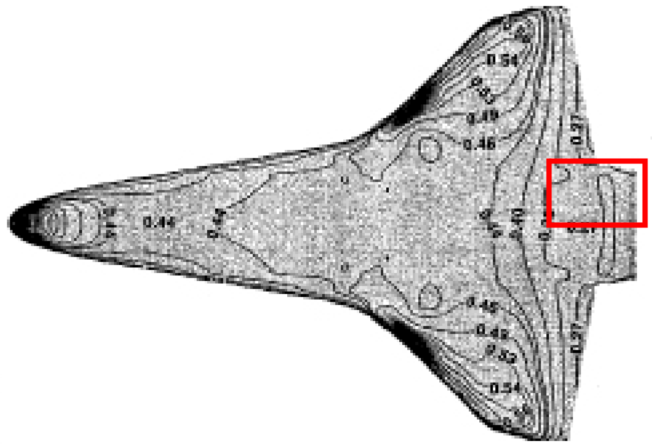
C_m: Flight Data



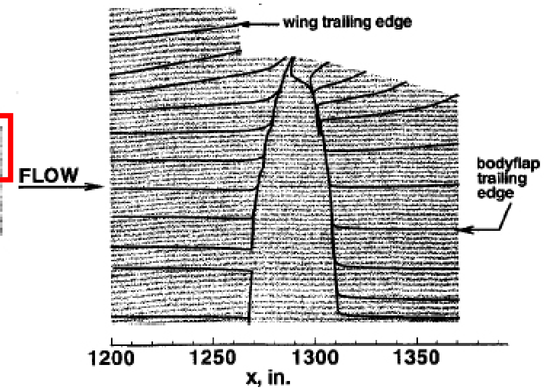
Bodyflap Pressures: $\alpha = 40°$ $\delta_{bf} = 20°$

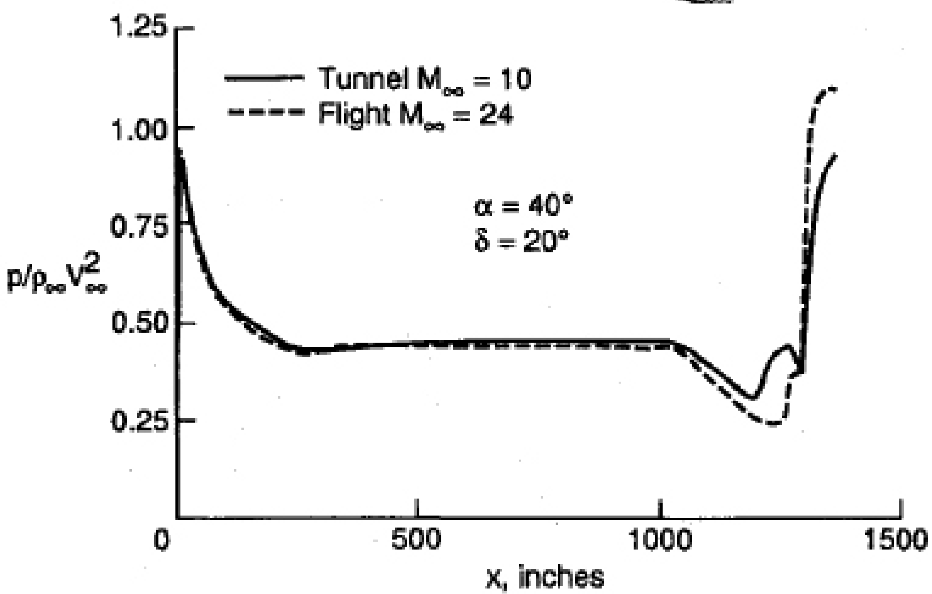
CA at Mach 10 perfect gas





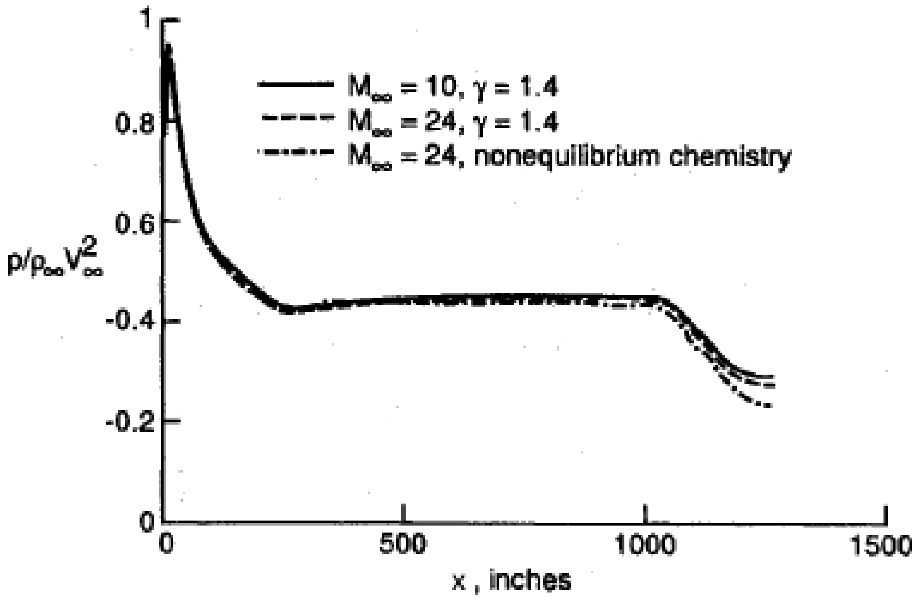
CA at Mach 24 reacting gas



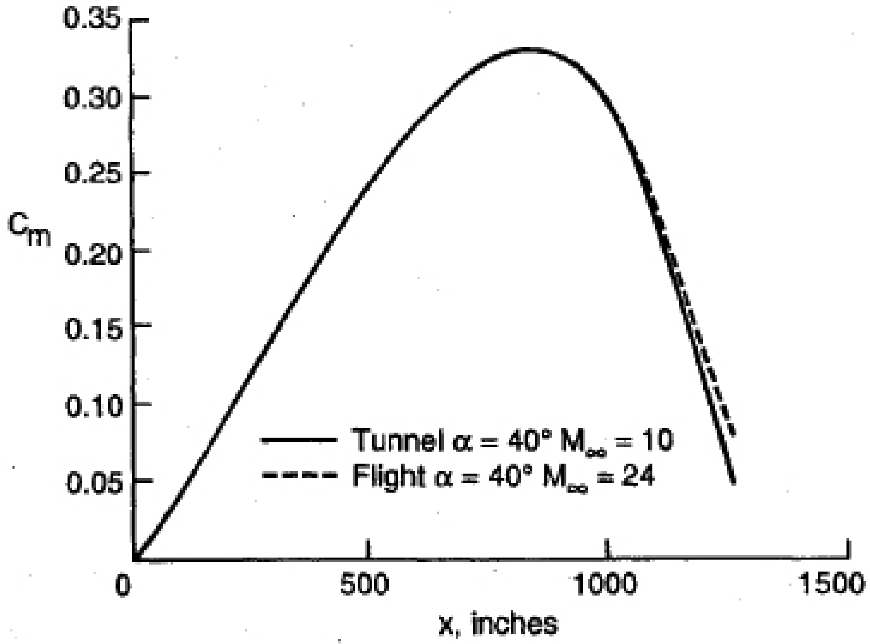


Integrated Moment Coefficient

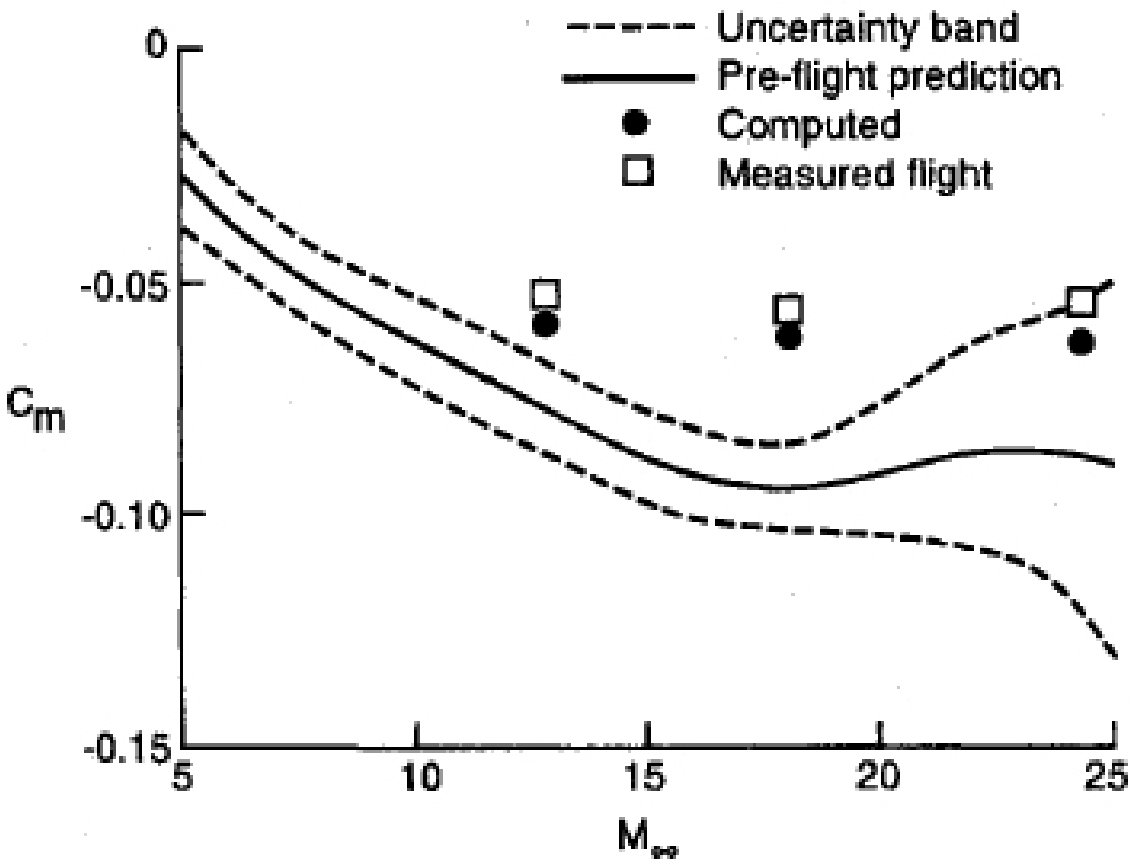
Centerline Pressures



Integrated C_m

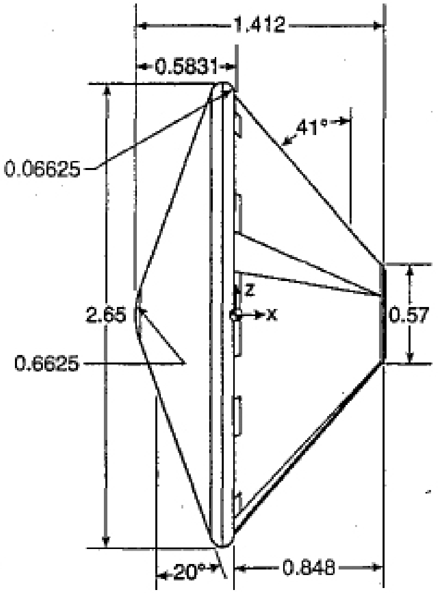


C_m: Flight Data and CA Simulation (1993)



Static Instability in Mars Pathfinder, July 1997

• Mars Pathfinder had same shape as Viking Lander but flew a different angle of attack and entry velocity - very limited ballistic range ground-based data existed to create aerodynamic data book.



• Hypersonic aerodynamic database was built from matrix of CA simulations including thermochemical nonequilibrium models for Martian atmosphere: (CO_2, CO, C, O, O_2, N_2, N, NO) and (T, T_V).

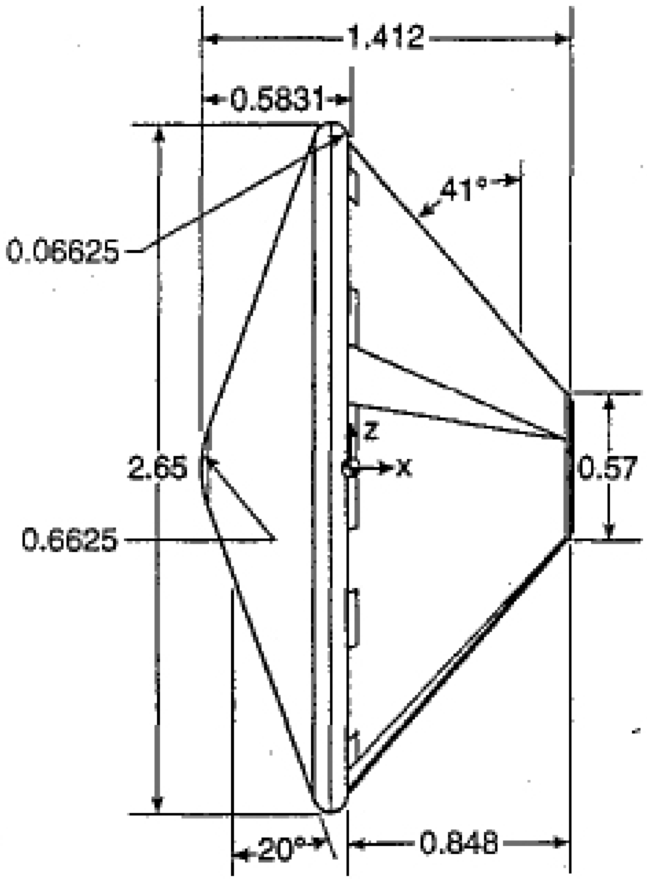
• At small angles of attack C_m was positive (and consequently $C_{m,\alpha}$ was positive and destabilizing) at two regions in velocity space (~7.0 km/s and ~3.5 km/s).

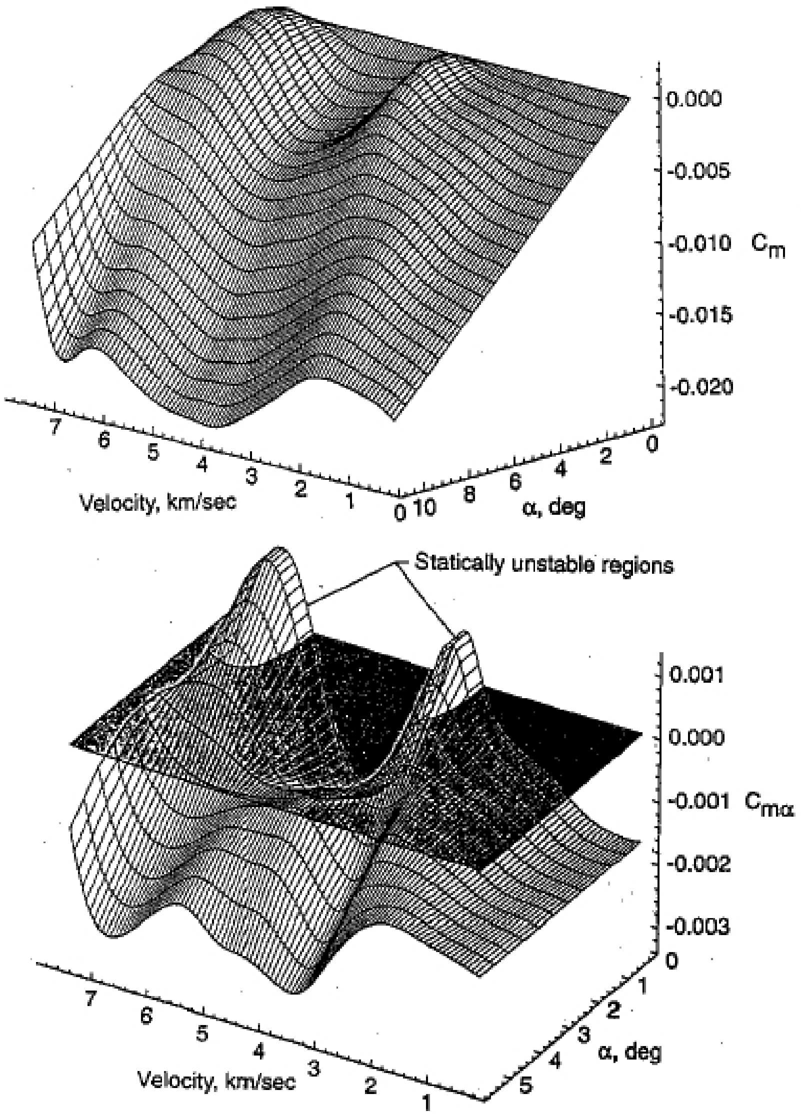
• Braun et. al., "Mars Pathfinder Six-Degree-of-Freedom Entry Analysis", JSR, Vol 32, No. 6, 1995.

• Gnoffo et. al., "Influence of Sonic-Line Location on Mars Pathfinder Aerothermodynamics", JSR, Vol. 33, No. 2, 1996.

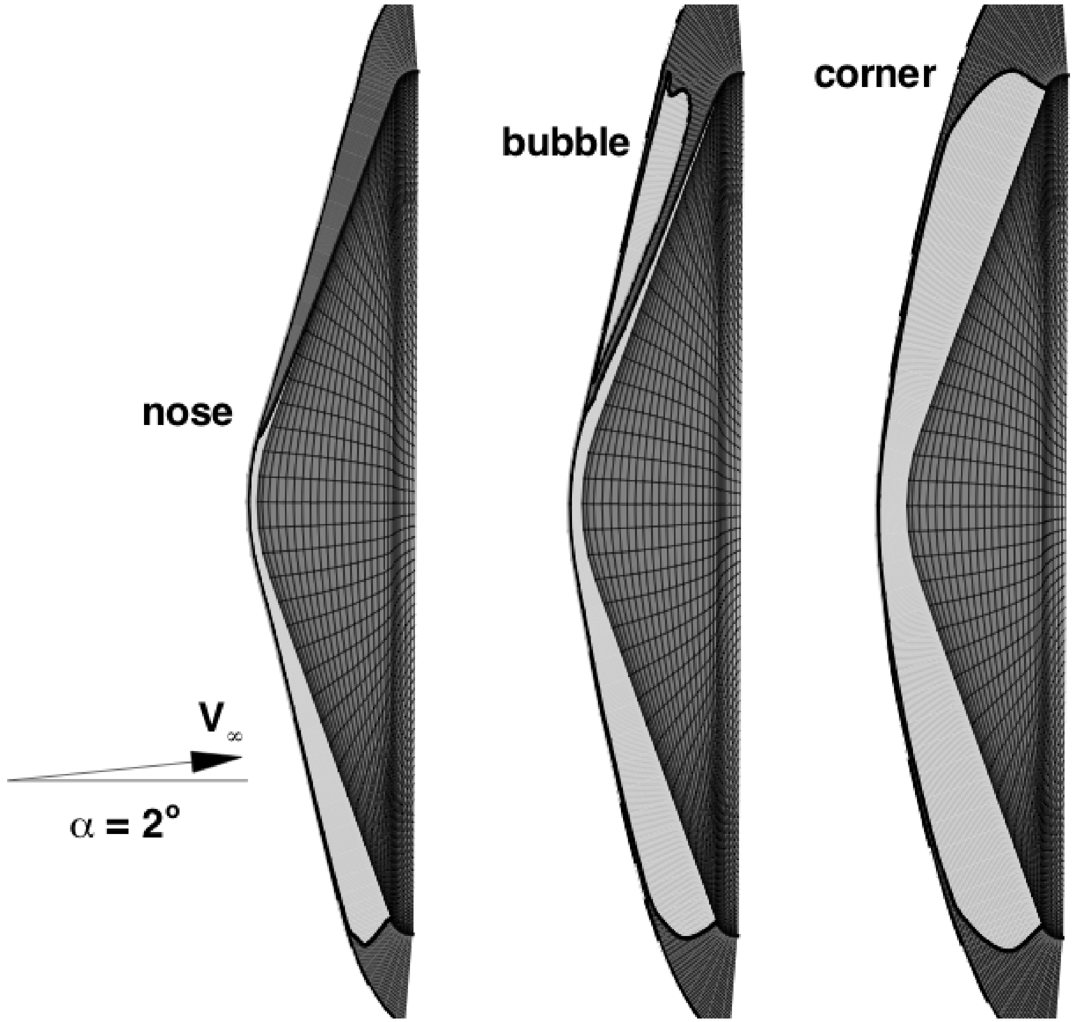
• A true prediction (as opposed to postdiction!) using LAURA, HALIS, and POST.

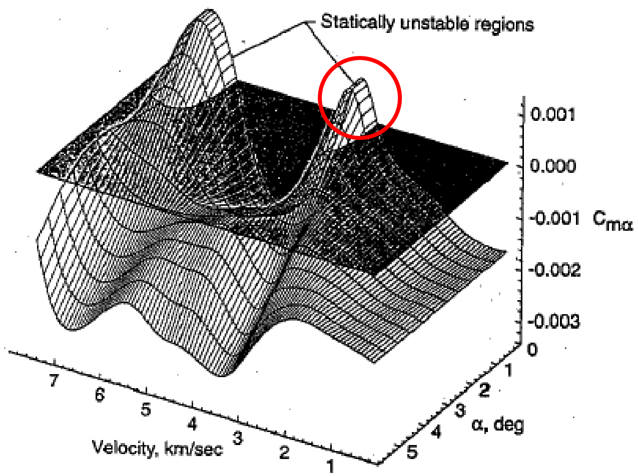
Mars Pathfinder Pitching Moment





Sonic Line Movement

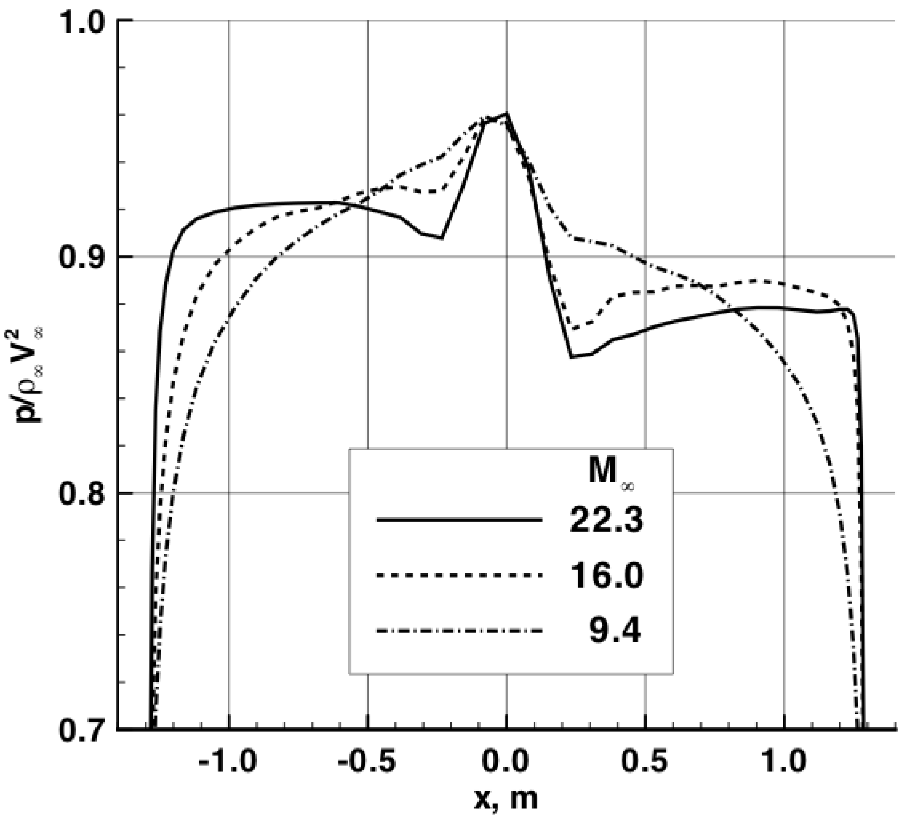




$M_\infty = 22.3$ $M_\infty = 16.0$ $M_\infty = 9.4$

Centerline Pressure Distributions

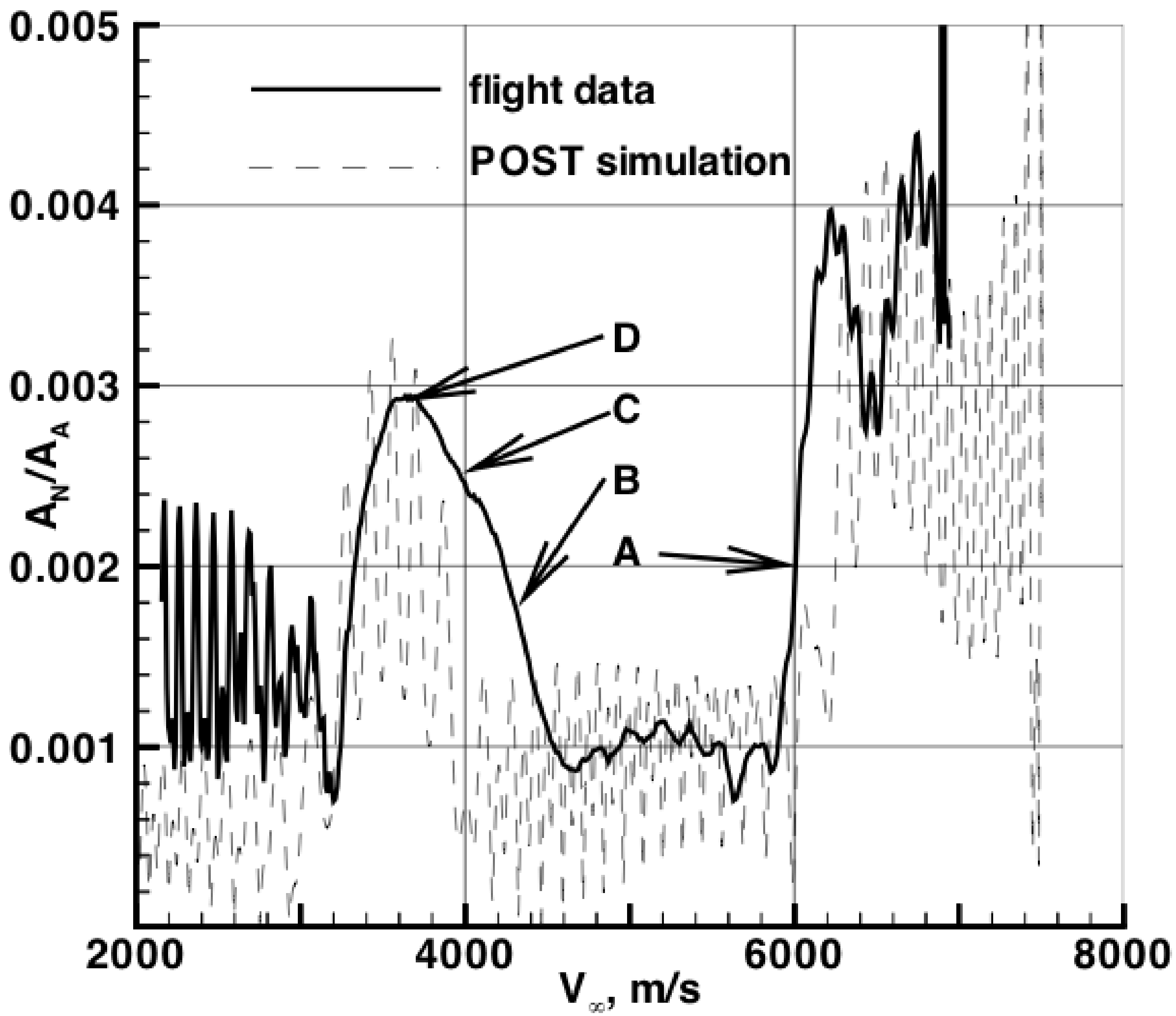
Sonic line on nose => Pressures flat on cone
Sonic line on shoulder => Pressures rounded on cone
Increasing degrees of freedom in gas (heat capacity) => Shock sits closer to body and sonic line moves toward nose



Analysis Highlights

- Conditions for a positive, destabilizing moment coefficient derivative occur twice in the Mars Pathfinder mission.
  - ($7.5 > V_\infty > 6.5$ km/s) translation in the sonic-line location as a function of gas chemistry changing from nonequilibrium to equilibrium.
  - ($4.0 > V_\infty > 3.1$ km/s) translation in the sonic-line location as a function of decreasing flow enthalpy in an equilibrium gas chemistry regime.
- The static instability provides a clearly defined signal on the accelerometers to validate the simulation.
  - The effect is a sensitive function of the computed pressure distributions as a function of gas chemistry.
  - A prediction of the event presents an important accomplishment in the validation of CA.

Comparison to Flight Data (1997)



Columbia Accident Investigation, Feb -July 2003

STS-107, Columbia, and its crew of seven astronauts were lost on entry on February 1, 2003. According to the Columbia Accident Investigation Board (CAIB) it "re-entered Earth's atmosphere with a pre-existing breach in the leading edge of its left wing in the vicinity of Reinforced Carbon-Carbon (RCC) panel 8. This breach, caused by the foam strike on ascent, was of sufficient size to allow superheated air (probably exceeding 5,000 degrees Fahrenheit) to penetrate the cavity behind the RCC panel."

Role of CA in Columbia Accident Investigation

• CA was used for first time as a forensic tool in an investigation that needed answers quickly with as much fidelity to the geometry and aerothermodynamic environment as possible.

• Evidence:

- Video of foam impact on ascent.
- Timeline of sensor losses.
- Timeline of off-nominal readings of temperatures on fuselage.
- Timeline of control surface response to progressing damage.

• Team effort involving experiment and numerical simulation including all NASA centers and Boeing.

• Focus here is on mass and energy influx as function of breach size.

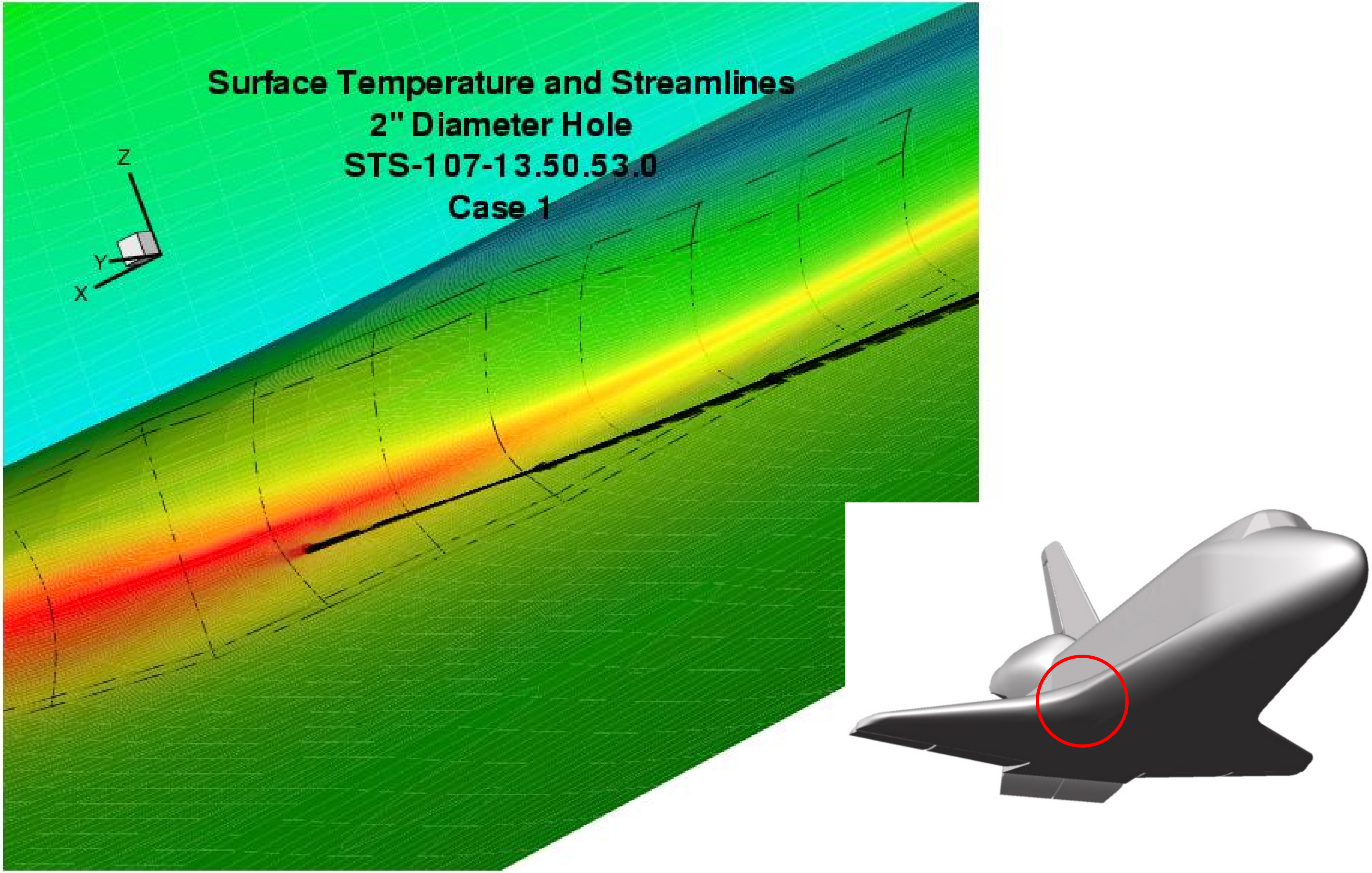
• Gnoffo and Alter, “Simulation of Flow Through A Breach in Leading Edge at Mach 24”, AIAA Paper 2004-2283.

• Campbell et. al, “Orbiter Return to Flight Entry Aeroheating”, AIAA-2006-2917

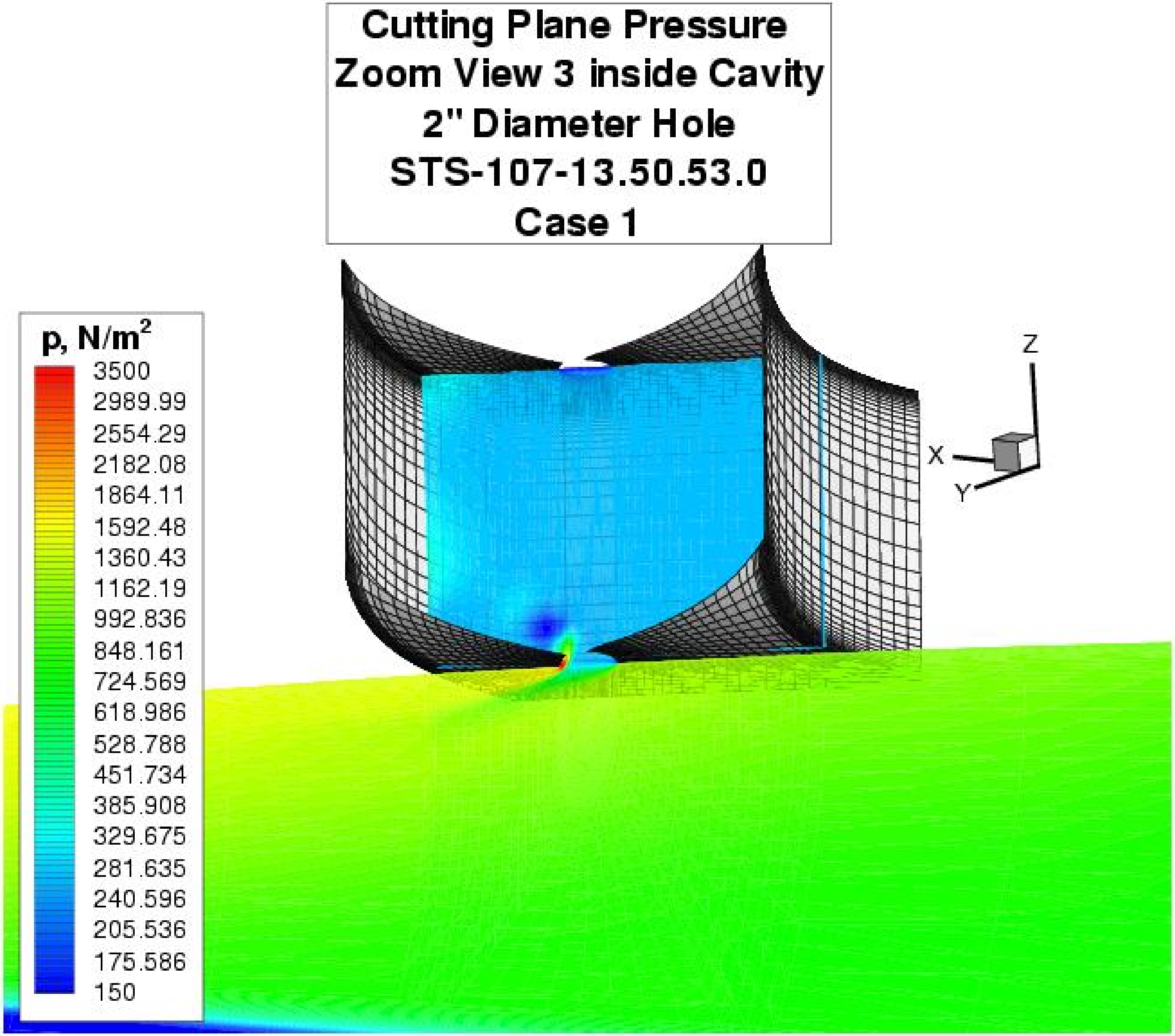
Procedure –Vented Hole and Vented Cavity

- Recover archived solutions and generate new solutions over undamaged vehicle. (5-species air, thermal equilibrium)
- Modify existing utility to embed hole with ¼ inch depth and diameters of 2, 4, and 6 inches in leading edge of panel 6 and merge with existing baseline solution of external flow for case 1 (Mach 24, 7350.6 m/s).
- Modify boundary condition on back side of hole to accommodate constant back pressure reservoir equal to 2 p_∞.
- Run simulations for 3 hole sizes - completed April 1, 2003.
- Extrude approximate cavity domain from surface grid surrounding hole and apply vent boundary condition.
- Completed 2 inch diameter hole, vented cavity April 10, 2003.
- Completed 1/4 inch diameter hole, vented cavity April 28, 2003.

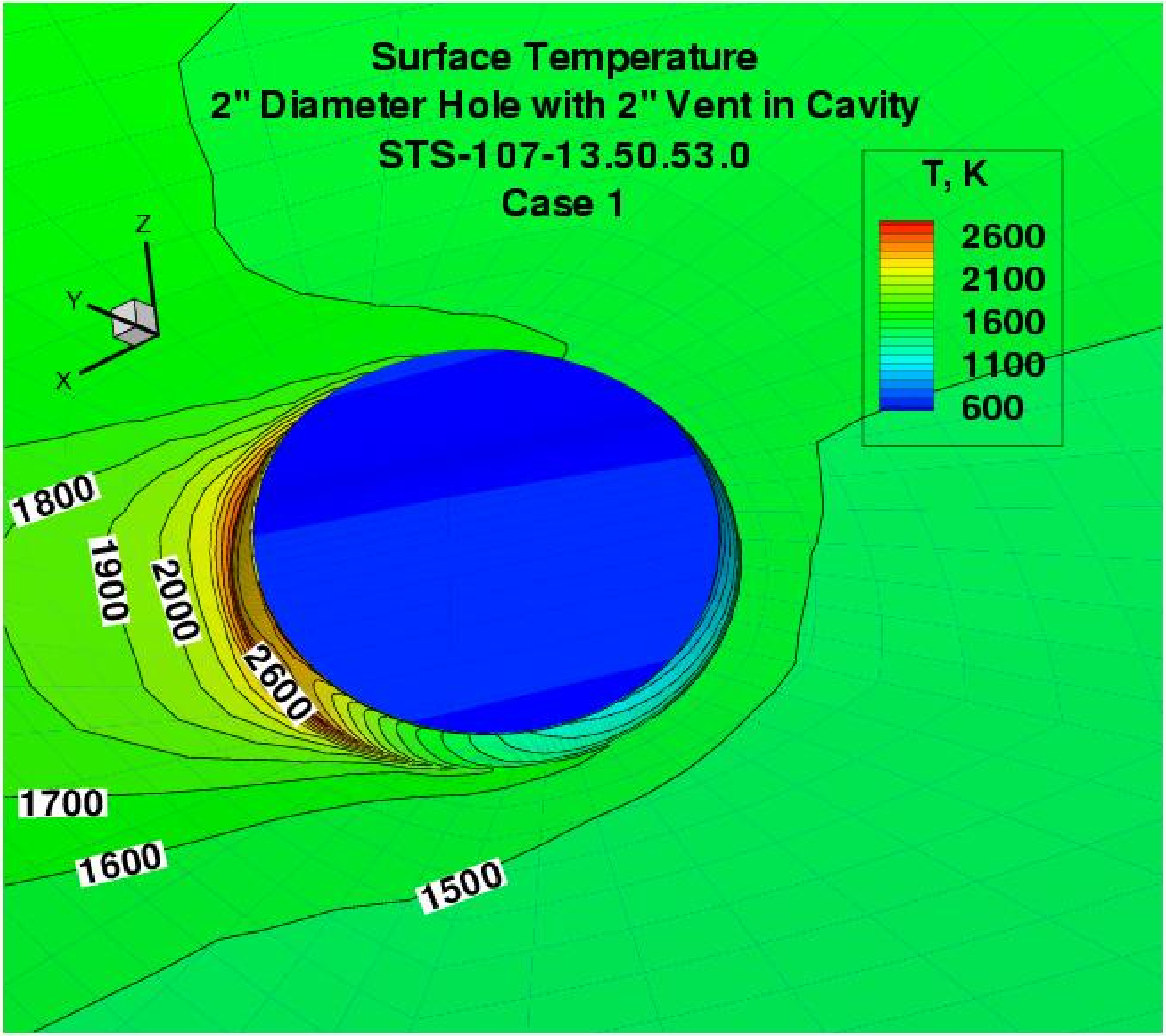
Streamline Path -Temperature



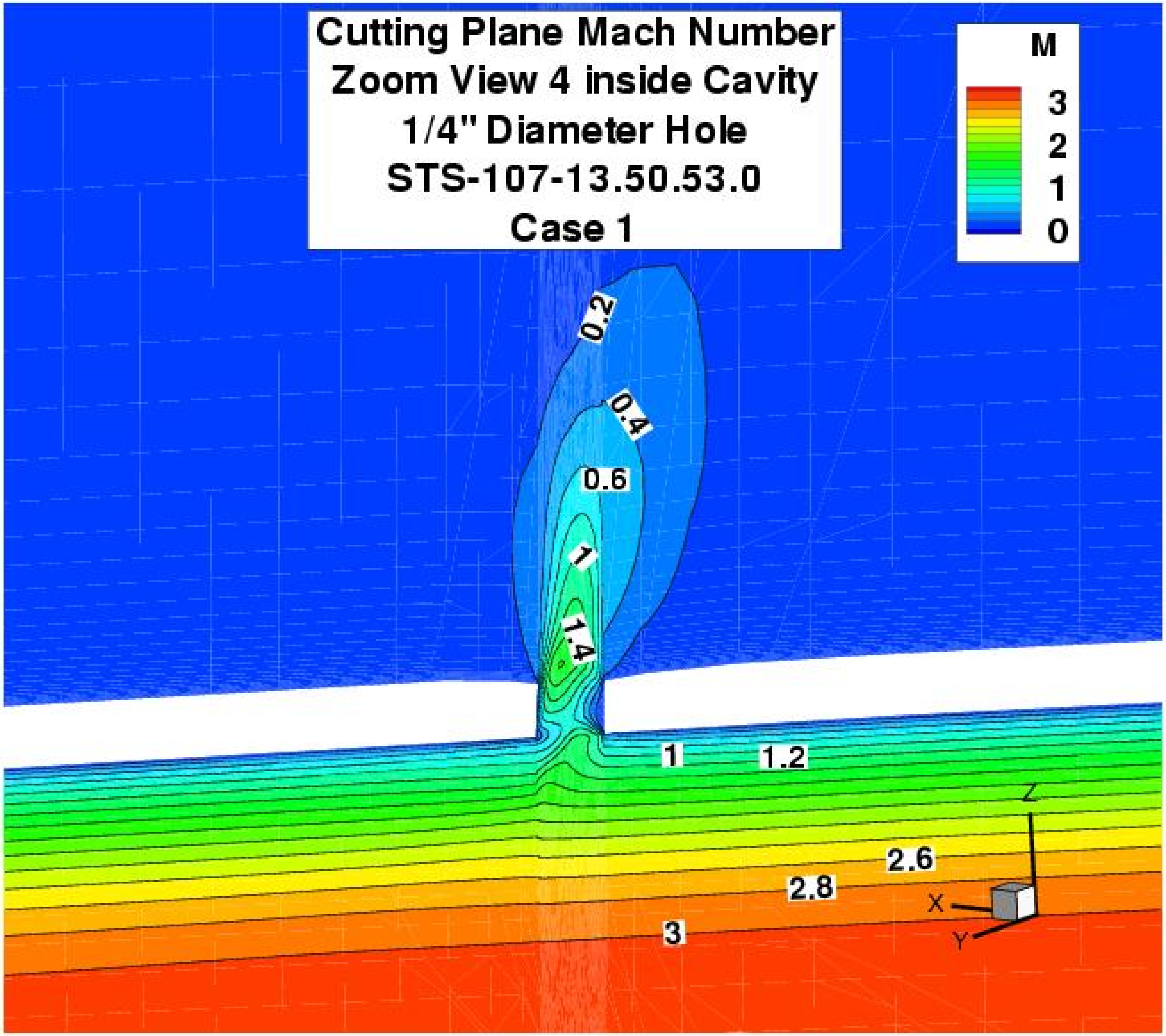
Cavity Mesh with View of 2 Inch Vent at Top



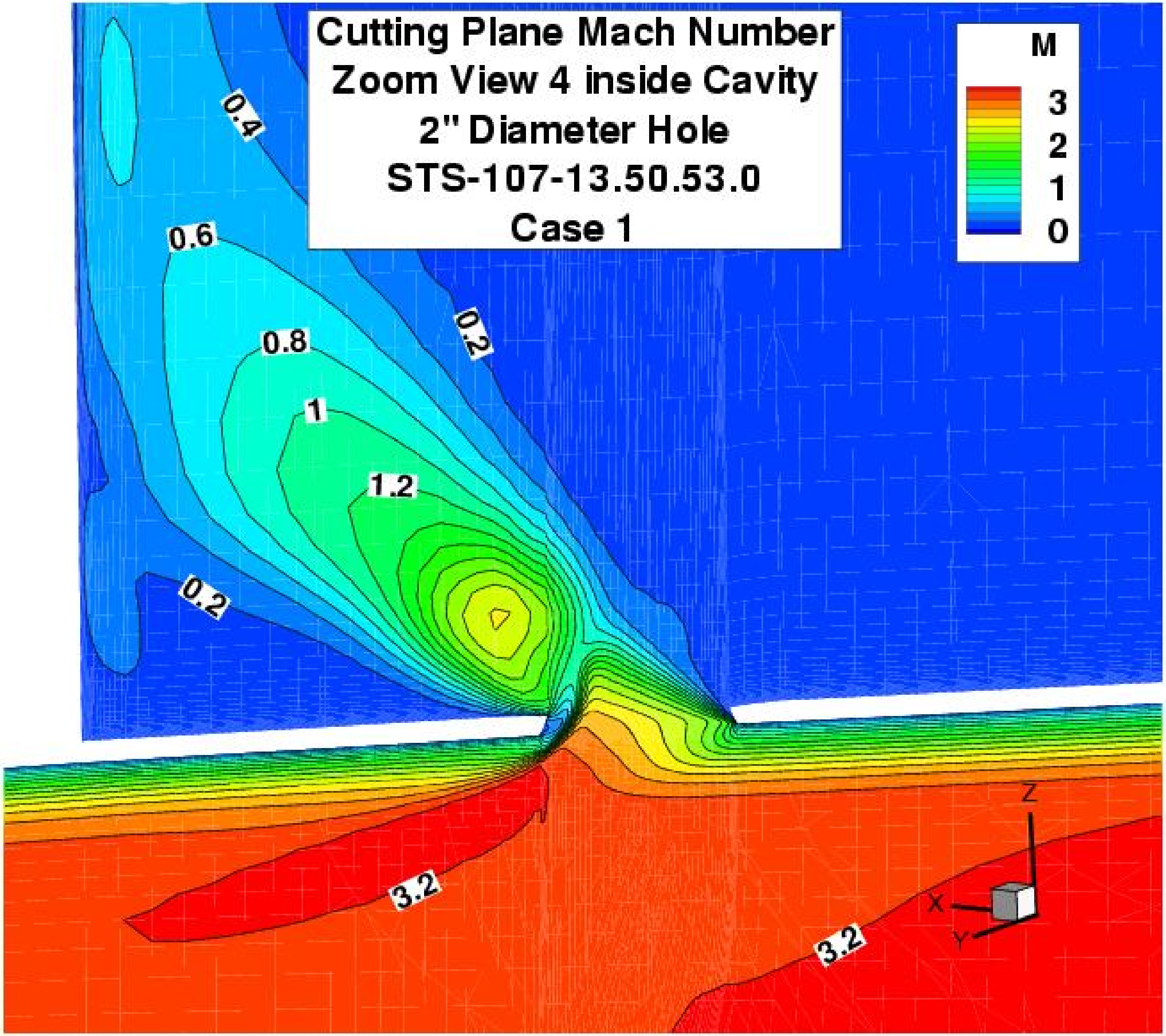
External Surface Temperatures



Mach Number through 1/4 Inch Hole

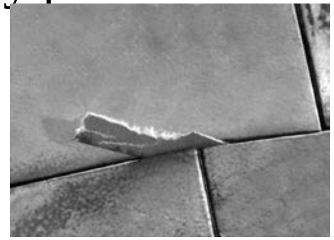


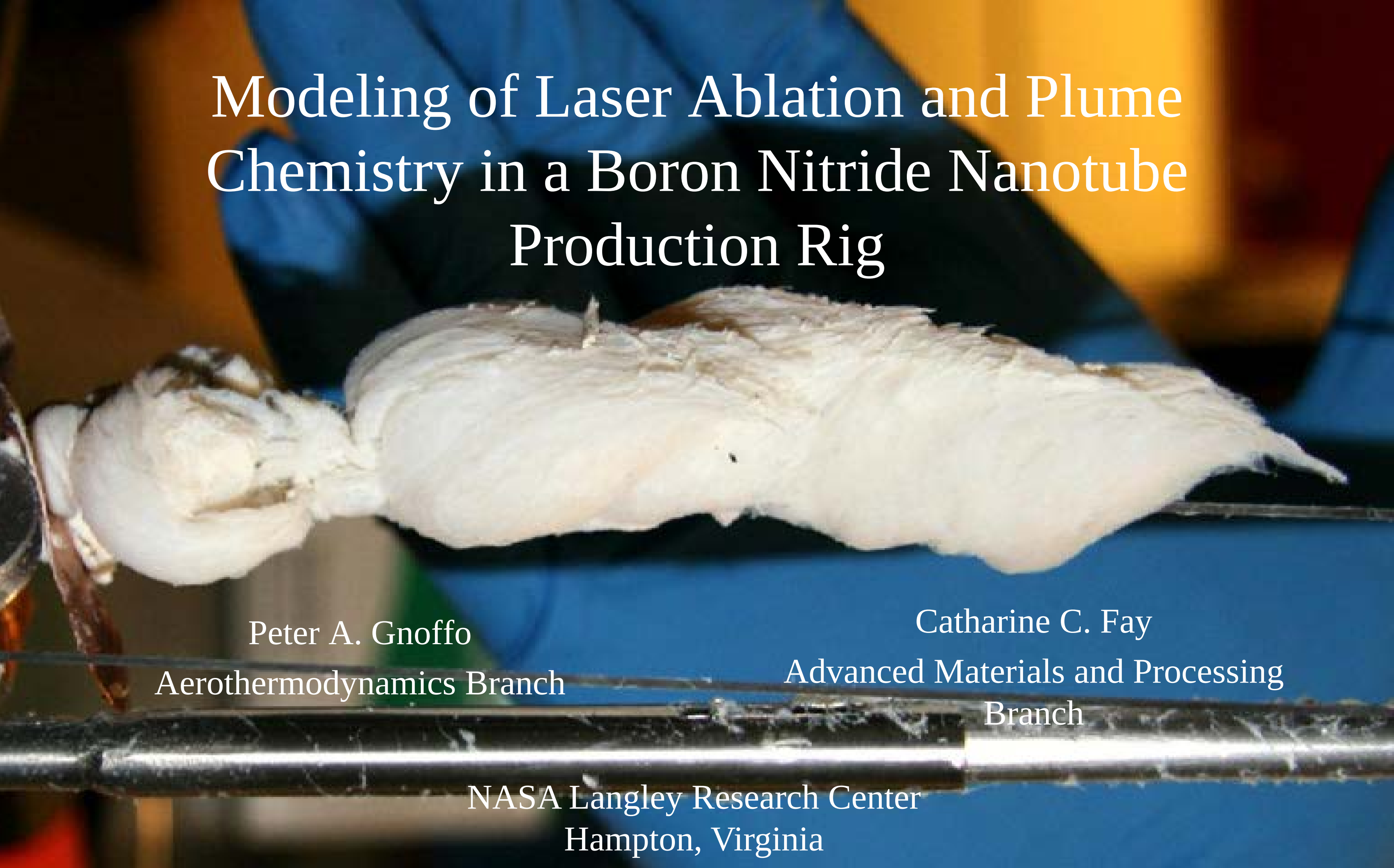
Mach Number through 2 Inch Hole



Impact of Investigation

- Delivered mass and energy influx rates as function of hole size at discrete locations - used to calibrate engineering models to define boundary conditions for internal flow models.
- Demonstrated potential to execute CA simulations quickly and the need for archived simulations of environment across a matrix of trajectory points.
- Impact on Return to Flight (RTF)
  - –Expand damage assessment processes to include cavities and protuberances
  - –CA with morphing tools deliver heating bump factors for “challenging” damage sites set into baseline simulations within 18 hours.
  - –Engineering tools are primary sources for repair decisions.
  - –Archived solutions are available for probing local conditions with Boundary Layer Transition Tool and Gap Filler Bending Tool



Modeling of Laser Ablation and Plume Chemistry in a Boron Nitride Nanotube Production Rig

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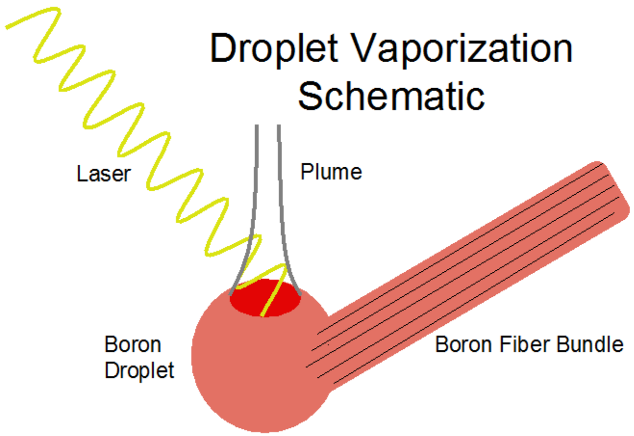
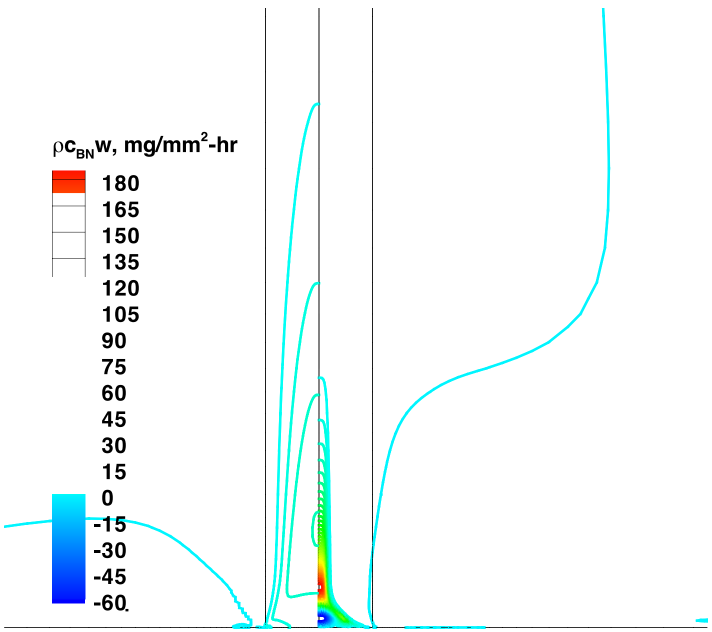
43rd AIAA Thermophysics Conference
June 25 - 28, 2012
New Orleans, Louisiana

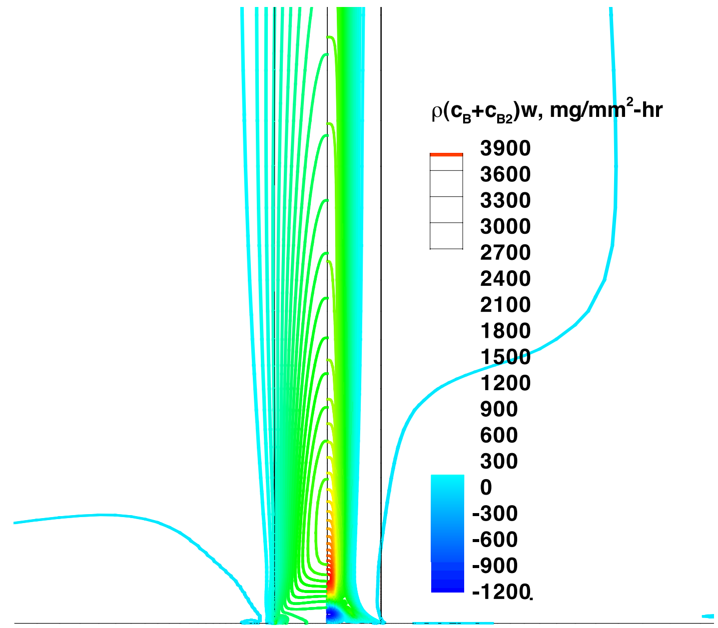
Boron flow rates at 0.1 kW



BN



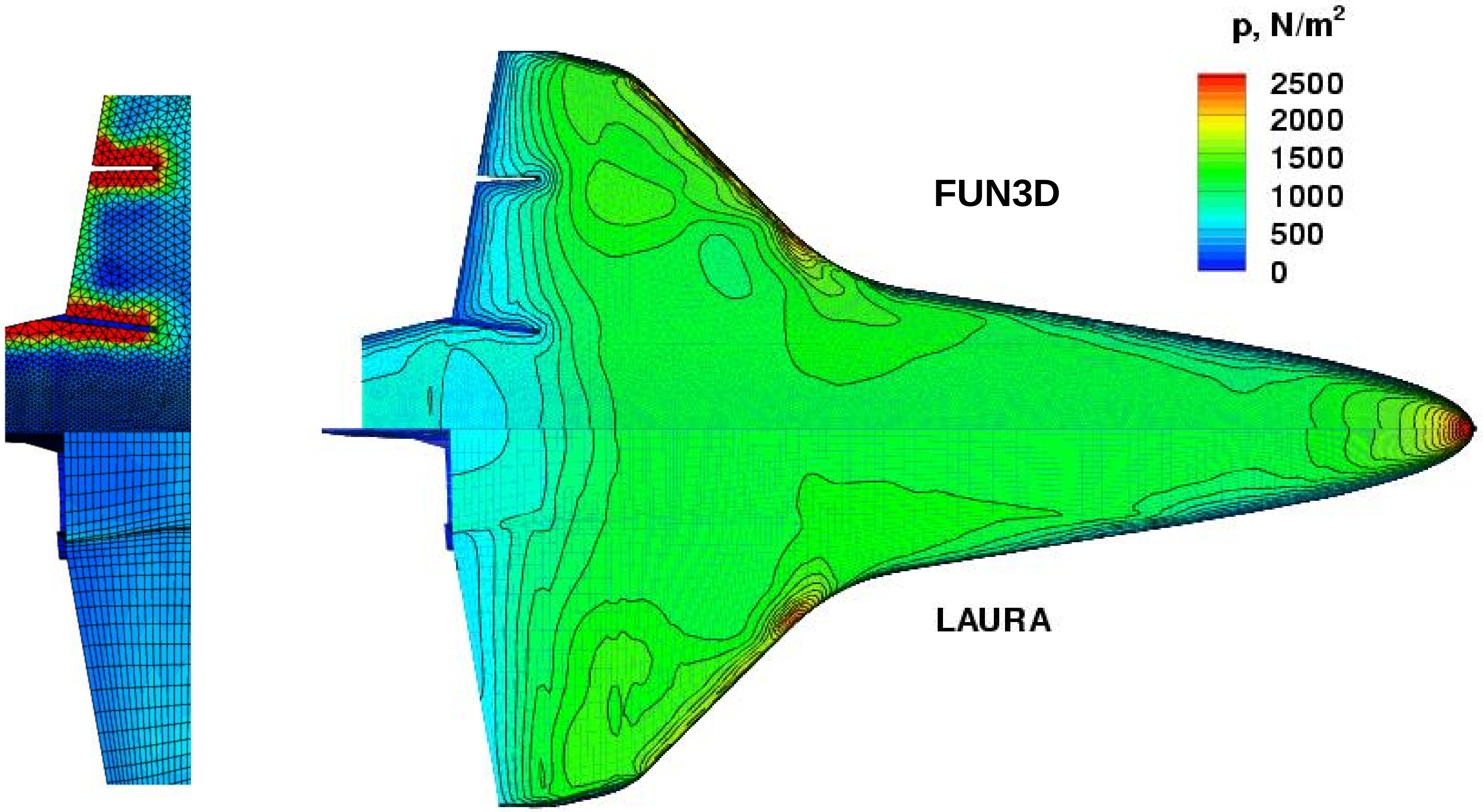
B, B2



Concluding Remarks

- First two examples involved using the code “as written”.
- Second two examples required significant modification to the baseline code.
  - Geometry interface
  - Boundary conditions
  - Source terms
- The codes of that era did not use object oriented design – but each had essentially one cook!
- Modern software design must accommodate multi-physics simulation and systems engineering optimization involving large, diverse teams.
- Strive to make future invention / ideation / 911 emergency response easier using the tools you are developing now by a multi-disciplinary user community.

Contemporary Unstructured Grid Simulation



Mars Pathfinder Predicted Attitude