



LAURA 5 -- Part I: Computational Hypersonic Reacting Flow Analysis for Entry Vehicles

Aerothermodynamics Branch



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TFAWS-2010

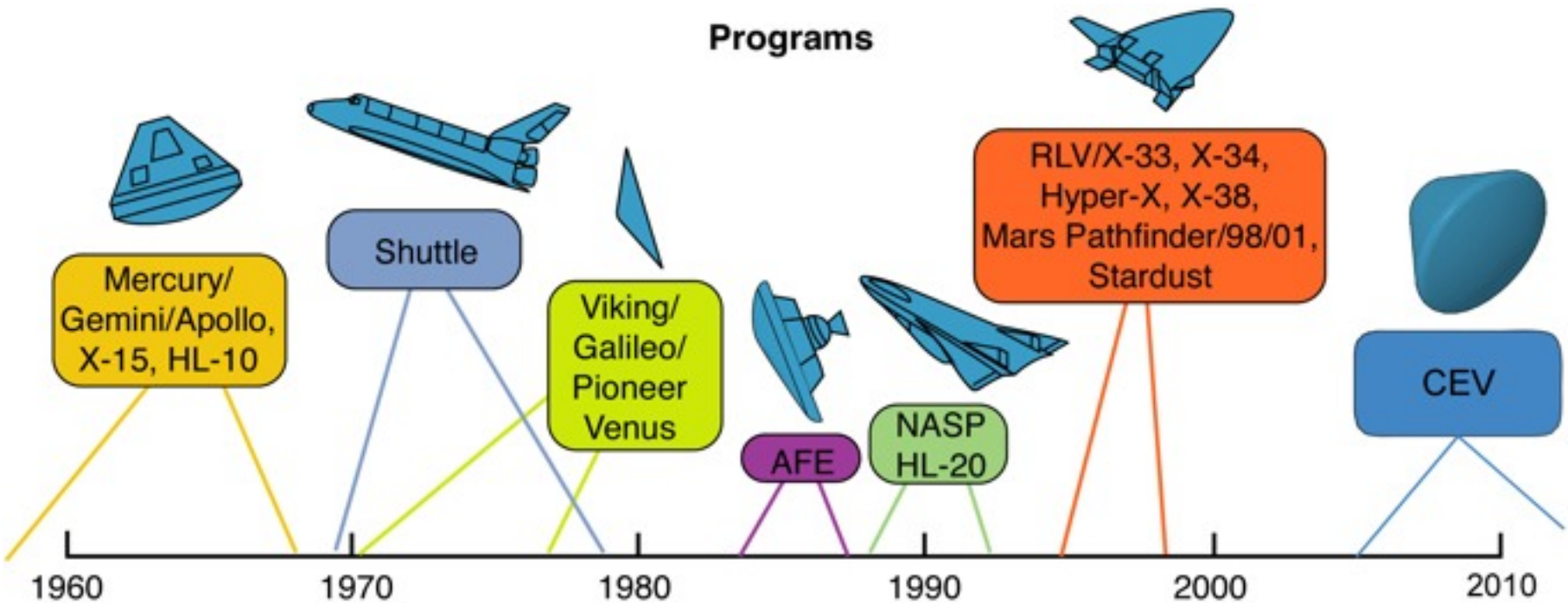
August 18, 2010



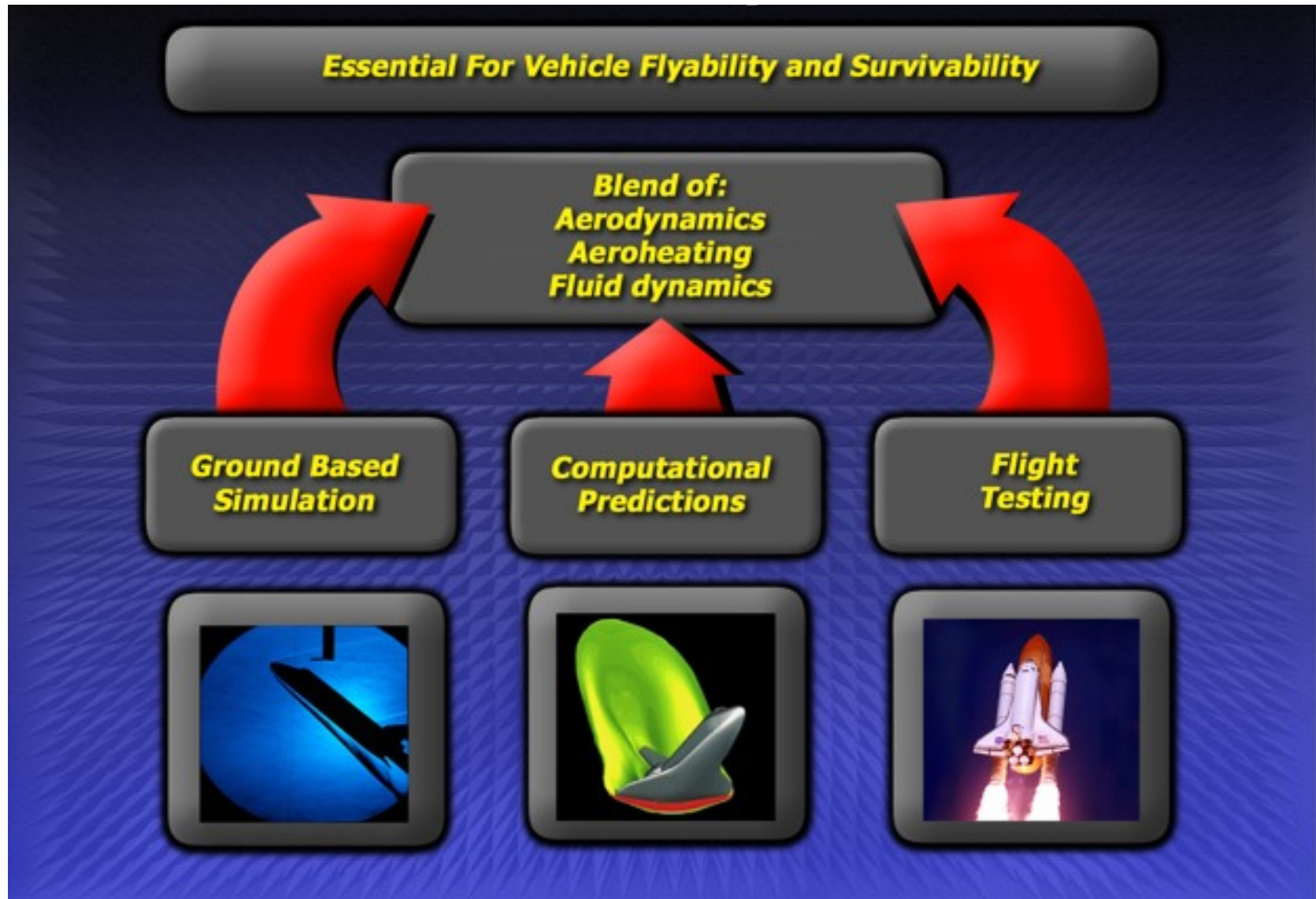
Topics

- Introduction
- Aerothermodynamics
 - Definition and challenges
 - Tools (wind tunnel, engineering, CFD)
 - Process
- LAURA CFD and examples
 - Vehicle assessment
 - Optimization
 - Benchmarking
- The next step – LAURA v5
 - Code overview
 - Enhancements

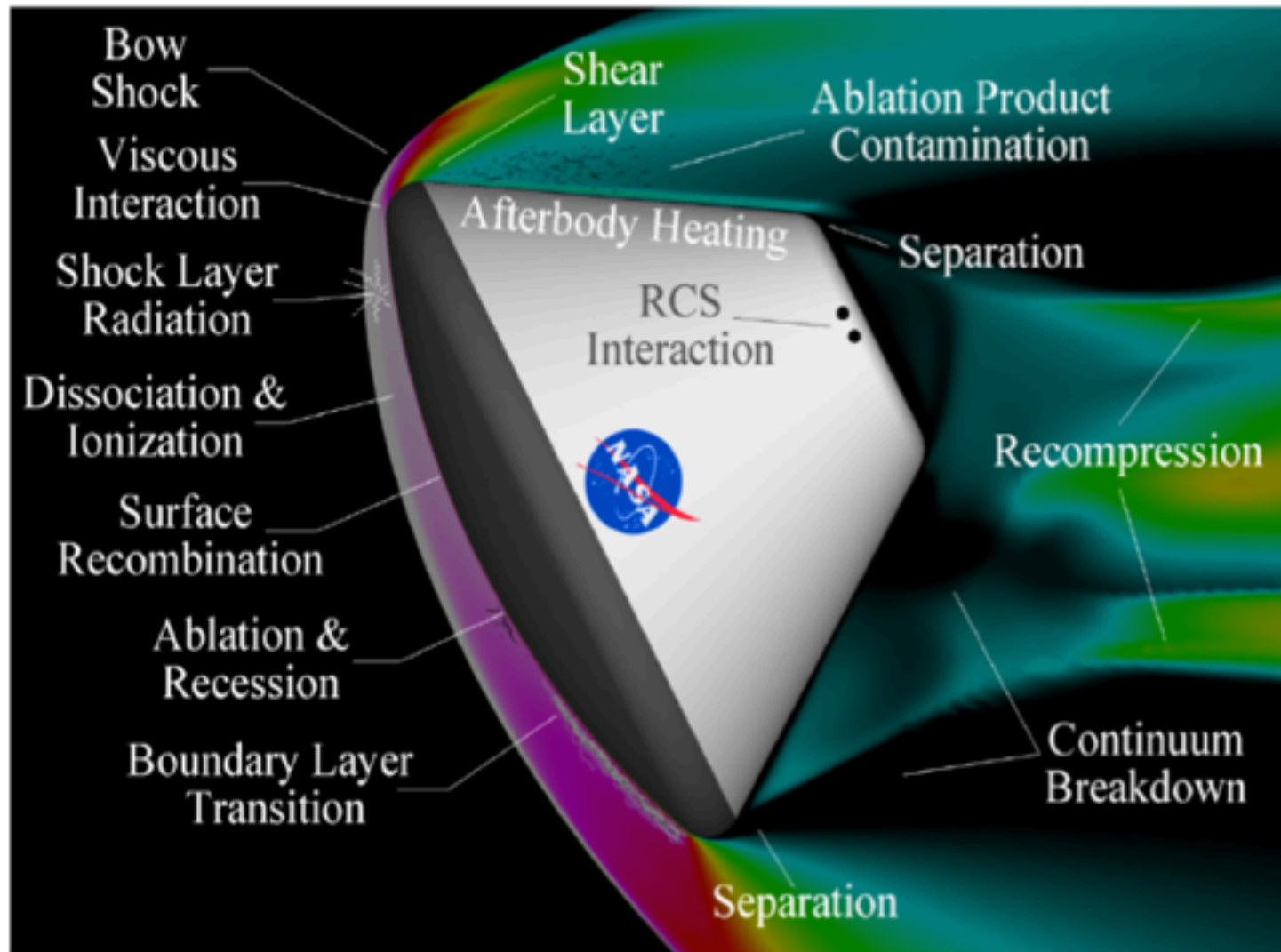
Aerothermodynamic Heritage



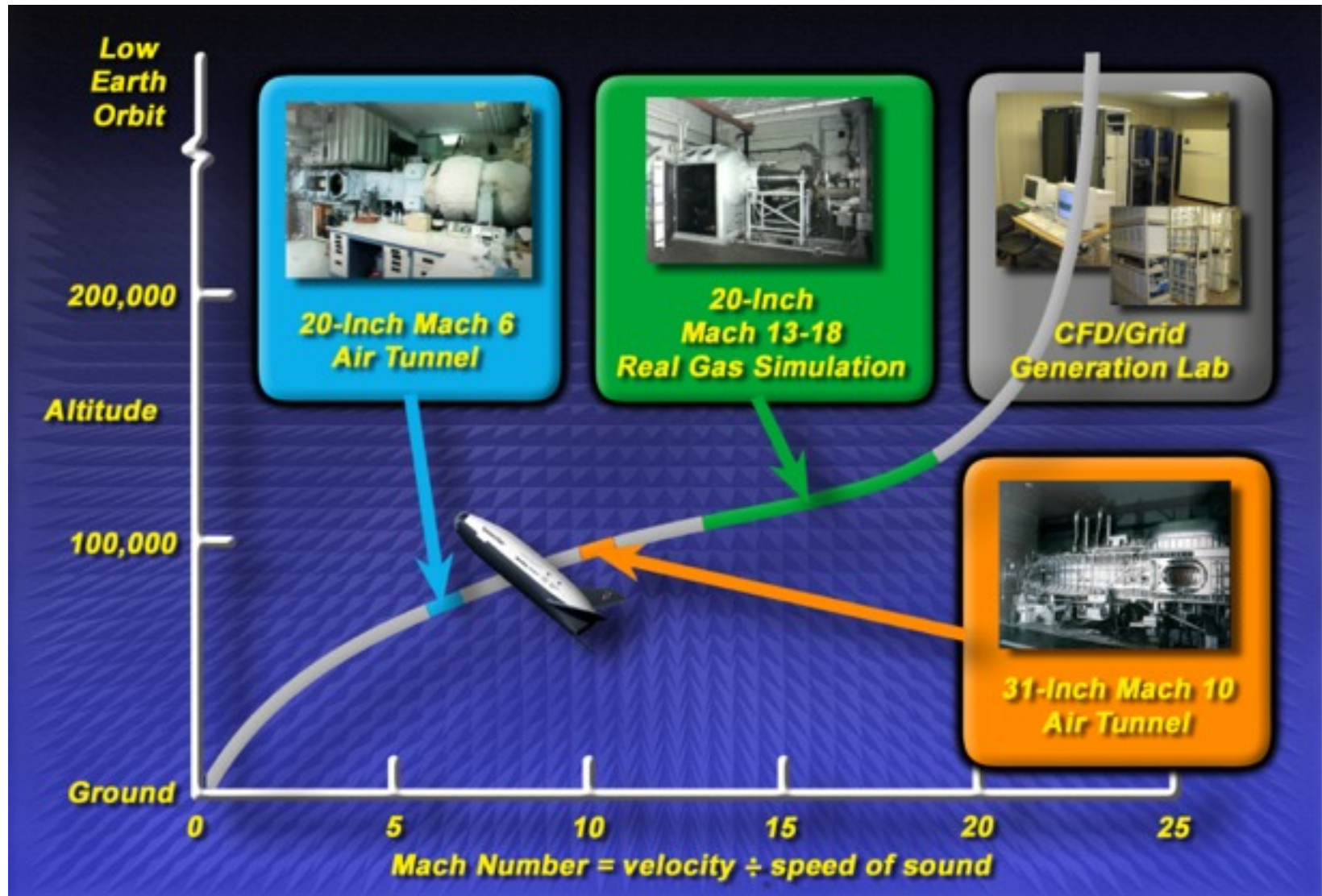
Aerothermodynamics



Aerothermodynamic Environment

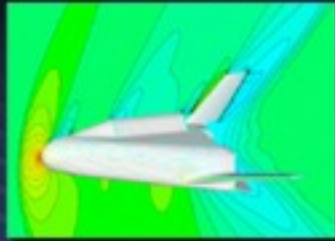


Part 1: Computational Hypersonic Reacting Flow Analysis for Entry Vehicles Aerothermodynamic Flight Simulation



Computational Predictions

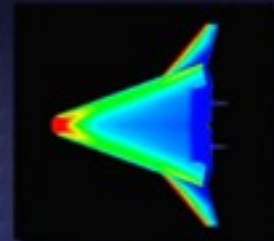
Software



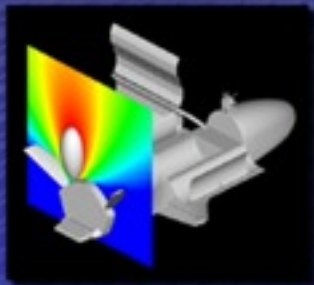
Inviscid Solvers



**Viscous Solvers
(Home of LAURA*)**



**Boundary
Layer Codes**



**Direct Simulation
Monte Carlo**



**Surface/Volume
Grid Generation**

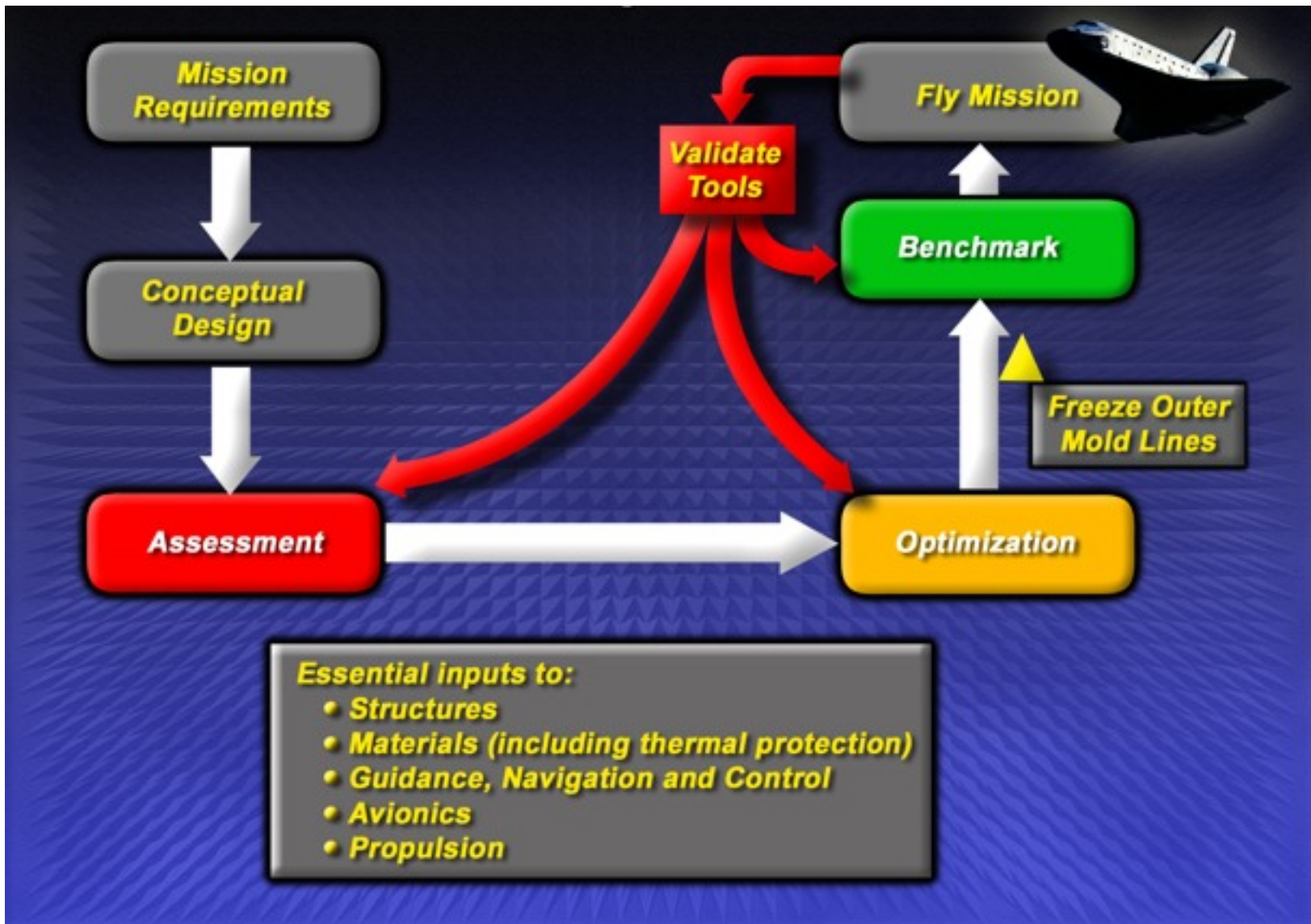
Hardware



**Aerothermodynamics
CFD/Grid Generation
Laboratory**

** Langley Aerothermodynamic Upwind Relaxation Algorithm - Developed by Dr. Peter A. Gnoffo*

Part 1: Computational Hypersonic Reacting Flow Analysis for Entry Vehicles Aerothermodynamic Process



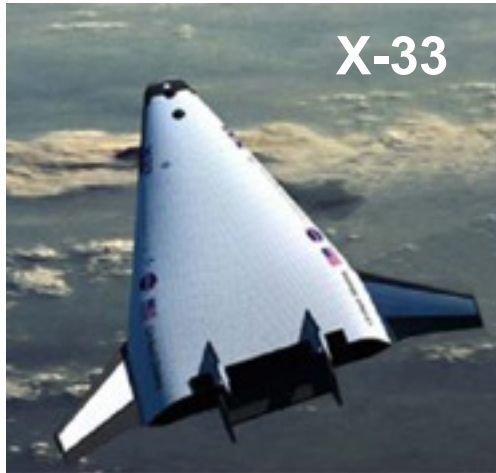


LAURA CFD

- **L**angley **A**erothermodynamic **U**pwind **R**elaxation **A**lgorithm
 - Finite-volume Navier-Stokes (viscous) and Euler (inviscid) flow solver
 - Point implicit and/or line implicit relaxation
 - Linearly scalable on large parallel systems
 - Kinetic, thermodynamic and transport models for air, CF_4 and major planets
 - Thermal and chemical nonequilibrium
 - Algebraic and two equation turbulence models
 - Grid adaptation procedure
- First release in 1992
- Extensive application and validation with broad spectrum of hypersonic vehicles

X-33 Body-Flap Impingement

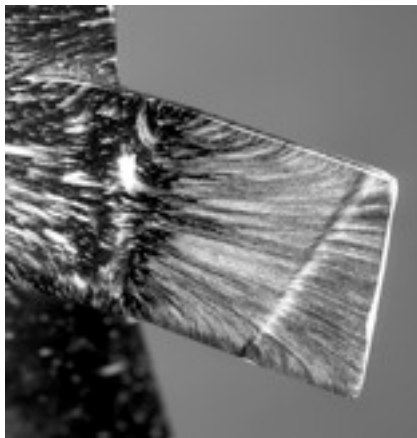
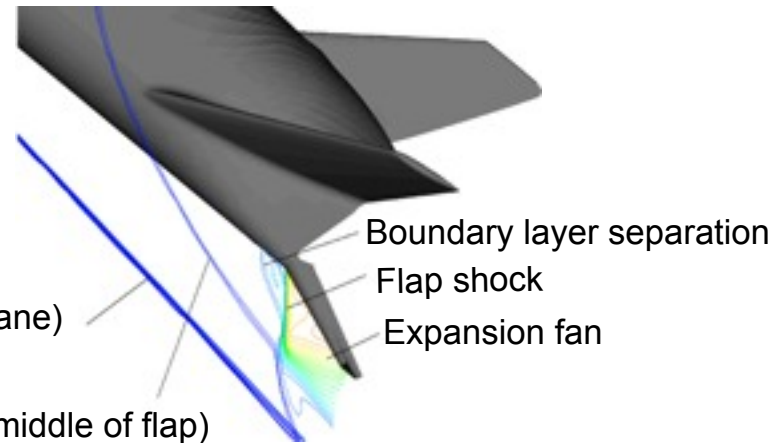
$$M_{\infty} = 6 \quad \alpha = 40^{\circ} \quad \delta_{BF} = 20^{\circ} \quad Re_{\infty} / ft = 4 \times 10^6$$



Predicted
density contours

Bow shock
(in symmetry plane)

Bow shock
(plane through middle of flap)



Body flap

Experimental streamlines

(Courtesy of Tom Horvath and Scott Berry)

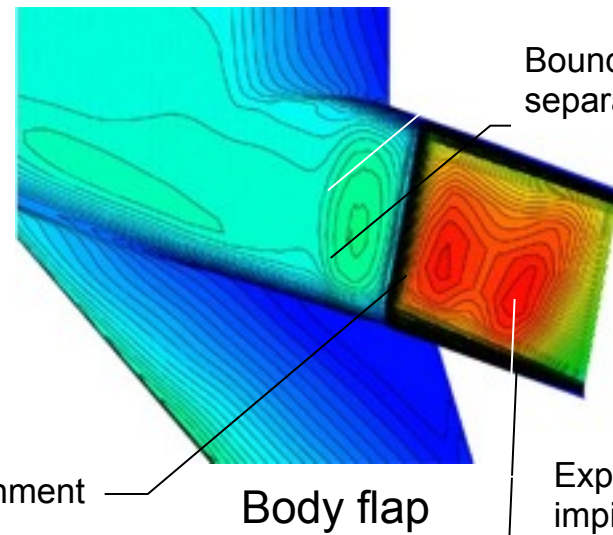
Predicted
surface pressure

Flow
reattachment

Body flap

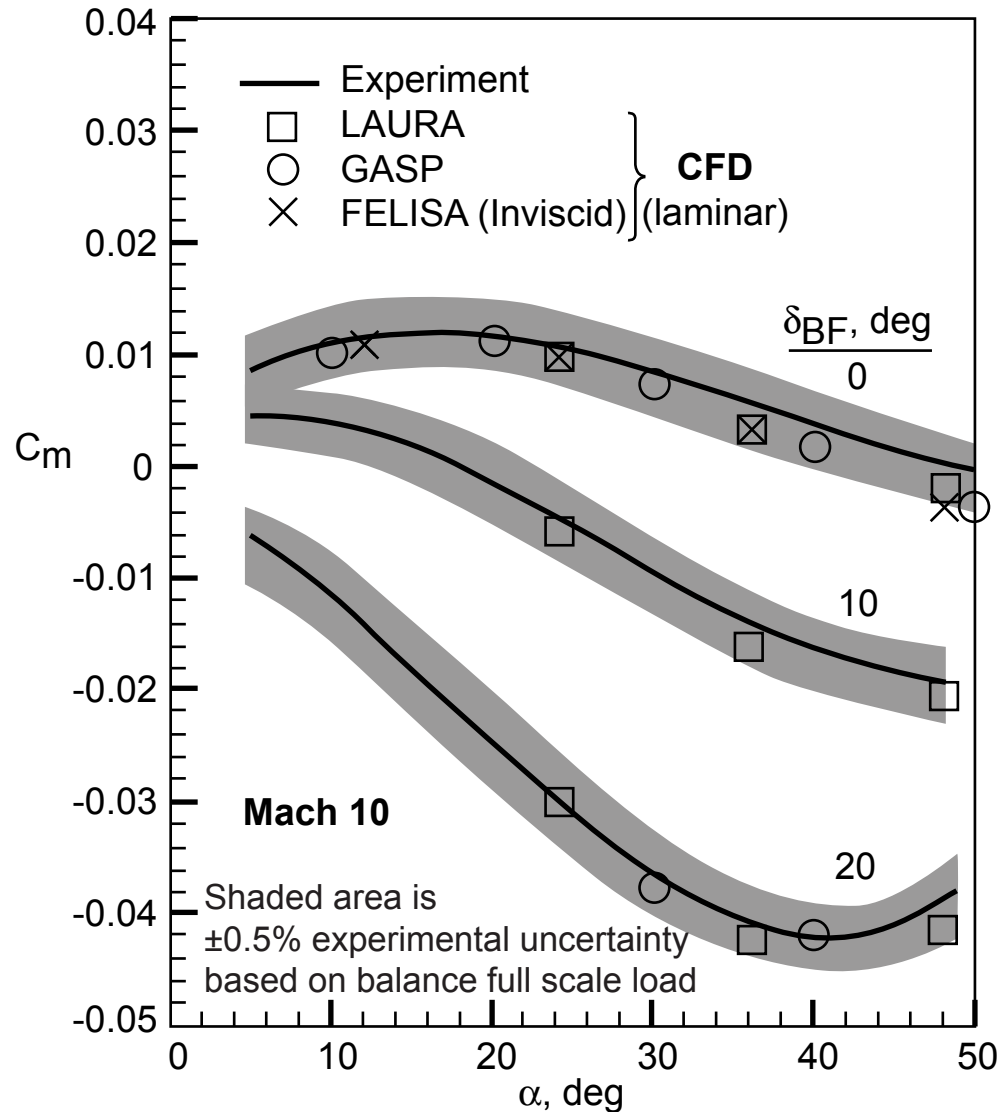
Boundary layer
separation

Expansion fan
impingement



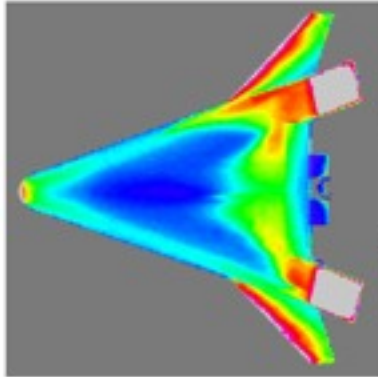
(Courtesy of Brian Hollis)

X-33 Pitching Moment



X-33 Boundary Layer Transition Methodology

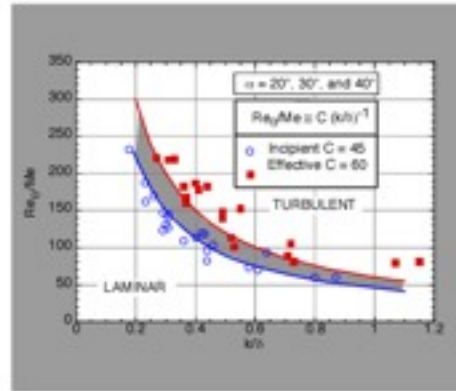
**Wind tunnel
measurements**



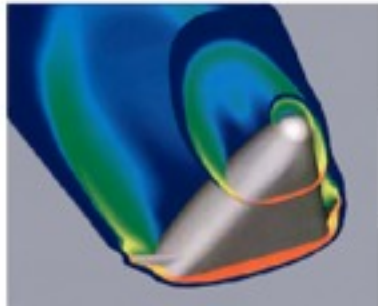
(Courtesy of Tom Horvath and Scott Berry)

Computational – Experimental Synergism

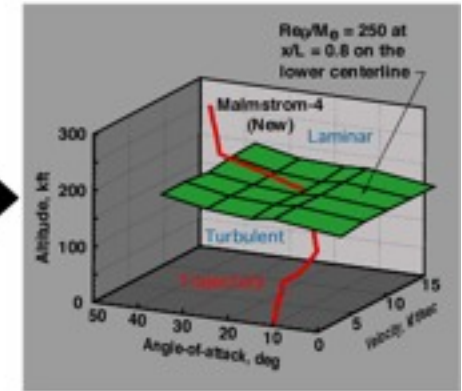
**Roughness
transition
correlation**



**Prediction of
boundary layer
edge properties**

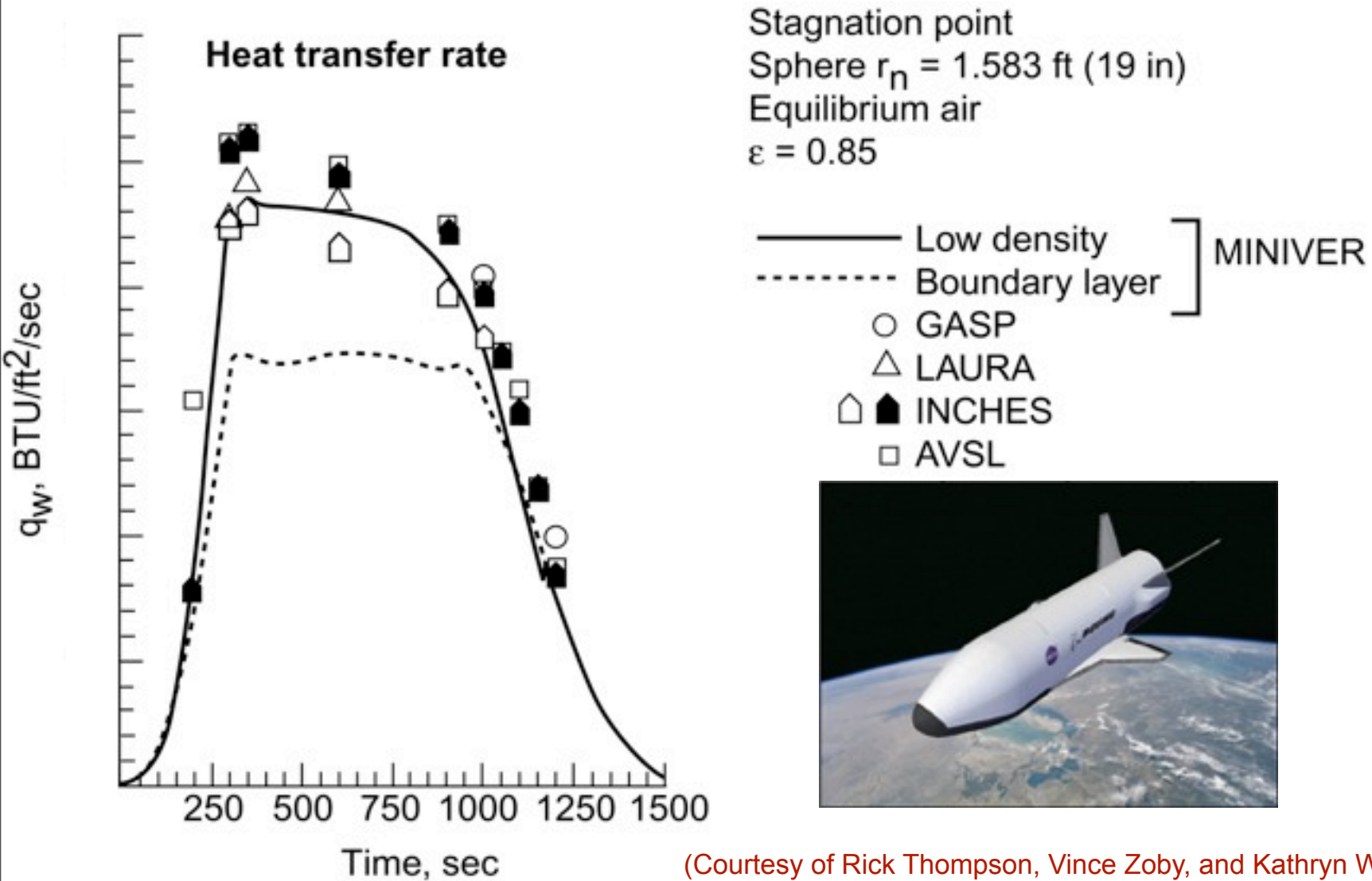


**Transition surface
in trajectory space**



(Courtesy of Rick Thompson)

Viscous Effects on X-37 Heating

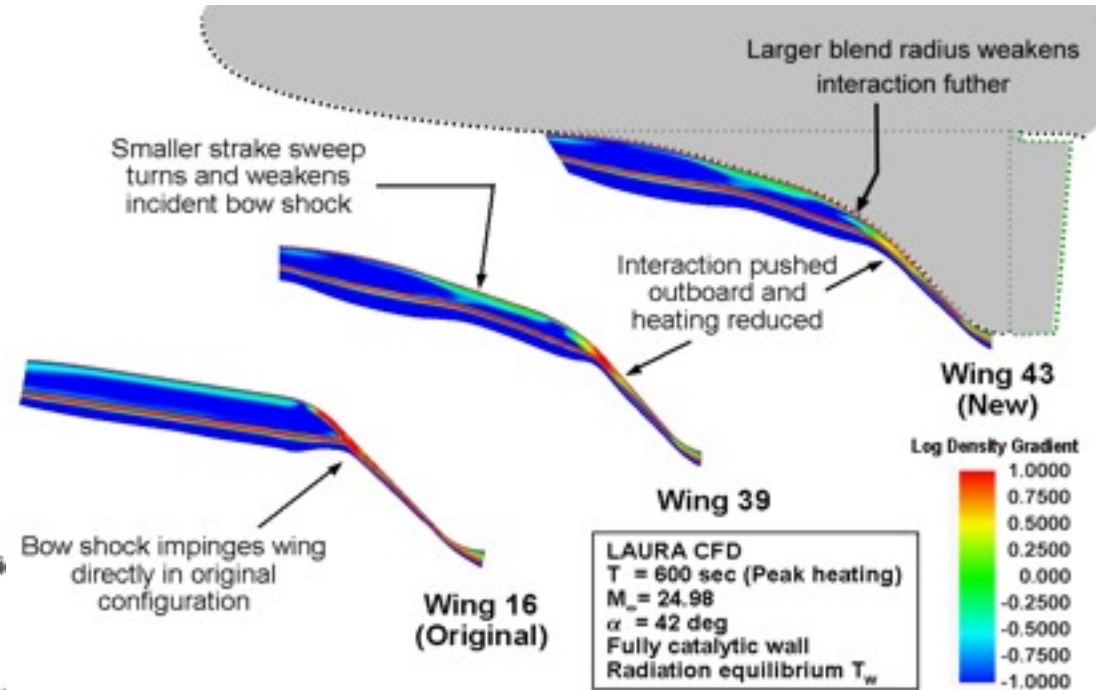
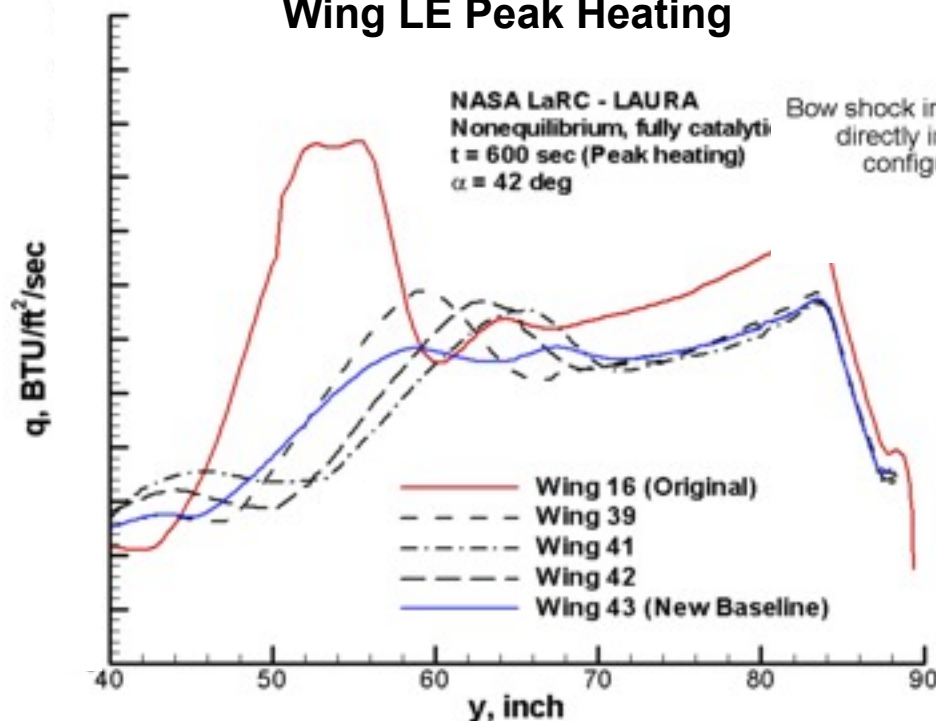


Part 1: Computational Hypersonic Reacting Flow Analysis for Entry Vehicles

X-37 Wing Redesign



Wing LE Peak Heating



Wing LE Shaping

(Courtesy of Rick Thompson)

Comparison with Shuttle Flight Measurements



Symbols – Flight gauges

Contours – LAURA (3/5/2003)

Laminar

Chemical Nonequilibrium (5 species)

Reaction Cured Glass (RCG) coating (partial catalytic)

Radiative equilibrium wall temperature

Std. dev. between prediction
and flight (65-70 measurements)

q , W/cm²



(Courtesy of Bill Wood)

STS-2
Mach = 24.3
 $\alpha = 39.4$ deg

Catalytic Tiles

$\sigma = 12.5\%$

STS-2
Mach = 18.1
 $\alpha = 41.2$ deg

Catalytic Tiles

$\sigma = 11.2\%$

STS-107 Columbia Accident Investigation

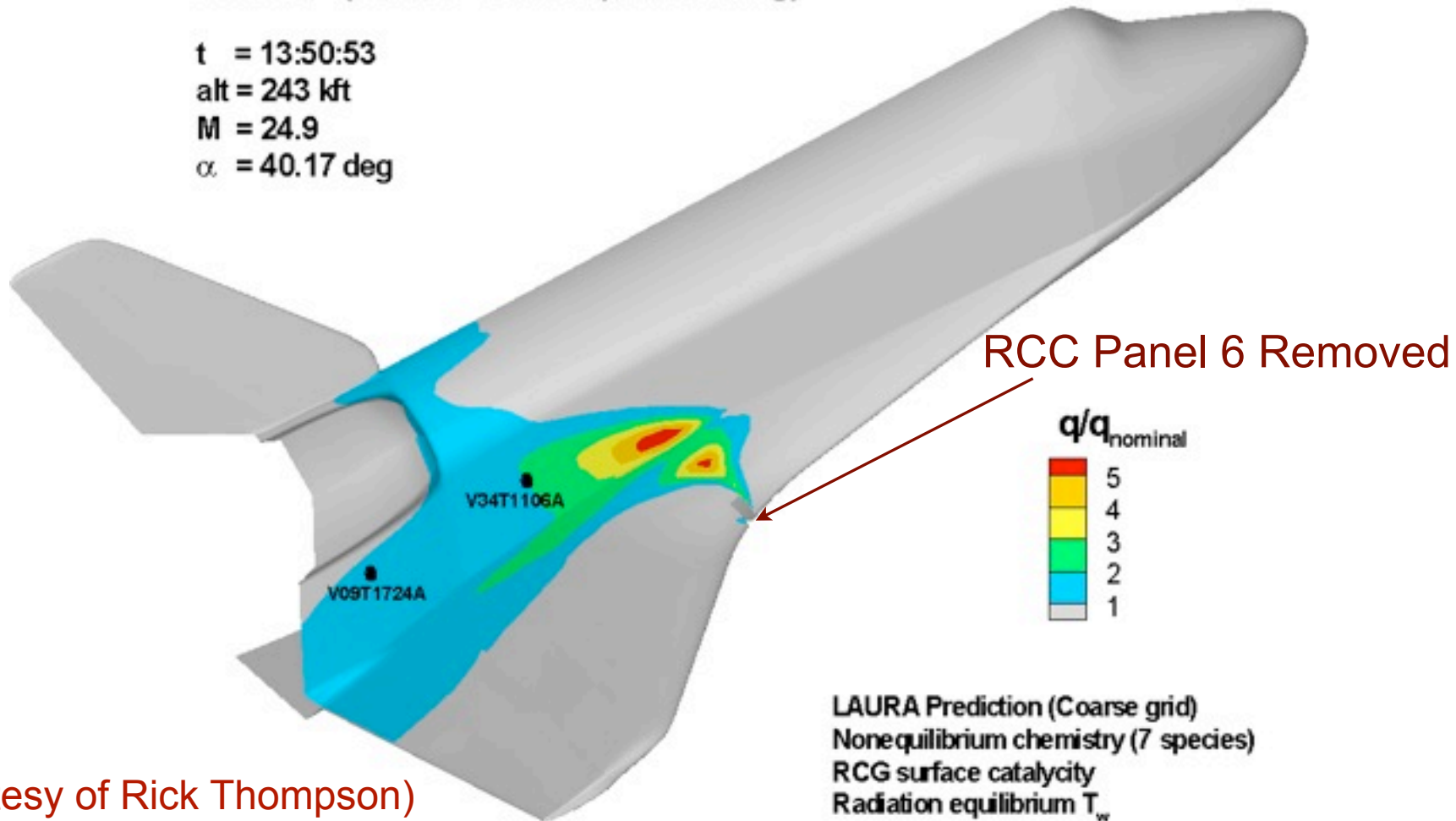
STS-107 (Point 1 - Start of peak heating)

$t = 13:50:53$

$alt = 243 \text{ kft}$

$M = 24.9$

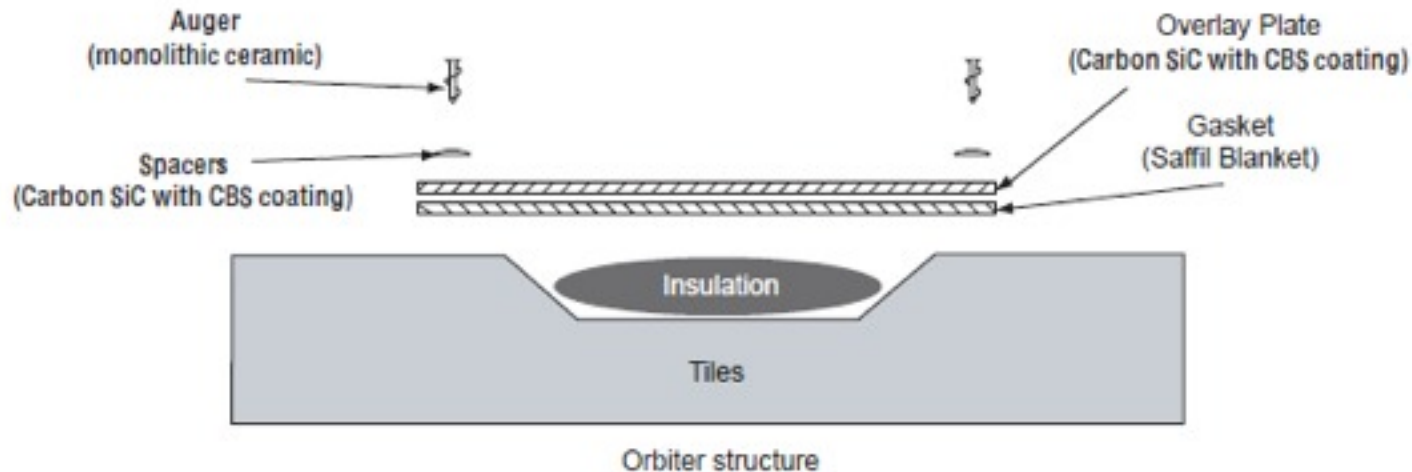
$\alpha = 40.17 \text{ deg}$



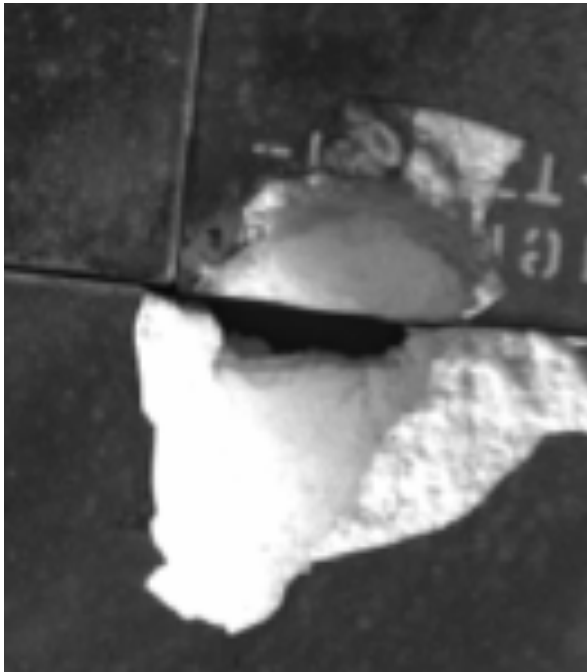
(Courtesy of Rick Thompson)

Shuttle Damage Assessment

- Recommendation from the Columbia Accident Investigation Board (CAIB) resulted in:
 - Agency-wide team and procedures for rapidly generating high fidelity CFD to assess damage sites and effect repairs
- CFD analysis provides:
 - Heating augmentation related to cavities and protuberances
 - Flowfield properties to anchor engineering analysis
 - Mission support of decision for focused inspection and repair

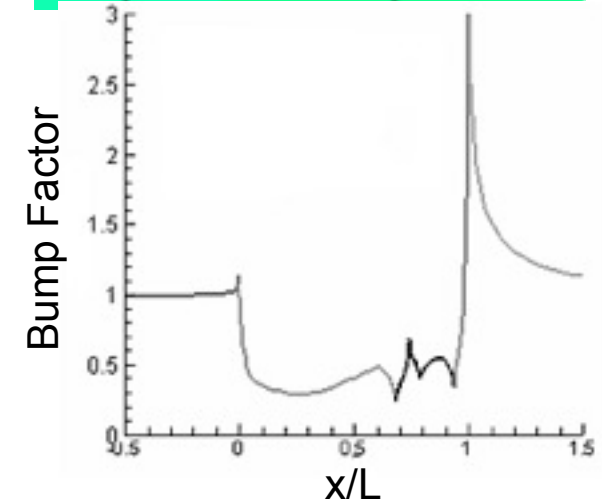
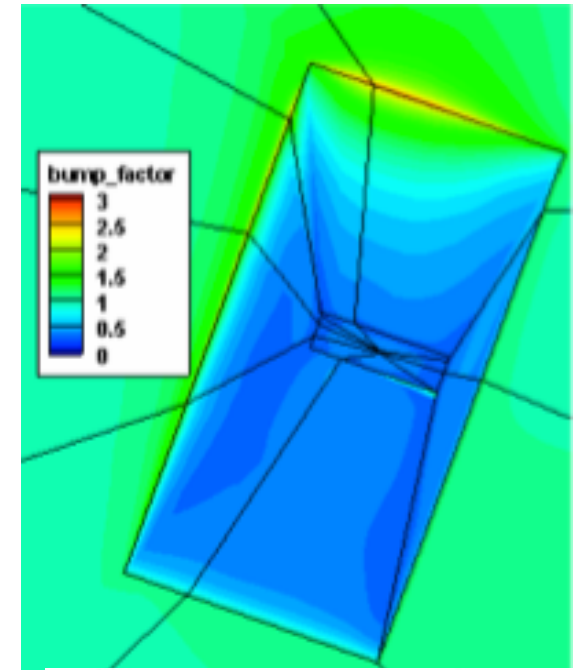
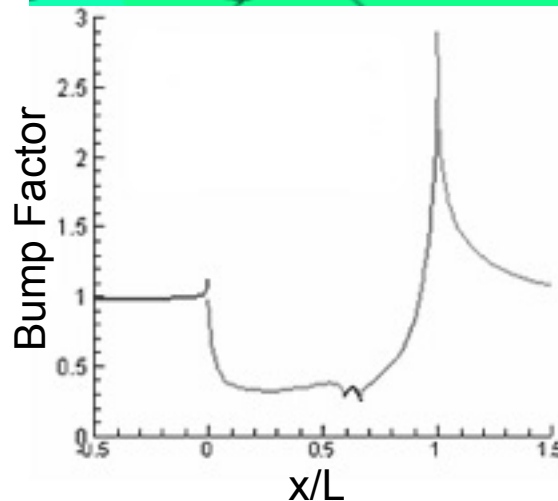
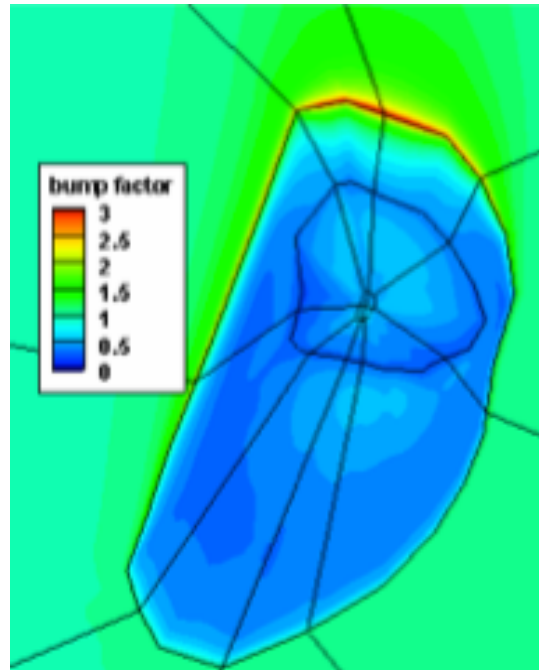


Tile Damage on STS-118 Flight

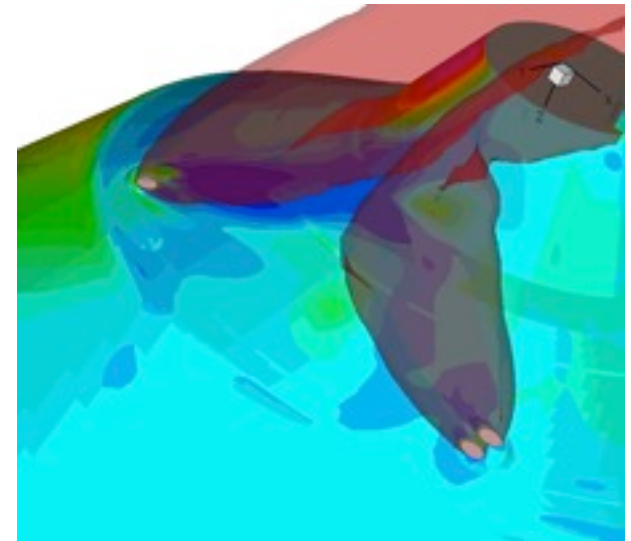
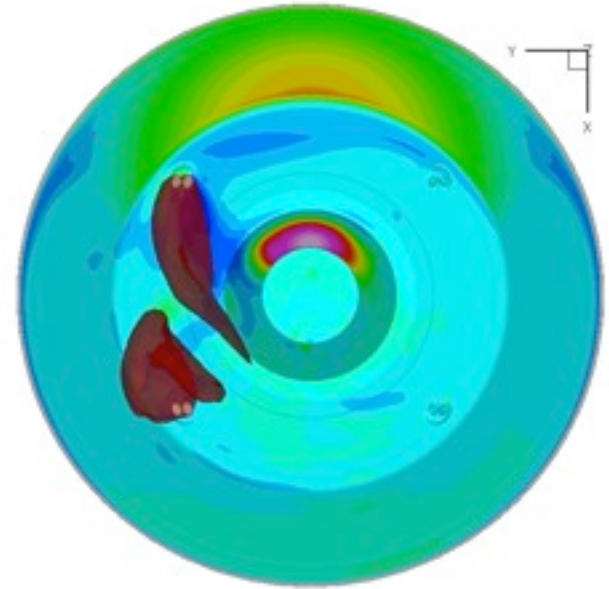
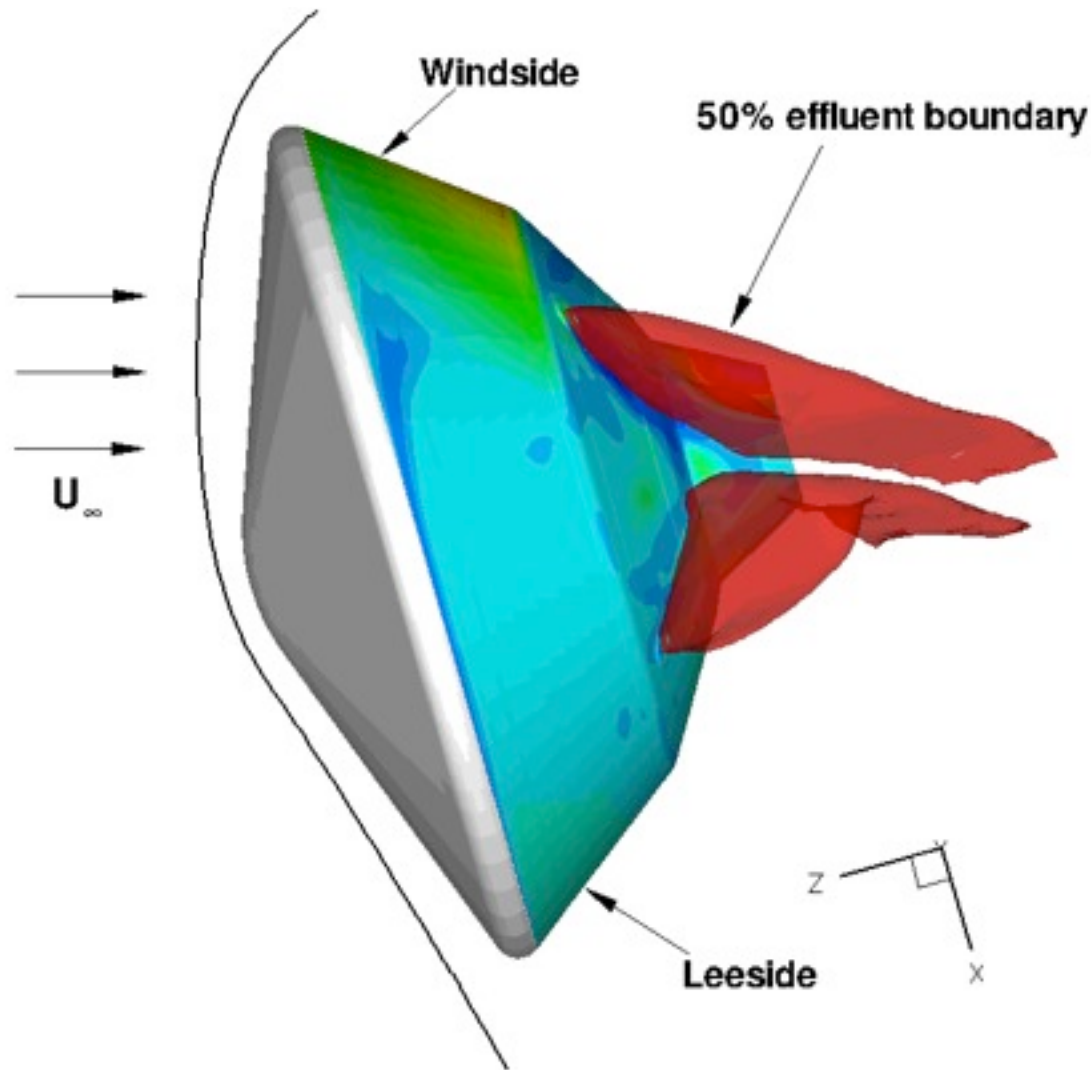


- Foam strike during launch exposed a 2 x 3 inch cavity on lower aft surface
- Focused inspection performed
- No repair

(Courtesy of Peter Gnoffo)



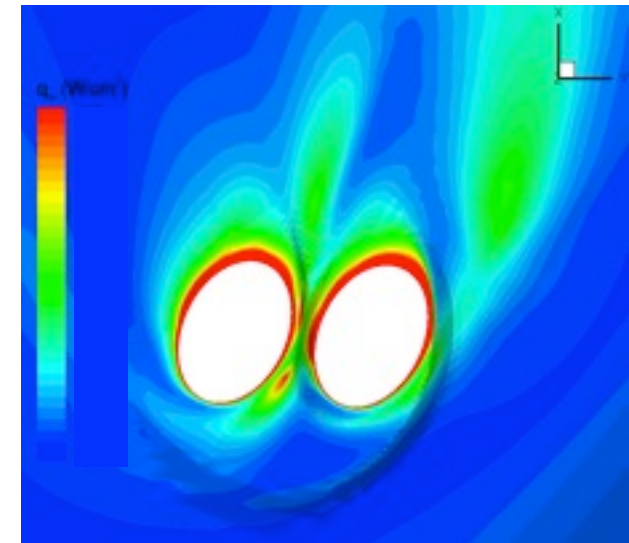
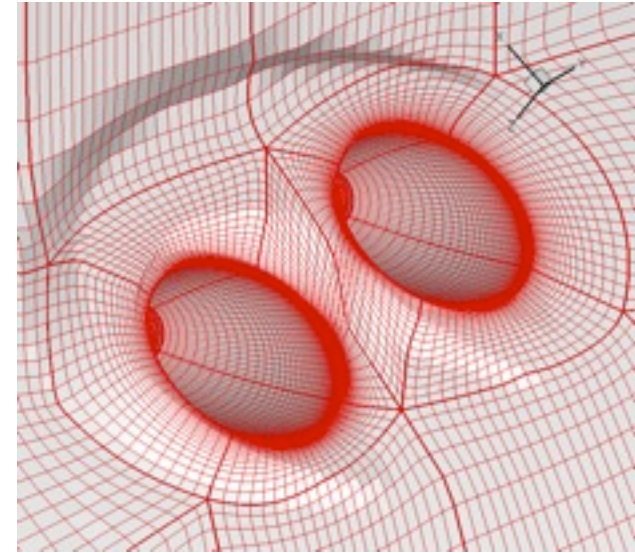
RCS Flowfield for MSL Vehicle



(Courtesy of Artem Dyakonov)

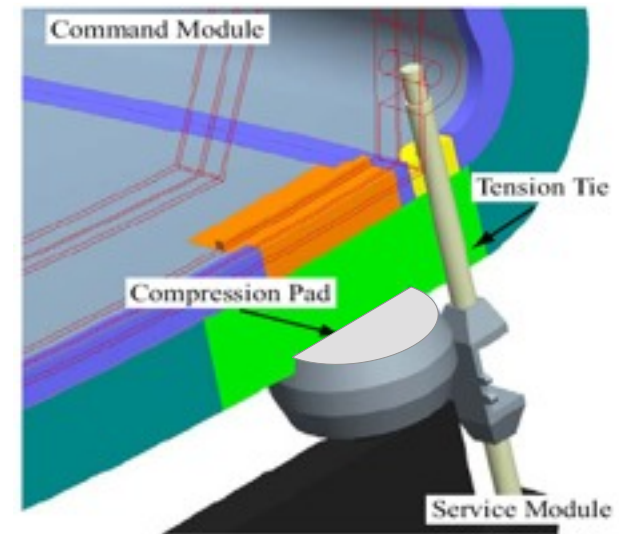
RCS Interference Heating

- Flight environments computed with LAURA
 - Laminar Navier-Stokes
 - Quazi-steady calculations
 - Flow in wake is unsteady
 - No time accuracy in the simulation
 - Non-equilibrium 8-species Mars gas + non-reacting NH₃ as jet exhaust
 - Radiative equilibrium wall temperature
 - Super-catalytic wall boundary
- Mesh size 7M to 60M elements



Orion Aerothermodynamics

- The CEV Aerosciences Project (CAP) is an agency-wide team led by JSC to provide Orion designers with:
 - reentry aerodynamics
 - reentry aeroheating environments
 - ascent aerodynamics and heating
- Aeroheating environments include smooth acreage heating and local heating from vehicle cavities and protuberances

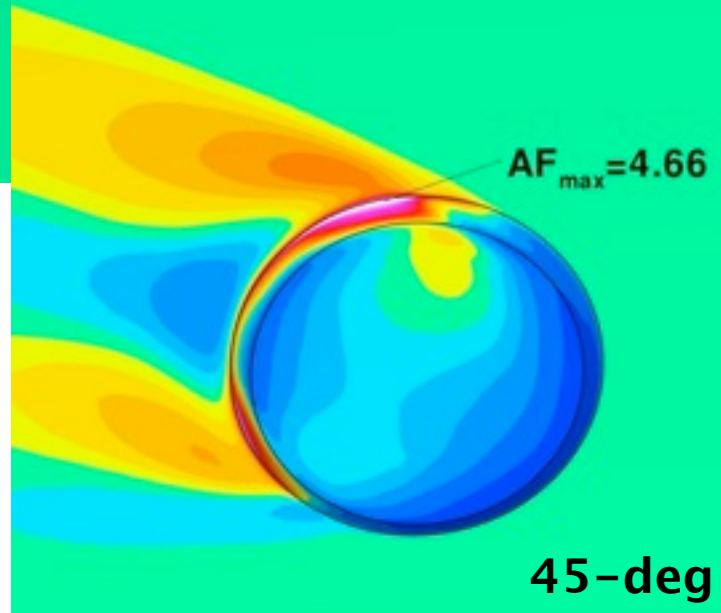
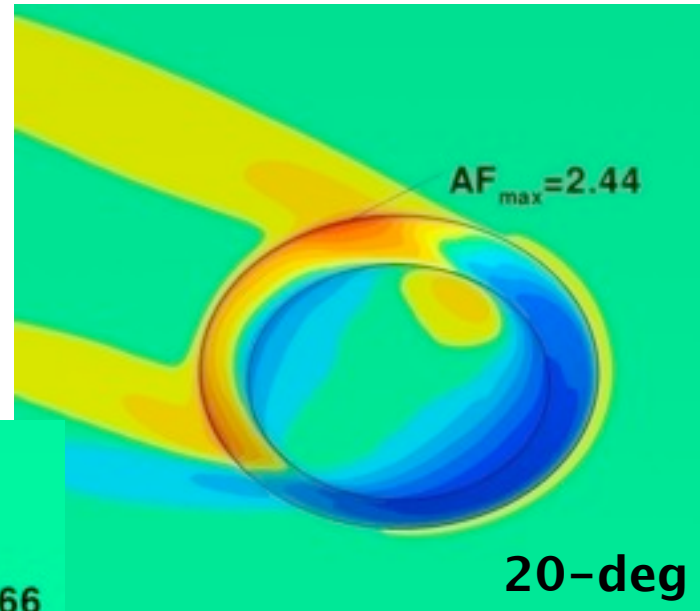
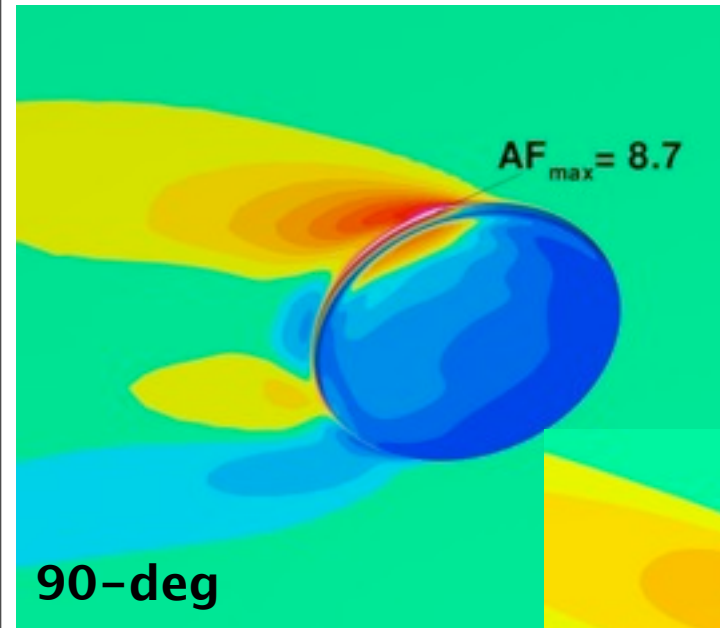


Example: Compression pads cavities formed by heatshield penetrations needed to transfer loads between command and service modules

Effect of Cavity Sidewall Angle on Heating

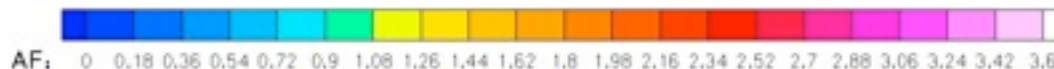
**Lunar Return
Trajectory**

Peak heating



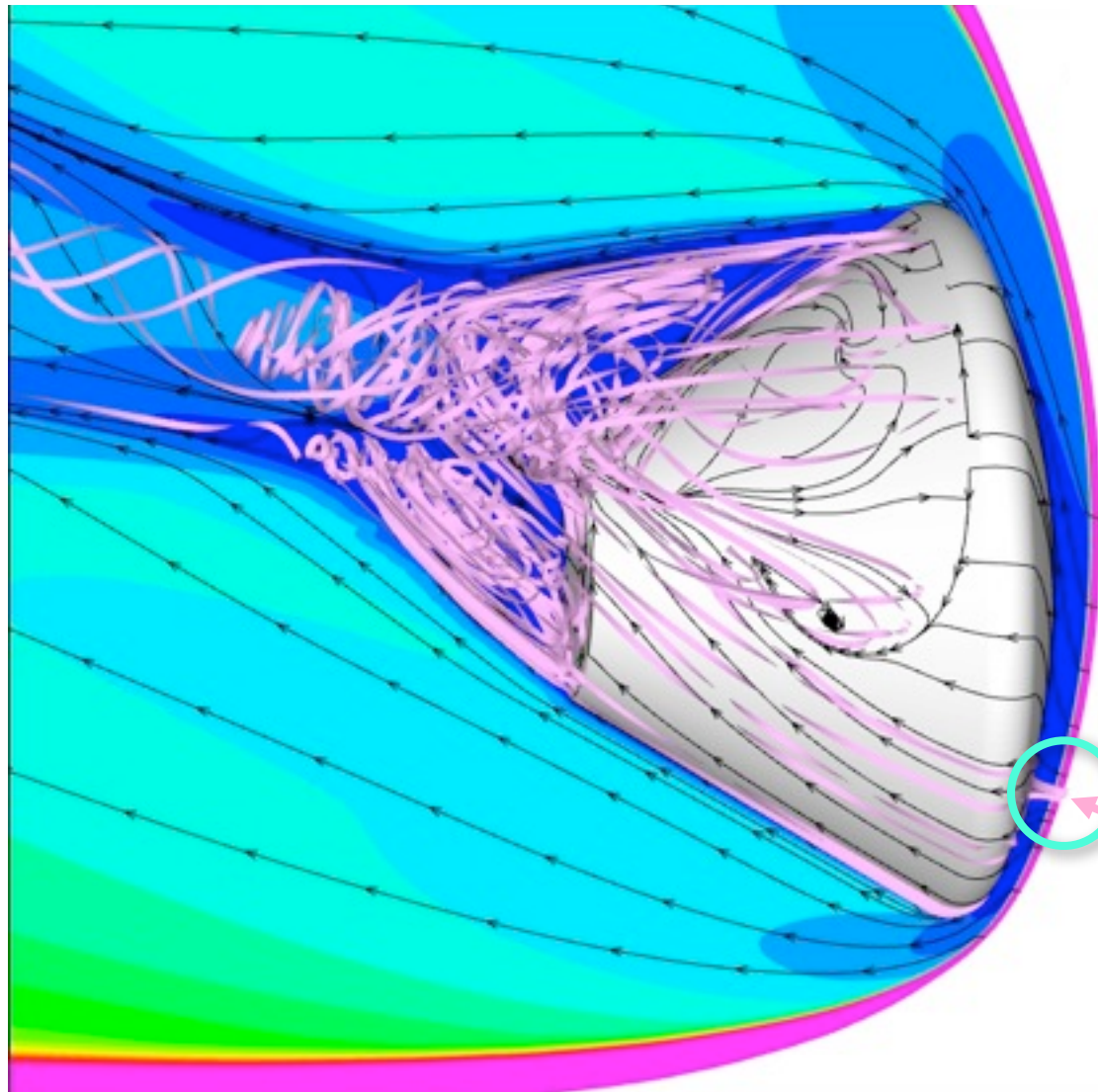
$$AF = \frac{q}{q_{smooth-OML}}$$

(Courtesy of Victor Lessard)



Part 1: Computational Hypersonic Reacting Flow Analysis for Entry Vehicles

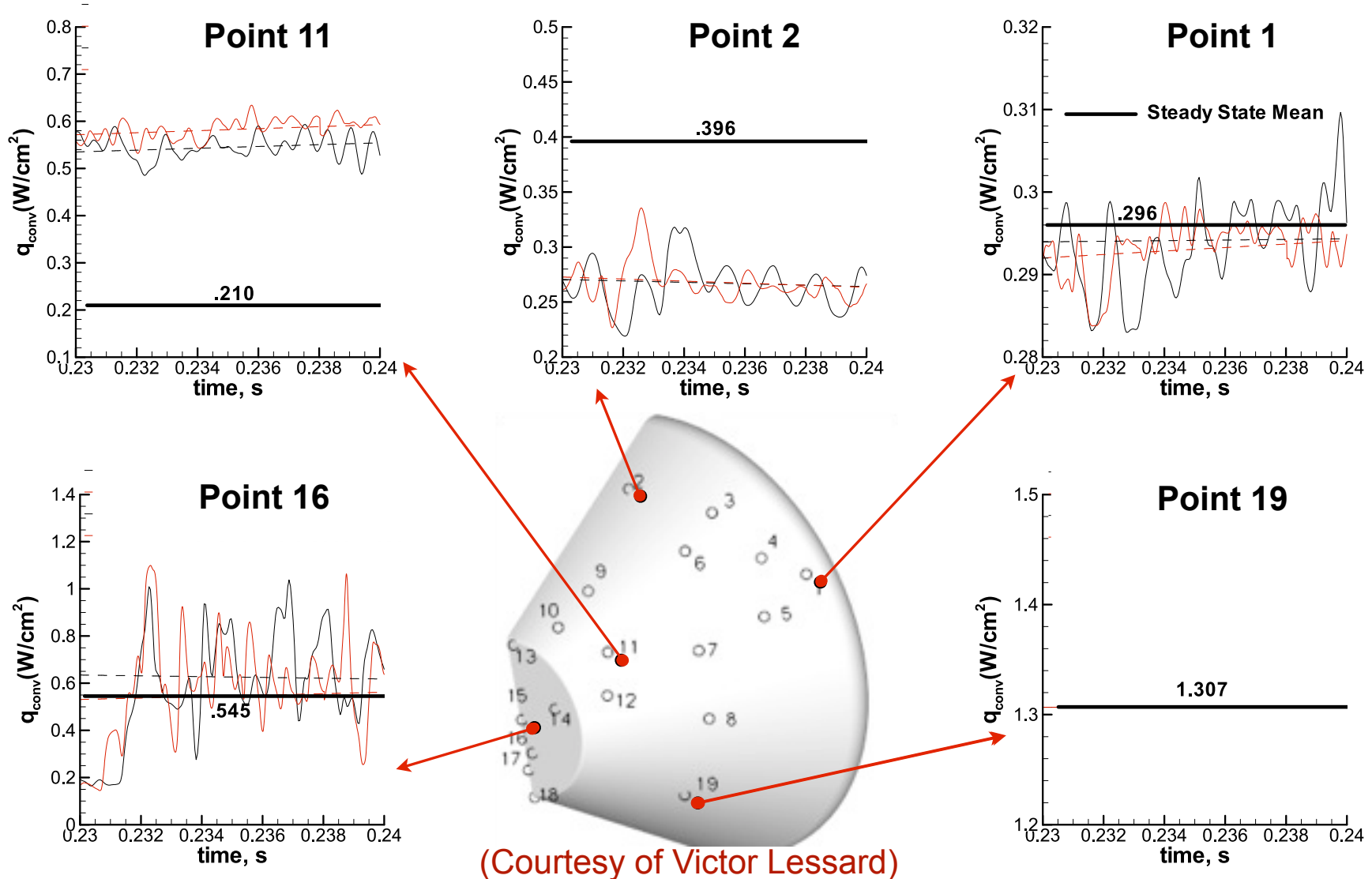
Unsteady Flowfield on Leeside Afterbody



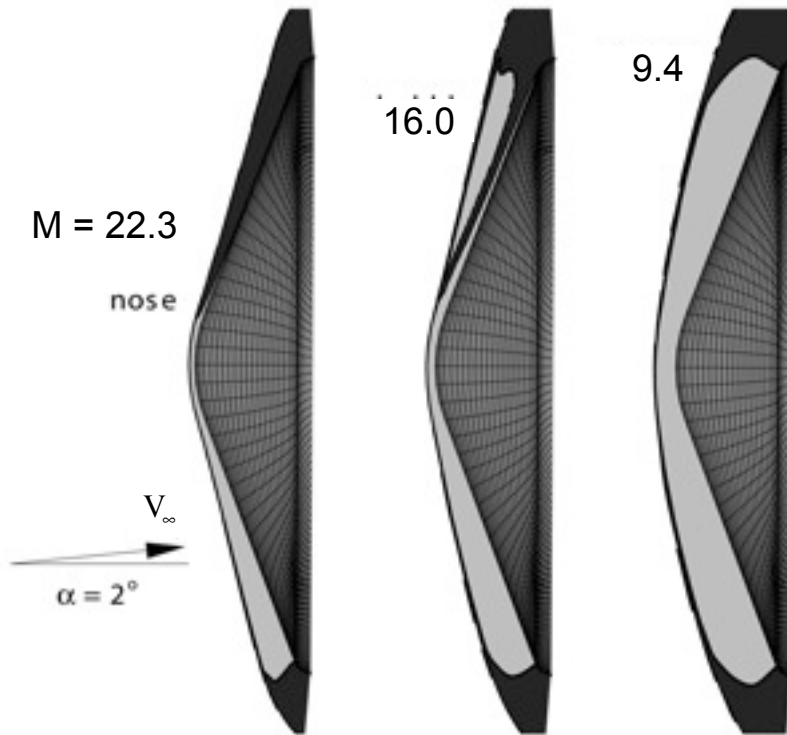
Entire separated flowfield
on leeside afterbody is
filled from windside

(Courtesy of Victor Lessard)

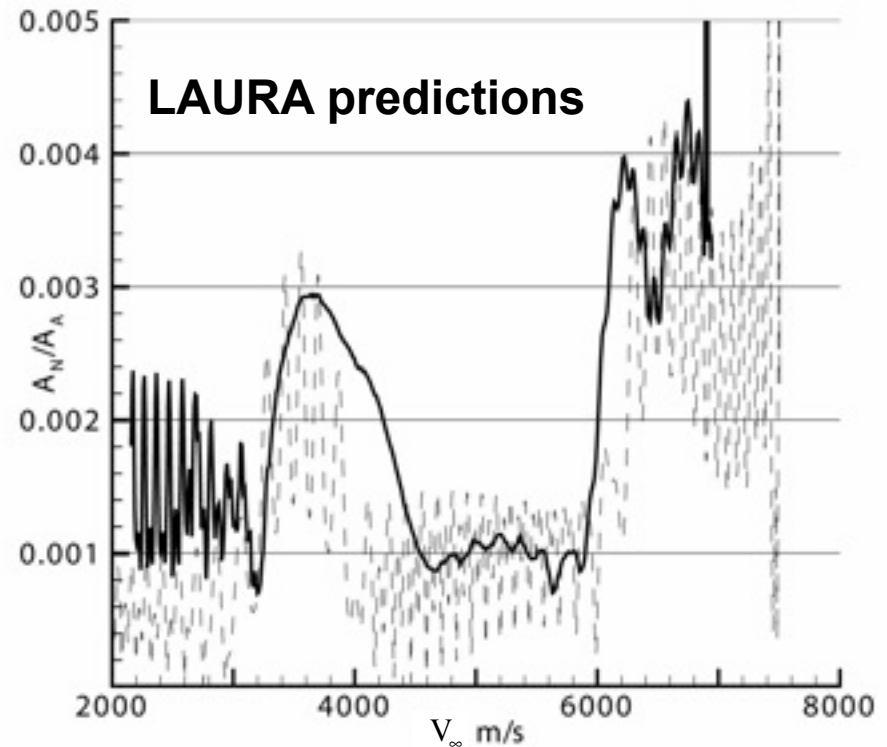
Selected Time Accurate Heating Results



Prediction of Mars Pathfinder Instability



Sonic line location showing the effect of gas chemistry.



Comparison of measured and CFD derived aerodynamic coefficients.

(Courtesy of Peter Gnoffo)

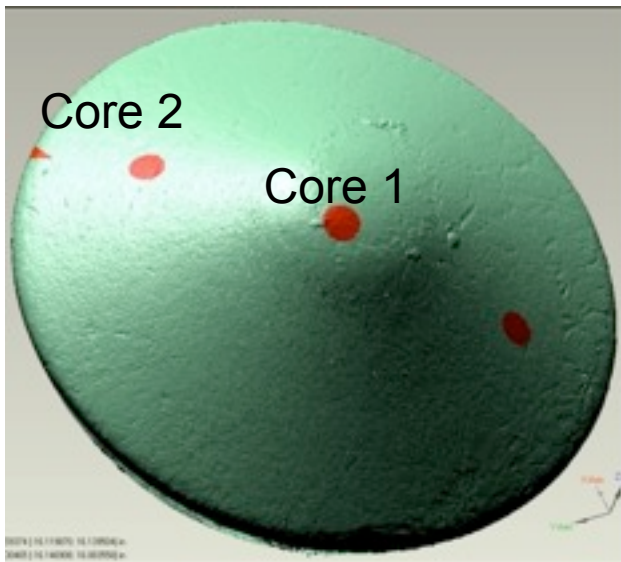
Part 1: Computational Hypersonic Reacting Flow Analysis for Entry Vehicles

Stardust Sample Return Mission



Stardust

- Laminar flow
- Minimal shock-layer radiation (~10%)
- PICA heatshield
- Heatshield recovered

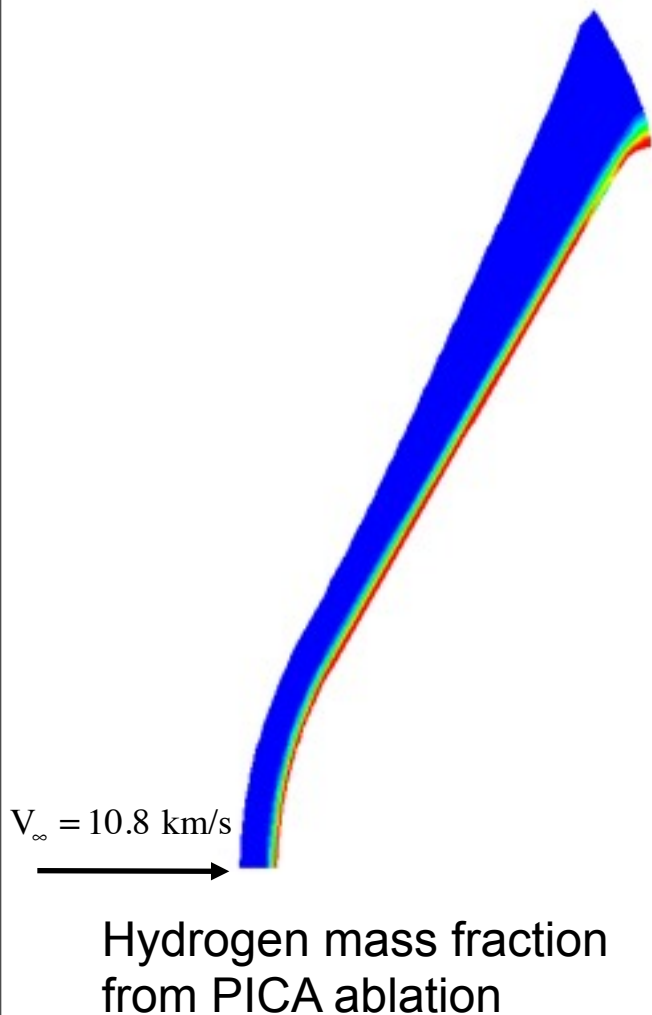


Surface recession

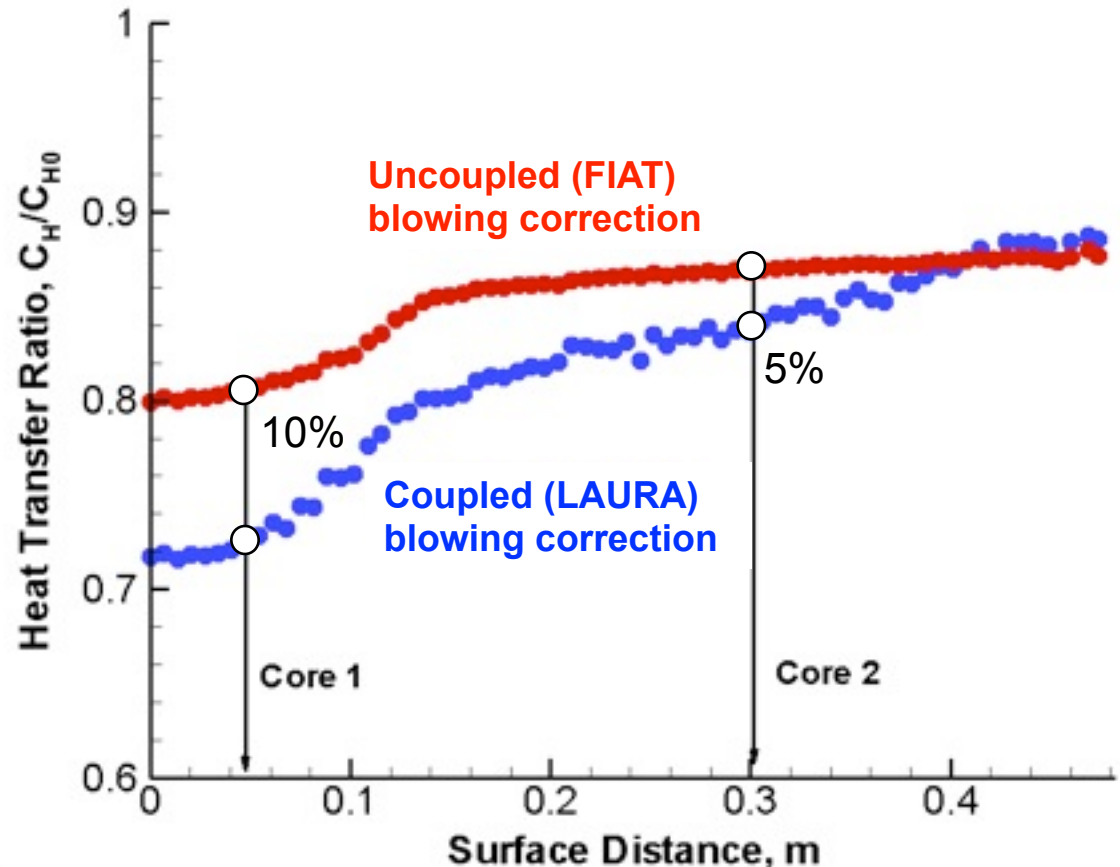
Location	Measured (cm)	Calculated (cm)
Stagnation Point	N/A	0.96
Core 1	0.57 +/- 0.03	0.86
Core 2	0.32 +/- 0.02	0.39

Stardust Solution with Coupled Ablation

- Coupled solution at peak heating ($t=51$ sec)
- PICA ablation (14 species, 27 reactions)
- Surface chemical equilibrium



(Courtesy of Rick Thompson)





The Next Step?

LAURA v5



Summary

- The complexity and importance of the aerothermodynamic process was described
- Examples of the process using a computational hypersonic tool (LAURA) for assessment, optimization, benchmarking, and validation were shown
- A new code (LAURA v5) was introduced that builds from the past to provide a platform for future advances



LAURA 5 -- Part II: Overview

Aerothermodynamics Branch



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Aging of LAURA-A

- Prior version (LAURA-A) first developed in 1992 and optimized for vector machine using Fortran 5
- Ad hoc parallelization and other enhancements
- Numerous steps required in solution process
- Outdated manual; complex input deck
- Frequent recompilation

Required LAURA-A Scripts

Utility	Function
BOUNDS	block-to-block connectivity
INITIALIZE	Initialize flowfield prior to solution
PERELUDE	Interactive Q/A about case setup
LOCALIZE	Use local source code for flag changes
F77, make	Recompile after most changes in inputs
STICHER2	Fix matching grid faces after adaptation
GRIDSWAP	Insert fix grid back into the restart file



LAURA uses Roe's Flux Differencing.

Langley Aerothermodynamic Upwind Relaxation Algorithm:

- Finite-volume formulation
- Roe's averaging flux
- Harten's entropy fix with 2nd order S-TVD
- Central difference for viscous terms.
- Point- and line-implicit relaxation algorithms
- Thermal and chemical nonequilibrium
- Laminar and Turbulent (algebraic, 1- and 2-equation models)
- Grid adaptation procedure



Objectives for LAURA v5

- Employ modern programming paradigms
 - FORTRAN 95
 - Dynamic memory
 - Version control
 - Libraries (e.g. physics module)
- Reproduce all LAURA-A functionality
- Optimized parallelization
- Simplified input (NAMELIST)
- Binary executable (no recompilation)
- Consolidate recent advanced features
- Comprehensive and up-to-date User Manual
- Provide stable platform for future development

All objectives have been met



Selected Features in LAURA v5

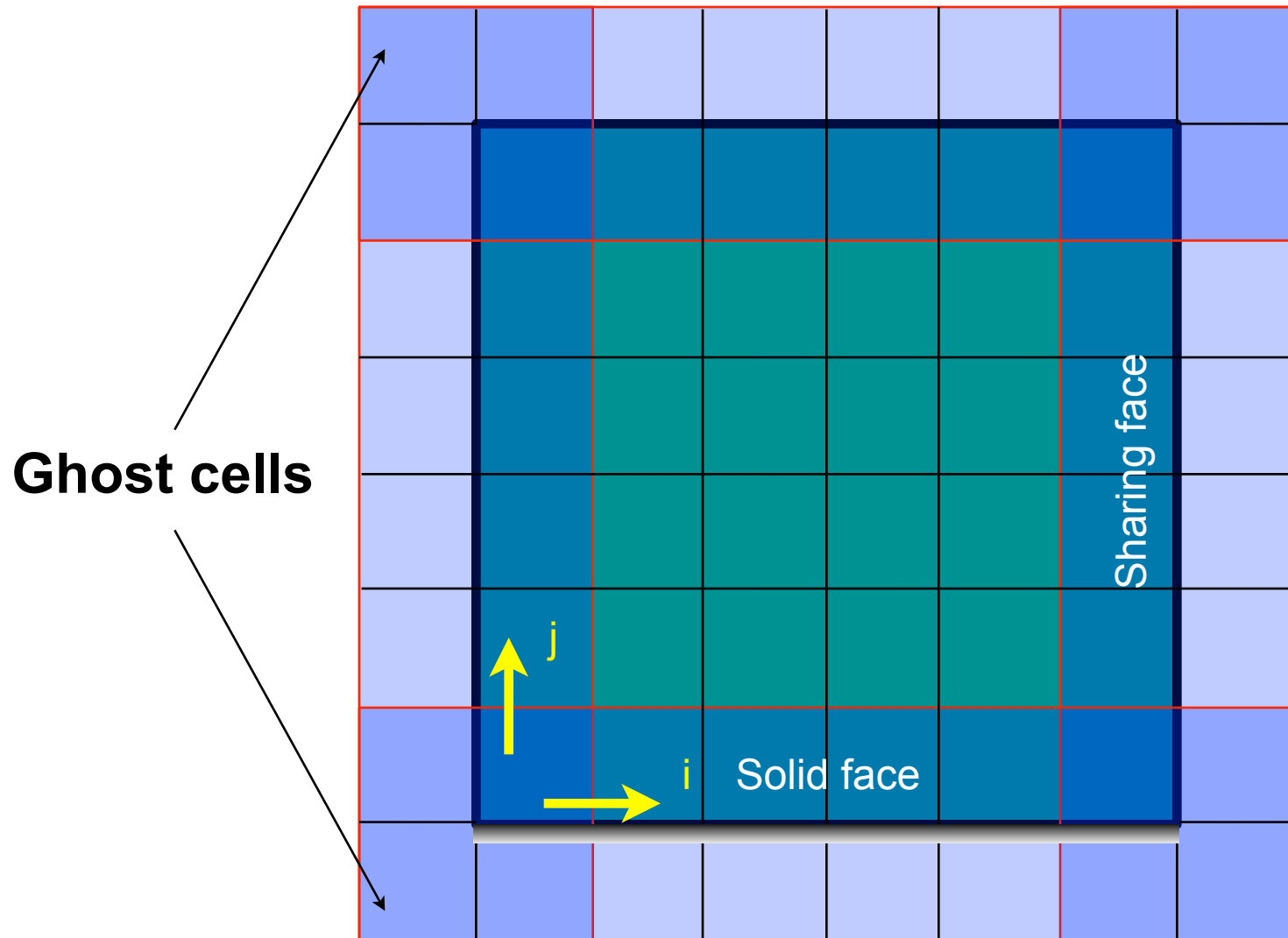
- Full Navier-Stokes, Thin-layer NS, inviscid Euler
- Thermal and chemical nonequilibrium
- Laminar, turbulent (algebraic, 1-eqn, several 2-eqn)
- 1st- and 2nd-order time accuracy
- Characteristic (subsonic) inlet boundary condition
- Blowing/suction boundary condition
- Built-in grid generation for conical shapes, aerobrakes
- Grid adaption (shock alignment) during solution
- Nonuniform surface properties (T_w , emissivity, catalytic)
- Free energy minimization
- Coupled ablation
- Coupled radiation
- Grid sequencing utility
- Multi-processor per block capability
- Various surface catalytic conditions
- Automatic load balancing
- Multi-processor per block capability
- Built-in boundary layer edge detection



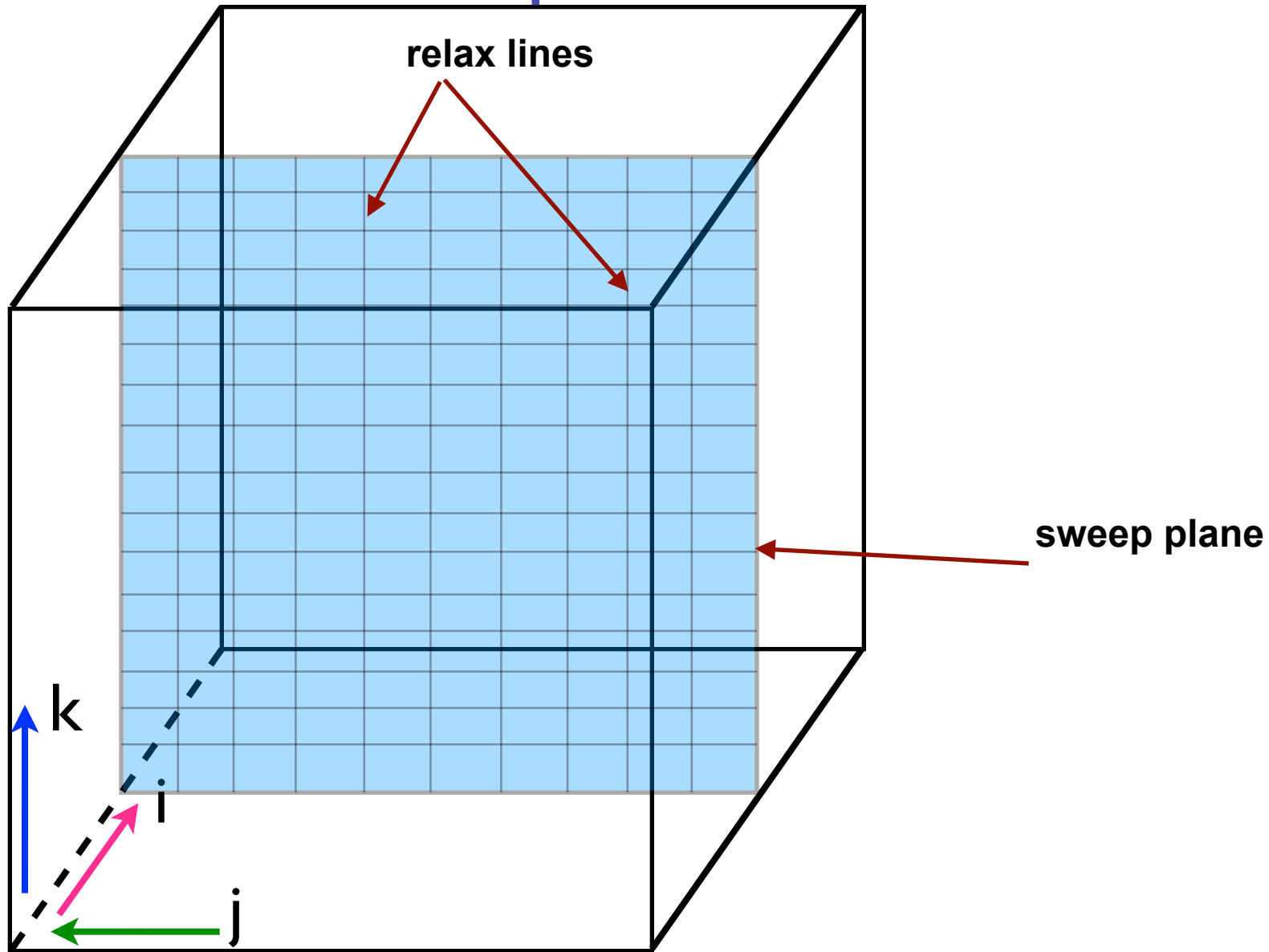
Advanced Model Options in LAURA v5

- Radiation (HARA code)
- Free Energy Minimization (FEM)
 - Equilibrium catalytic wall
 - Equilibrium ablation chemistry
 - Equilibrium shock layer chemistry
- Ablation
 - User specified elemental mass fraction for char and pyrolysis gas
 - Specified (blowing rate and surface temperature)
 - Equilibrium char, quasi-steady ablation
 - Char blowing rate and surface temperature computed assuming gas-solid equilibrium and surface energy balance (Milos & Rasky)
 - Pyrolysis gas blowing rate computed assuming equivalent recession rates
 - Equilibrium char, FIAT computes pyrolysis
 - Trajectory data file to compute heating environment history

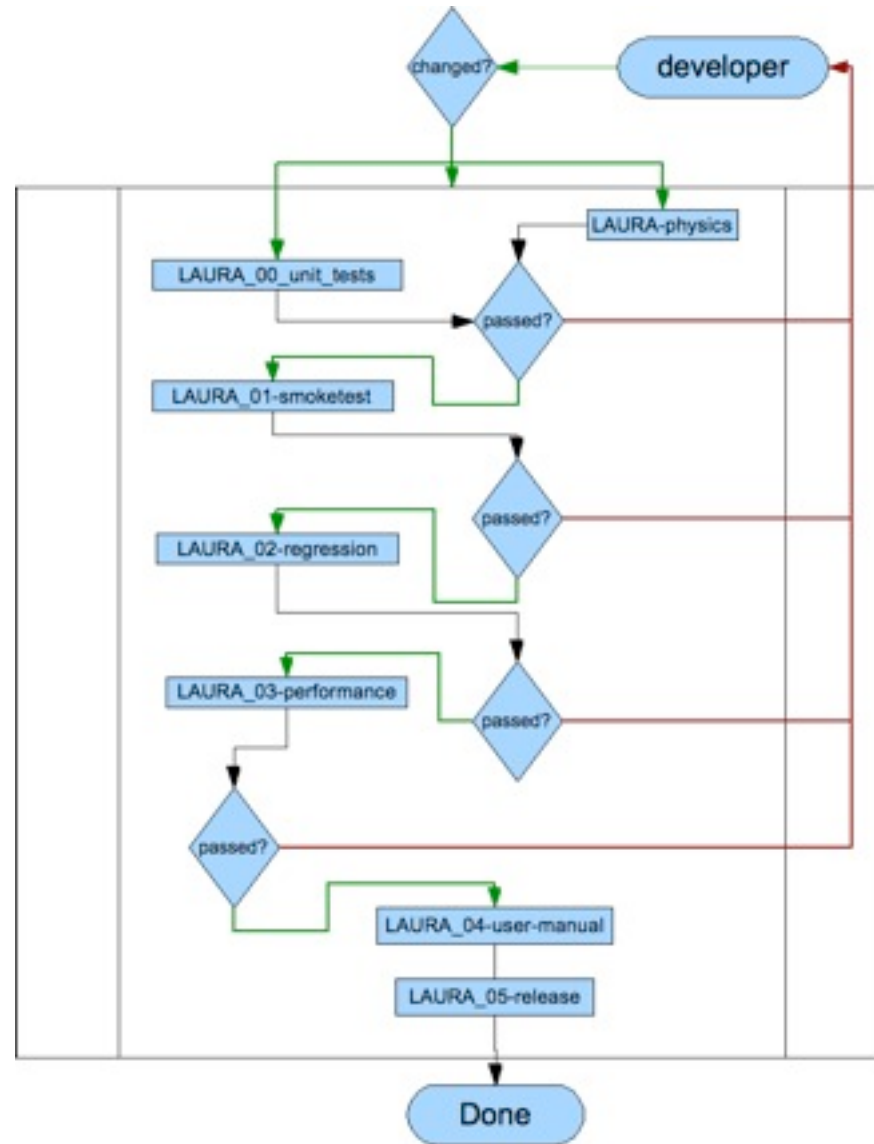
LAURA v5 is 2nd order throughout.



All sweep directions are available.



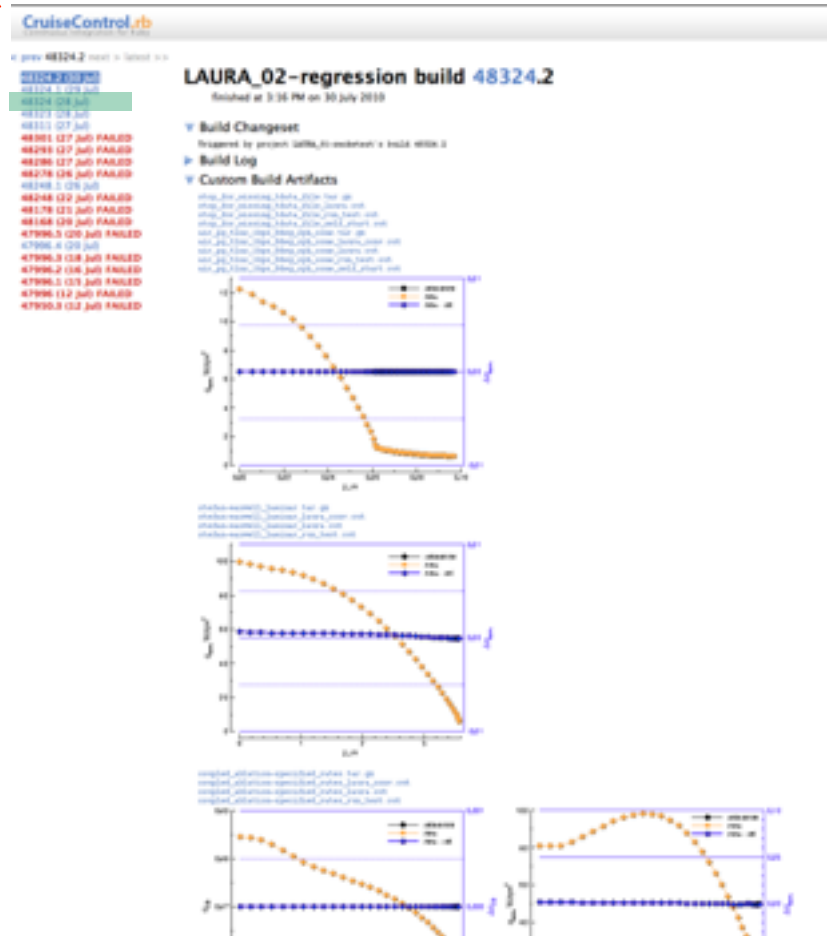
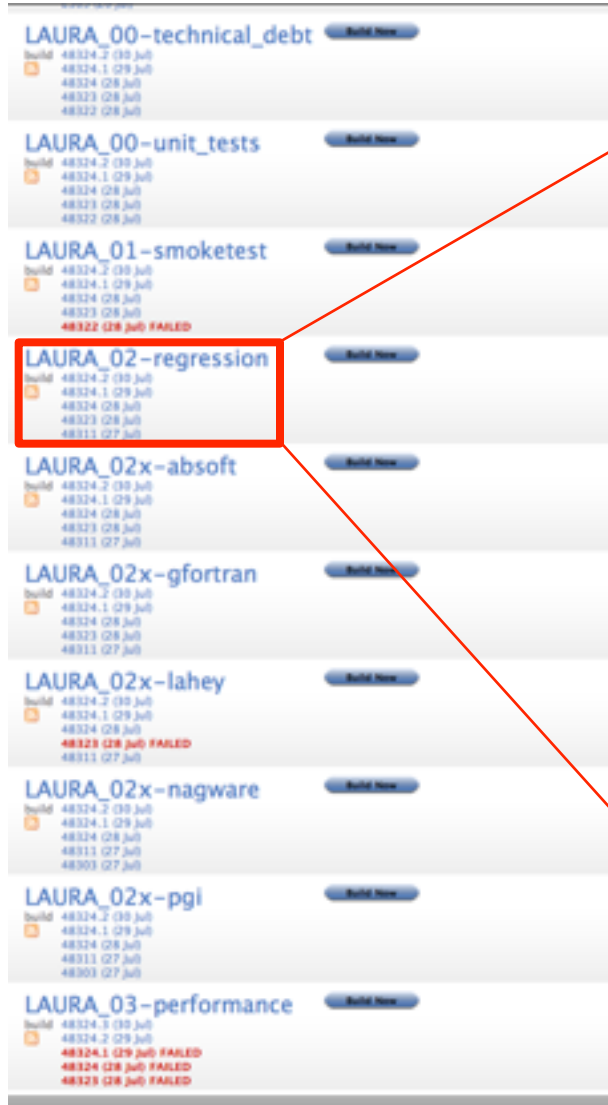
LAURA v5 is extensively controlled.



(Courtesy of Bil Kleb)

LAURA v5 lives in

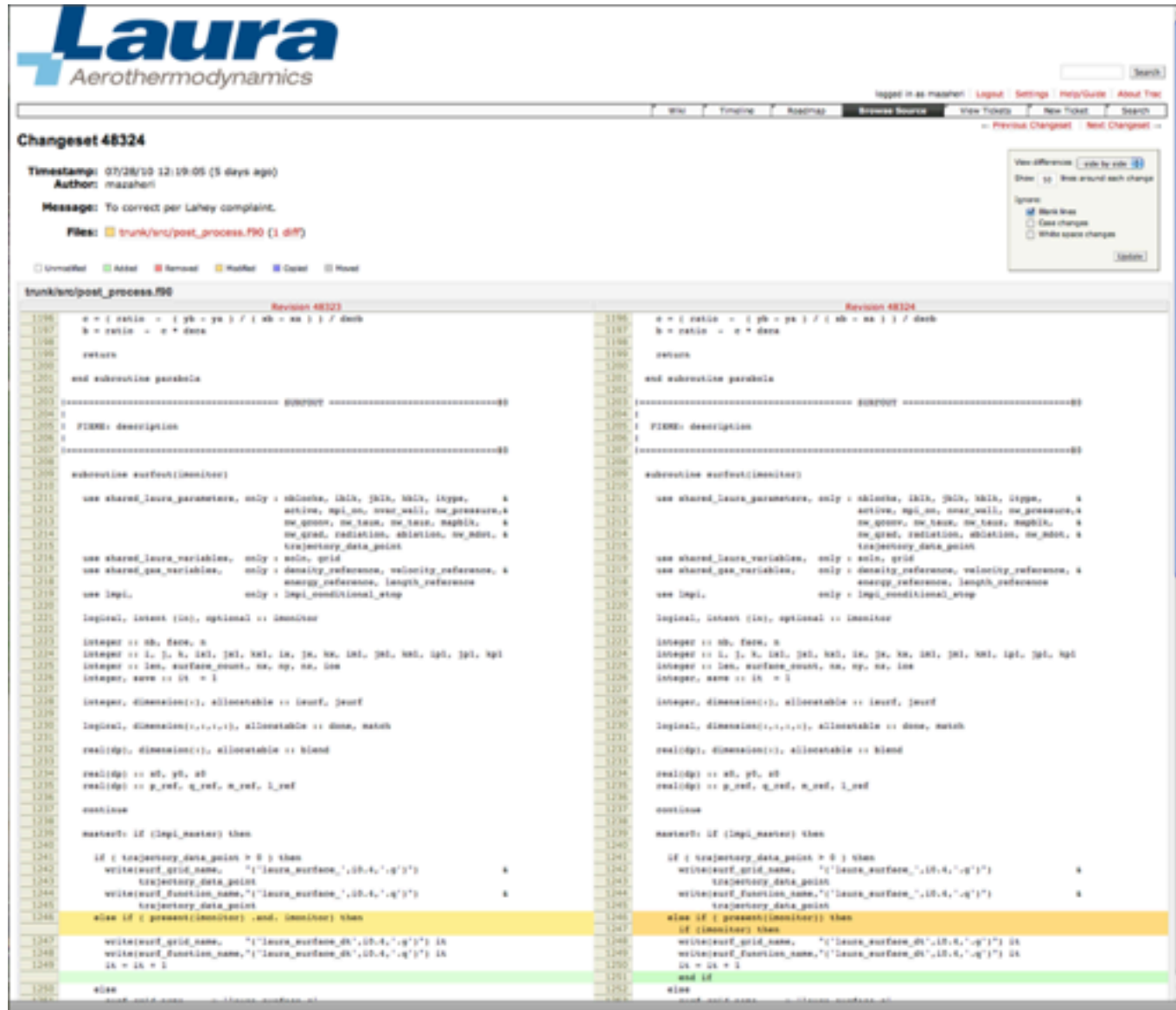
a controlled and traceable environment.



(Courtesy of Bil Kleb)

Part 2: LAURA 5 Overview

LAURA v5 remembers changes made to files.



The screenshot displays the Laura Aerothermodynamics web interface. At the top, the logo "Laura Aerothermodynamics" is visible. Below it, the "Changeset 48324" is highlighted. The interface shows a comparison between two revisions of a file named "trunk/tn/post_process.F90".

Changeset 48324 Details:

- Timestamp: 07/28/10 12:19:05 (5 days ago)
- Author: mazaheri
- Message: To correct per Lahey complaint.
- Files: [trunk/tn/post_process.F90](#) (1 diff)

Comparison Controls:

- View differences: [side by side](#) (selected) | [line by line](#)
- Show: [all](#) | [lines around each change](#)
- Ignore: ☒ Blank lines, ☐ Case changes, ☐ White space changes
- Update

File Comparison:

The comparison shows two versions of the file "trunk/tn/post_process.F90". The left version is Revision 48323, and the right version is Revision 48324. The changes are highlighted in yellow.

Key Changes in Revision 48324:

- Line 1241: `IF (trajectory_data_point > 0) THEN` changed to `IF (trajectory_data_point > 0) THEN` (no change in logic, but the comment is updated).
- Line 1242: `write(surface_grid_name, "(I4.0,'g')")` changed to `write(surface_grid_name, "(I4.0,'g')")` (no change in logic, but the comment is updated).
- Line 1243: `trajectory_data_point` changed to `trajectory_data_point` (no change in logic, but the comment is updated).
- Line 1244: `write(surface_function_name, "(I4.0,'g')")` changed to `write(surface_function_name, "(I4.0,'g')")` (no change in logic, but the comment is updated).
- Line 1245: `trajectory_data_point` changed to `trajectory_data_point` (no change in logic, but the comment is updated).
- Line 1246: `ELSE IF (present(surface)) .AND. (surface) THEN` changed to `ELSE IF (present(surface)) THEN` (removal of `.AND. (surface)`).
- Line 1247: `IF (surface) THEN` changed to `IF (surface) THEN` (no change in logic, but the comment is updated).
- Line 1248: `write(surface_grid_name, "(I4.0,'g')")` changed to `write(surface_grid_name, "(I4.0,'g')")` (no change in logic, but the comment is updated).
- Line 1249: `write(surface_function_name, "(I4.0,'g')")` changed to `write(surface_function_name, "(I4.0,'g')")` (no change in logic, but the comment is updated).
- Line 1250: `IS = IS + 1` changed to `IS = IS + 1` (no change in logic, but the comment is updated).
- Line 1251: `END IF` changed to `END IF` (no change in logic, but the comment is updated).
- Line 1252: `ELSE` changed to `ELSE` (no change in logic, but the comment is updated).



Part 2: LAURA 5 Overview

LAURA v5 Users Manual is always up-to-date.

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2

140001 2010-07-27 16:00:00Z

5.4.17 Turbulent Transport Models

coupled.tke

Logical flag indicating if turbulent kinetic energy is treated as part of the total energy in the energy equation. Default: true.

prandtl.turb

Turbulent Prandtl number. Default: 0.9

schnidt.turb

Turbulent Schmidt number. Default: 0.9

turb.int.inf

Farfield turbulent kinetic energy non-dimensionalized by square of the reference velocity. If negative, use recommended far field boundary conditions: $(\mu^*)_{\infty} = 0.01\mu_{\infty}$ and $(\rho\mu^*)_{\infty} = 2$. Default: -0.0001

turb.model.type

An integer flag to select turbulence modeling. Default: 0

Options are:

-1: Baldwin-Lomax algebraic turbulence model. [K]

-2: Cebeci-Smith algebraic turbulence model. [K]

0: Laminar flow, i.e., no turbulence model.

1: Spalart-Allmaras one-equation turbulence model.

2: Menter two-equation turbulence model.

3: Menter-SST two-equation turbulence model.

4: Wilcox $k-\omega$ 1998 turbulence model.

6: Wilcox $k-\omega$ 2006 turbulence model.

turb.comp.model

Integer flag (1=on, 0=off) to engage compressibility correction for turb. model.type = 2, 3, 4. Sometimes observed to cause spike in turbulent kinetic energy crossing bow shock. Expect small effect in boundary layer but large effect in free mixing layer. Default: 0

turb.visc.ratio.inf

Farfield ratio of turbulent to laminar viscosity. Default: 0.001

xtx

Transition location along x-axis in grid units. Engaged only for algebraic models. Default: 0.0

35

140001 2010-07-27 16:00:00Z

5.4.18 Viscous Boundary Condition Flags

vacuum.pressure.coefficient

This parameter, which is in N/m^2 sets the pressure coefficient behind type 6 boundaries (see Section 5.3 on page 14), which forces flow out of the domain. This coefficient is defined as

$$vacuum.pressure.coefficient = \frac{P_0 - P_{\infty}}{2} \quad (30)$$

where P_0 is back pressure where the gas is venting out, and P_{∞} is fielded

NASA/TM-2010-217777



LAURA Users Manual: 5.3-48311

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July 2010



Part 2: LAURA 5 Overview

LAURA v5 uses simple input decks.

laura_namelist_data

```
&laura_namelist
irest                = 1
dimensionality        = '3D'
length_ref            = .0254
navier_stokes         = .true.

velocity_ref          = 5536.49
density_ref           = 0.26099e-03
alpha                 = 10.
tref                  = 238.48

surface_temperature_type_0 = "radiative equilibrium"
catalysis_model_0      = "Stewart-RCG"
emiss_a_0              = 0.89

twall_bc              = 1000.
ncyc                   = 2000
nitfo                  = 0

jupdate               = 10
ntran                  = 10
nexch                  = 2

movegrd                = 0
maxmoves              = 1
re_cell                = 1.0
fsh                    = 0.8

rf_inv                 = 3.0
rf_vis                 = 1.0
frac_line_implicit    = 1.0
/
```

tdata

```
Two Temperature
N
O
N2 0.76
O2 0.24
NO
N+
O+
N2+
O2+
NO+
e-
```

screen output

```
Reading block sizes from laura.g
1 blocks: 1_31x2x65
nb = 1 No. Divisions = 2 procs: 0 1
proc = 0 nb= 1 division= 1 start= 1 stop= 15
proc = 1 nb= 1 division= 2 start= 16 stop= 30
INFO: no viscous specification file (laura_vis_data) detected.
INFO: no laura_trajectory_data file found.
INFO: no transition specification file (laura.trn) detected.
INFO: File species_thermo_data does not exist. Not using.
Reading perfect_gas
INFO: no surface property file (surface_property_data) detected.
Setting gamma = 1.4000 rather than default value of 1.4000
density0_i: 1.000
density0: 1.000
molecular_weight0: 28.80
temperature0_j: 200.0
energy0_j: 0.5774E-02
cv0_j: 0.2887E-04
pressure0_k: 0.2310E-02
sonic0_k: 0.5686E-01
enthalpy0_ij: 0.8083E-02
pressure0_jac: 0.000 0.4000
v_ref: 5000.
l_ref: 1.000
rho_ref: 0.1000E-01
Mach_ref: 17.59
AoA: 0.000
Reynolds_ref: 0.3762E+07
step = 0 time = 0.19
block = 1 task = 1 Linf: 0.39E+03 14 1 1 1 L2eq: 0.53E-01 0.14E-01 0.00E+00 0.16E-01 0.12E-01
block = 1 task = 2 Linf: 0.18E+04 22 1 59 1 L2eq: 0.12E+00 0.77E-01 0.00E+00 0.63E-01 0.58E-01
step = 10 time = 0.70 sum(abs(task error)) = 0.42E+00 L2 norm = 0.11E-03

block = 1 task = 1 Linf: 0.72E+03 11 1 60 1 L2eq: 0.57E-01 0.12E-01 0.00E+00 0.14E-01 0.10E-01
block = 1 task = 2 Linf: 0.15E+04 23 1 60 1 L2eq: 0.99E-01 0.64E-01 0.00E+00 0.48E-01 0.47E-01
step = 20 time = 1.22 sum(abs(task error)) = 0.35E+00 L2 norm = 0.87E-04

block = 1 task = 2 Linf: 0.11E+04 25 1 59 1 L2eq: 0.68E-01 0.40E-01 0.00E+00 0.34E-01 0.30E-01
block = 1 task = 1 Linf: 0.11E+04 12 1 60 1 L2eq: 0.60E-01 0.13E-01 0.00E+00 0.14E-01 0.11E-01
step = 30 time = 1.72 sum(abs(task error)) = 0.27E+00 L2 norm = 0.54E-04
```



LAURA uses enhanced parsing algorithm.

- Users do not need to change any of the physics-based data.
- Developers/researchers may change the physics-based data with no modification of source files.
- Physics-based data are simple ASCII files

Kinetic data can be modified with no changes in the LAURA v5.

N2 + M <=> 2N + M

7.000e+21 -1.60 1.132e+05

teff1 = 2

exp1 = 0.7

C = 4.3

O = 4.3

N = 4.3

H = 4.3

Si = 4.3

e- = 0.

! JTHT Vol 15 No 1 pp76-90 2001 (Ref 1)

$$K_f = c_f T^\eta e^{-\epsilon_0/kT}$$

$$T = T^{e_1} T_v^{1-e_1}$$

O2 + M <=> 2O + M

2.000e+21 -1.50 5.936e+04

teff1 = 2

exp1 = 0.7

t_eff_min = 1000.

t_eff_max = 50000.

C = 5.0

O = 5.0

N = 5.0

H = 5.0

Si = 5.0

e- = 0.

! JTHT Vol 15 No 1 pp76-90 2001 (Ref 1)



Part 2: LAURA 5 Overview

Species thermodynamic data can be modified with no changes in the LAURA v5.

SiN

&species_properties

disoc_ener = 5.63

alantel = 104.3

mol_wt = 42.1

/

2

-1.464672152E+04 1.374993497E+02 3.678508580E+00 -6.158499200E-03

2.309417067E-05 -2.294461481E-08 7.395665680E-12 0.0000000000E+00

4.673212990E+04 6.494564115E+00 **200.000 1000.000**

-2.932685132E+06 5.853688590E+03 1.321451677E+00 1.258329284E-03

-3.773886360E-07 6.887761040E-11 -4.189842590E-15 0.0000000000E+00

6.527148810E+03 2.553145732E+01 **1000.000 6000.000**

C2H2

&species_properties

alantel = 343.9

mol_wt = 26.04

/

2

1.598112089E+05 -2.216644118E+03 1.265707813E+01 -7.979651080E-03

8.054992750E-06 -2.433307673E-09 -7.529233180E-14 0.0000000000E+0

3.712619060E+04 -5.244338900E+01 200.000 1000.000

1.713847410E+06 -5.929106660E+03 1.236127943E+01 1.314186993E-04

-1.362764431E-07 2.712655786E-11 -1.302066204E-15 0.0000000000E+0

6.266578970E+04 -5.818960590E+01 1000.000 6000.000

$$c_p(T)/R = a_1 T^{-2} + a_2 T^{-1} + a_3 + a_4 T + a_5 T^2 + a_6 T^3 + a_7 T^4$$

$$h(T)/RT = -a_1 T^{-2} + a_2 T^{-1} \ln T + a_3 + a_4 \frac{T}{2} + a_5 \frac{T^2}{3} + a_6 \frac{T^3}{4} + a_7 \frac{T^4}{5} + \frac{a_9}{T}$$

$$s(T)/R = -a_1 \frac{T^{-2}}{2} - a_2 T^{-1} + a_3 \ln T + a_4 T + a_5 \frac{T^2}{2} + a_6 \frac{T^3}{3} + a_7 \frac{T^4}{4} + a_{10}$$



Species transport data can be modified with no changes in the LAURA v5.

Ar N 1 1 1 (c)

-1.5770918E-03 1.9984531E-02 -2.8213247E-01 9.6454110E+01
-1.4719259E-03 1.8826034E-02 -2.6780376E-01 1.0559112E+02
2.1014557E-04 -3.0961952E-03 2.6263889E-02 1.0336502E+00

$$\pi\Omega^{1,1} = D_1 T^{A_1} (\ln T)^2 + B_1 \ln T + C_1$$

$$\pi\Omega^{2,2} = D_2 T^{A_2} (\ln T)^2 + B_2 \ln T + C_2$$

C2H C 1 1 0 (d)

5.7617984E-03 -1.5877048E-01 1.0396576E+00 6.0598452E+00
0.0000000E+00 0.0000000E+00 -3.9863137E-01 4.9647126E+02

$$B_{ij} = D_3 T^{A_3} (\ln T)^3 + B_3 \ln T + C_3$$

C2H O 1 1 0 (d)

5.7617984E-03 -1.5192401E-01 9.1659645E-01 1.0417506E+01
-1.1523597E-02 3.1411773E-01 -3.2302884E+00 2.2852678E+06

C2H N 1 1 0 (d)

5.7617984E-03 -1.5192401E-01 9.1659645E-01 1.0908468E+01
0.0000000E+00 0.0000000E+00 -3.9863137E-01 5.1986923E+02

C2H H 1 1 0 (d)

0.0000000E+00 0.0000000E+00 -3.9863137E-01 3.5966163E+02
5.7617984E-03 -1.4850078E-01 8.7167551E-01 1.0954333E+01

C2H Ar 1 1 0 (d)

0.0000000E+00 -1.0269705E-02 -1.3099144E-01 1.3176381E+02
5.7617984E-03 -1.7588666E-01 1.4635780E+00 9.4059680E-01



Backup



HARA Radiation Code

- HARA is the **H**igh-temperature **A**erothermodynamic **R**adiation model recently developed at NASA Langley.
- Applies the following for atomic radiation:
 - Atomic line data from the NIST database with additional data from the Opacity Project.
 - Stark broadening widths from a combination of experimental and theoretical sources.
 - Detailed atomic photoionization cross-sections from the TOPbase.
 - Negative ion photodetachment cross-sections from theoretical sources.
- Applies the smeared-rotational band (SRB) method for molecular band radiation.
- Atomic and molecular electronic state populations modeled using recently compiled electron-impact excitation rates.
- Tangent-slab radiation transport applied.
- Typical computational time for a single line-of-sight is 20 - 50 seconds.
- Radiation updates implemented on order of 300 to 3000 relaxation steps in flow solver with user specified update fraction.



LAURA 5 -- Part III: Examples & Challenges

Aerothermodynamics Branch



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TFAWS-2010

August 18, 2010

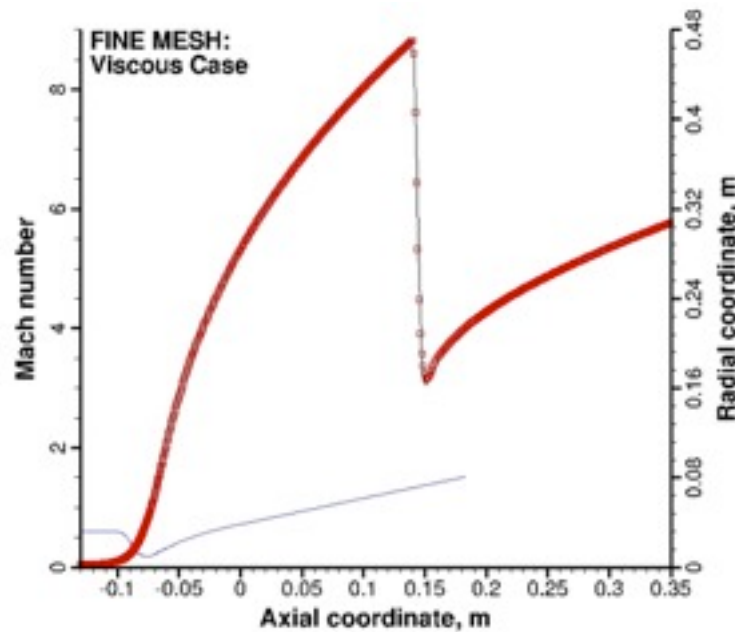
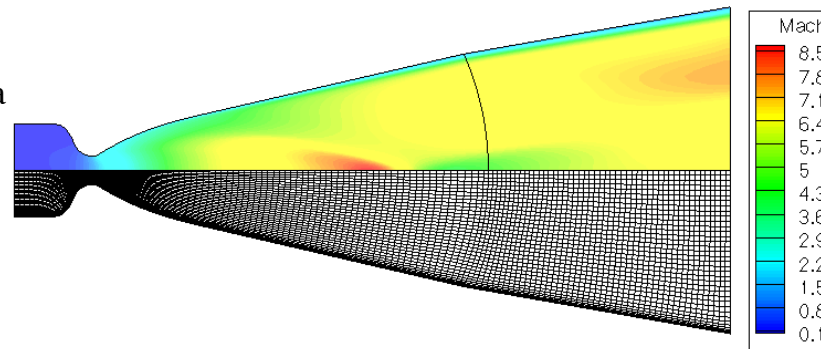
Nozzle-only solution:

$$P_0 = 2.1357 \text{ Mpa}$$

$$T_0 = 300. \text{ K}$$

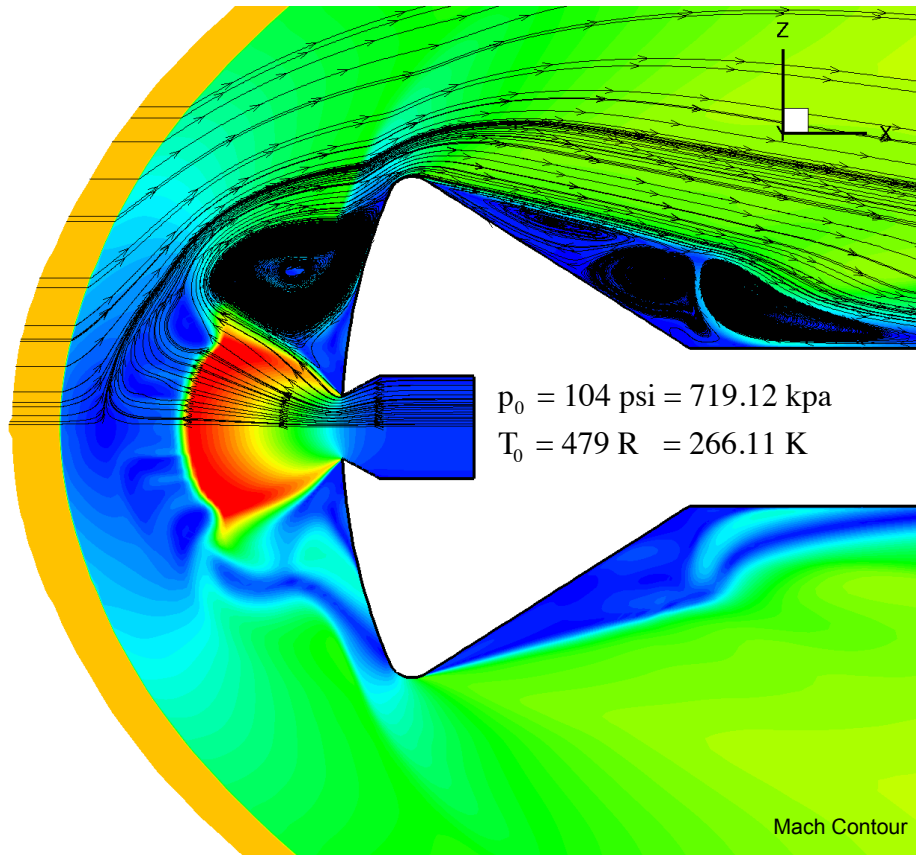
$$N_2 = 92\%$$

$$H_2 = 8\%$$



Supersonic Retro Propulsion (SRP) with 2.6% Apollo Capsule

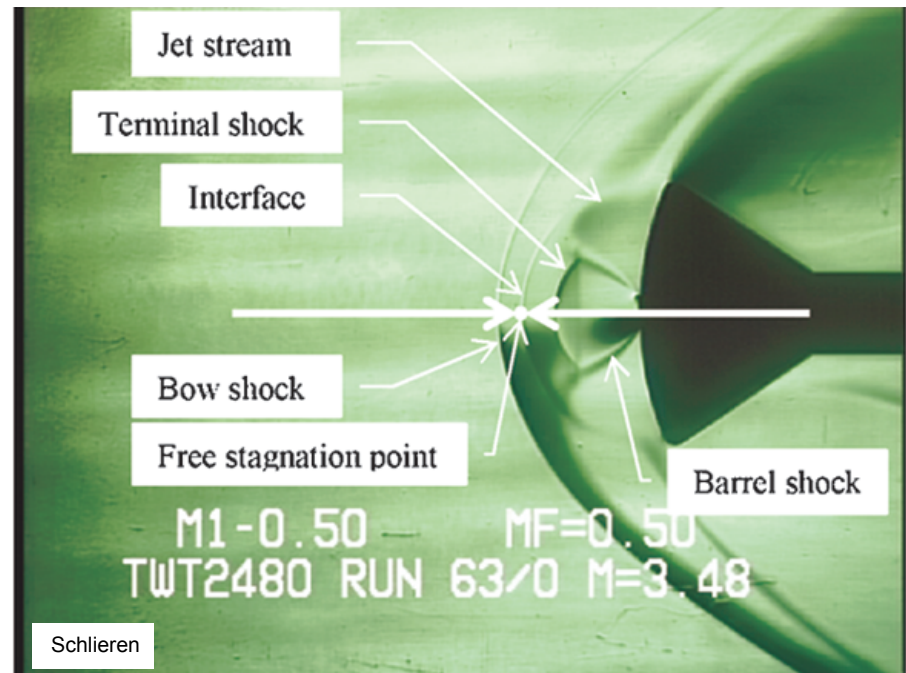
$v_\infty = 690.3 \text{ m/s}$, $T_\infty = 97.3\text{K}$, $\text{Mach} = 3.48$



CFD Solution

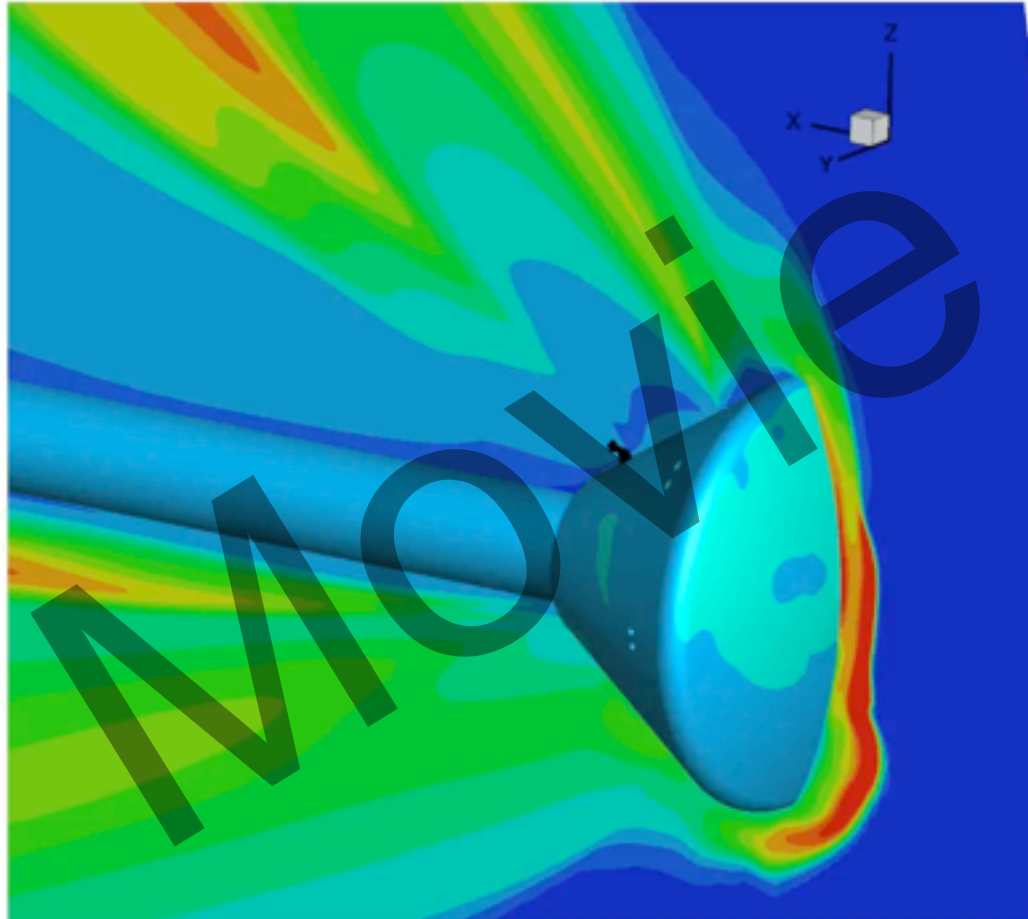
Comparison between the computed and measured data

	CFD (LAURA 5)	Exp. (Daso et al)	Diff, %
δ / D	0.555	0.54	2.8



Taken from Daso et al AIAA J, Vol. 47(6), 2009

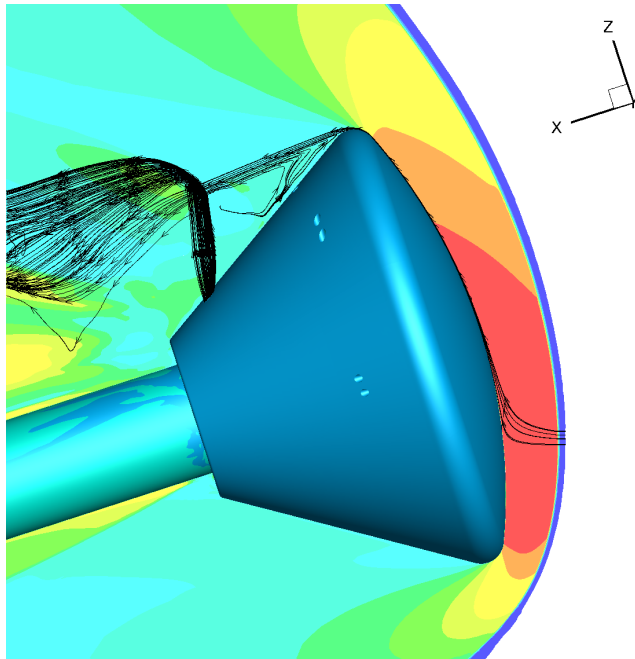
Reaction Control System (RCS) with 5% CEV Capsule



This movie shows the evolution of the solution.

Reaction Control System (RCS) with 5% CEV Capsule

The CUBRC Schlieren movie shows the same behavior as observed in LAURA-5 CFD.

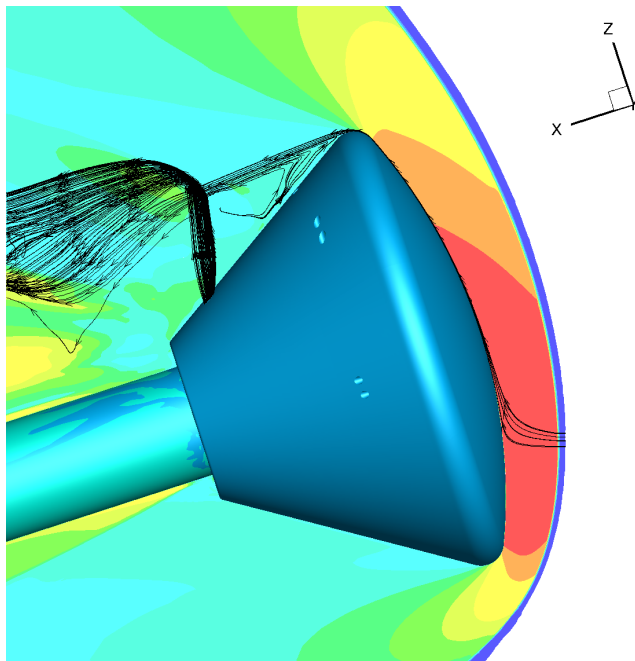


Temperature contour with PD streamlines

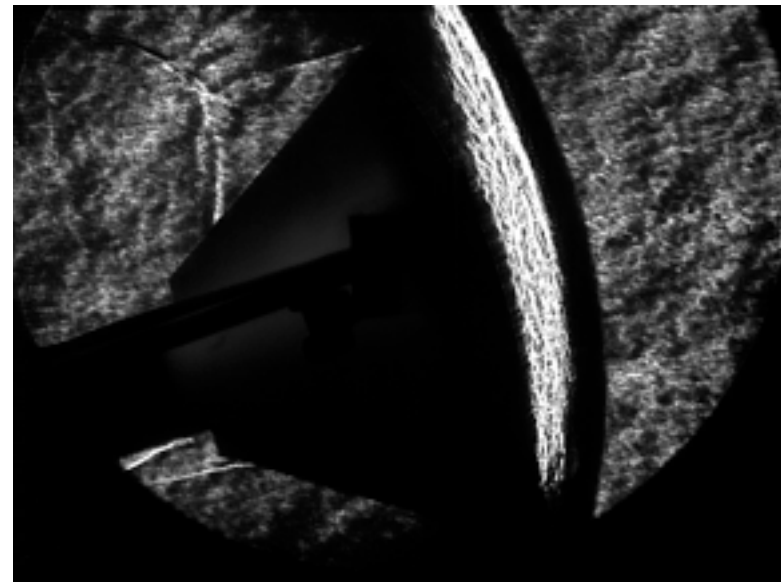
CUBRC Schlieren movie

Reaction Control System (RCS) with 5% CEV Capsule

The CUBRC Schlieren movie shows the same behavior as observed in LAURA-5 CFD.



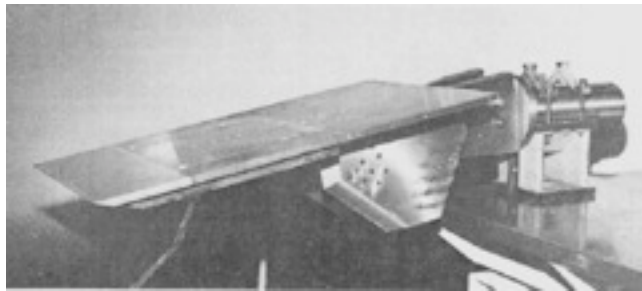
Temperature contour with PD streamlines



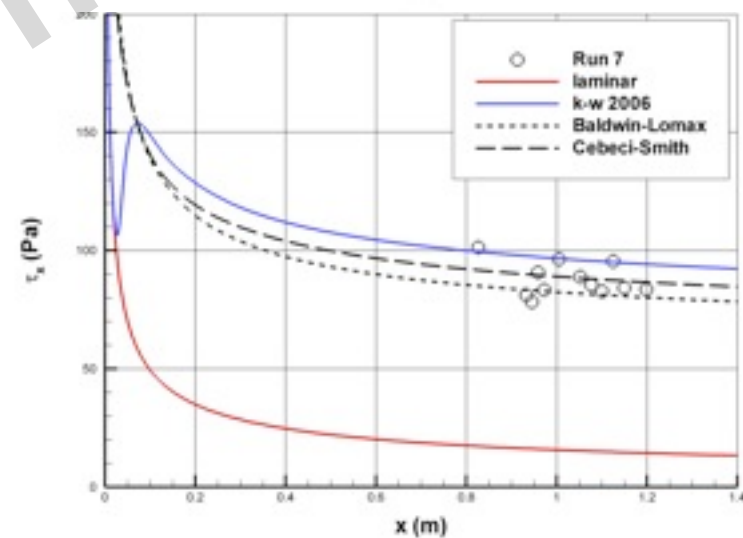
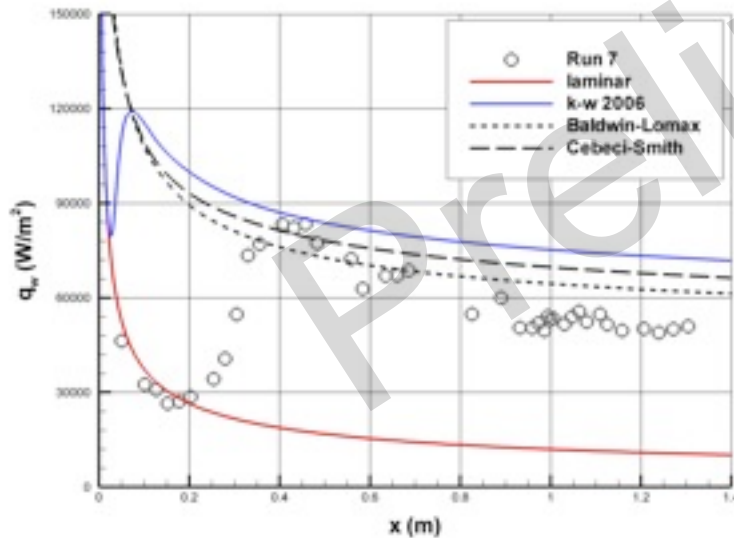
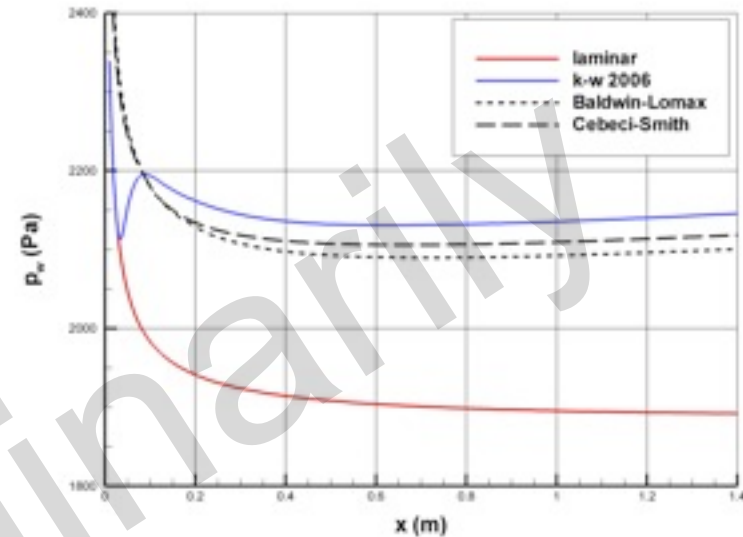
CUBRC Schlieren movie

Part 3: LAURA 5 Examples & Challenges

CUBRC Run 7: Laminar/Turbulent Flat Plate

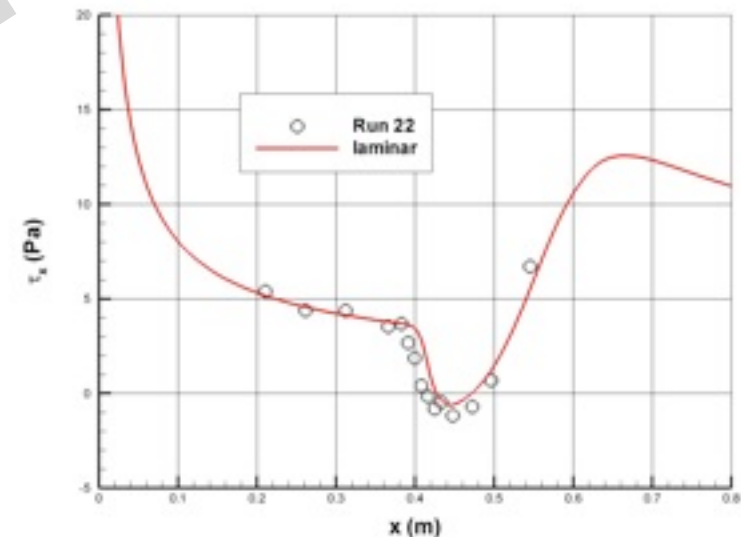
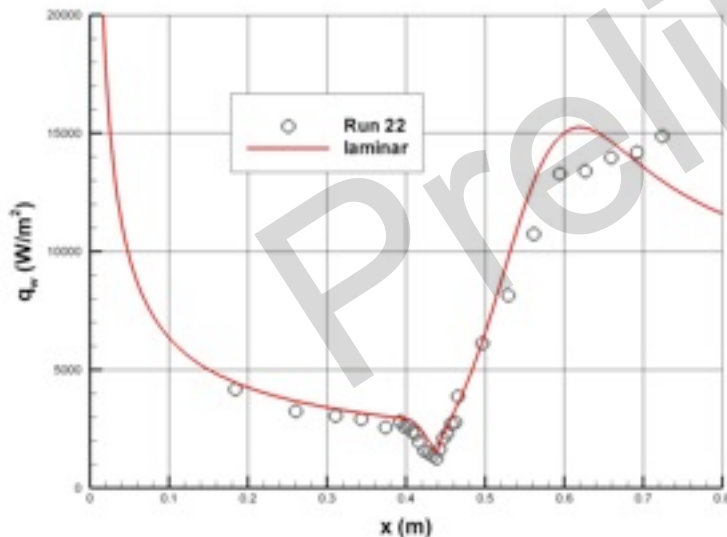
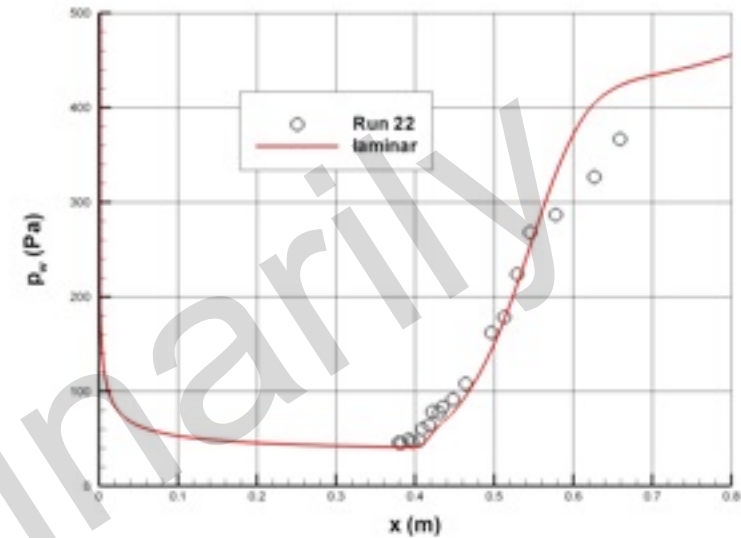
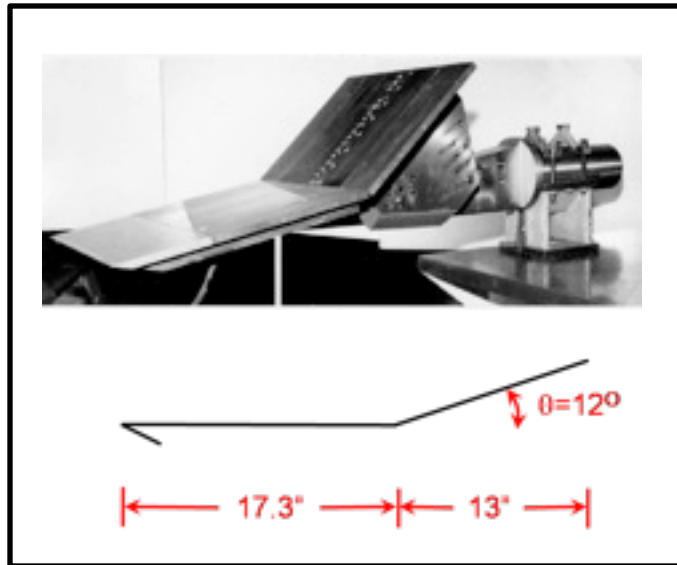


- flat plate only
- 0° angle of attack
- transition



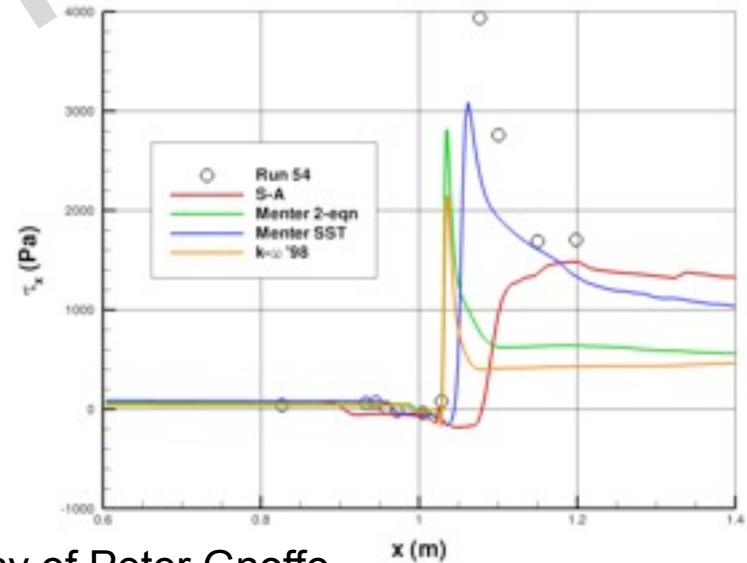
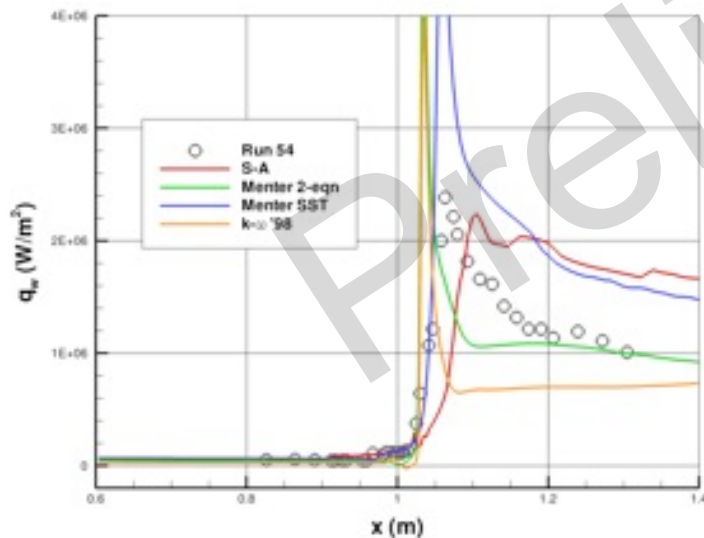
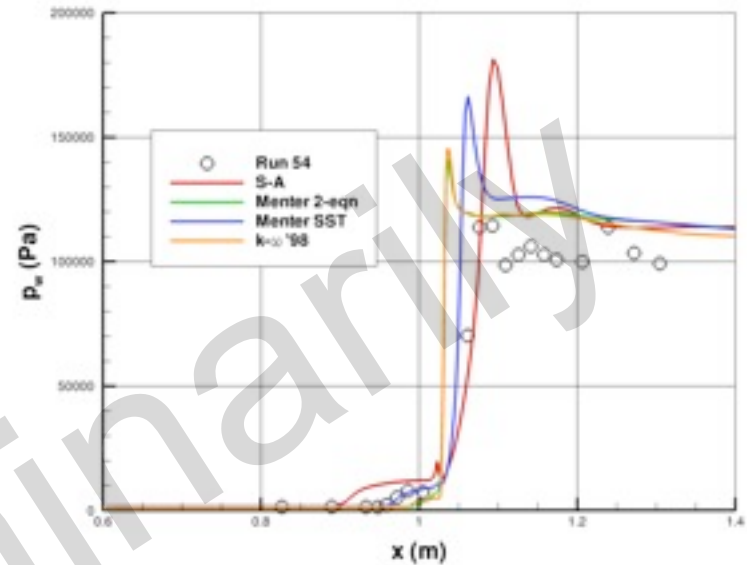
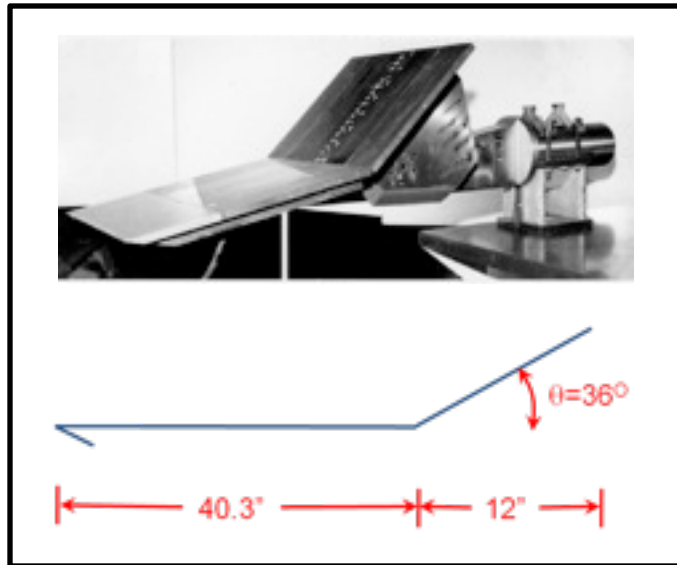
Modeling: Courtesy of Peter Gnoffo.

Part 3: LAURA 5 Examples & Challenges CUBRC Run 22: Laminar Wedge (12°)



Modeling: Courtesy of Peter Gnoffo.

Part 3: LAURA 5 Examples & Challenges CUBRC Run 54: Turbulent Wedge (36°)



Modeling: Courtesy of Peter Gnoffo.



LAURA 5 -- Part IV: Live Examples

Aerothermodynamics Branch



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TFAWS-2010

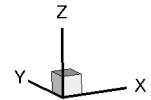
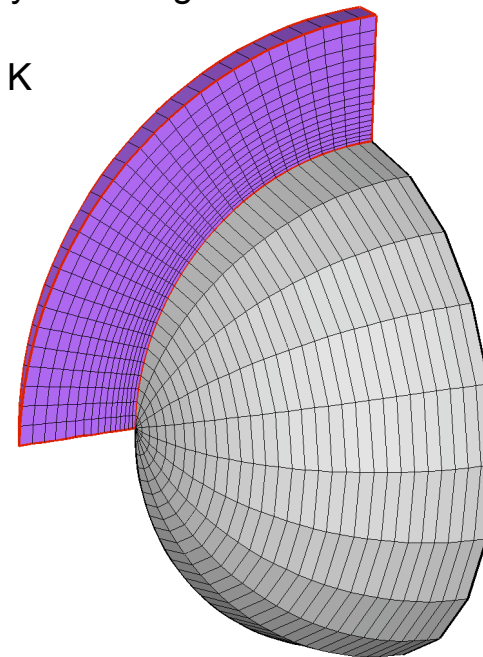
August 18, 2010

Example 1: hemisphere_pg_air

- **Gas model:** perfect gas air
- **Geometry:** 1-m in radius hemisphere
- **Free stream condition:** $U = 5$ km/s, $T = 200$ K, Density = 0.01 kg/m³
- **Surface condition:** Constant wall temperature of 300 K

You will learn how:

- ▶ to generate grid using ***self_start***
- ▶ to set boundary conditions
- ▶ to activate point- and/or line-implicit
- ▶ to setup and modify input decks



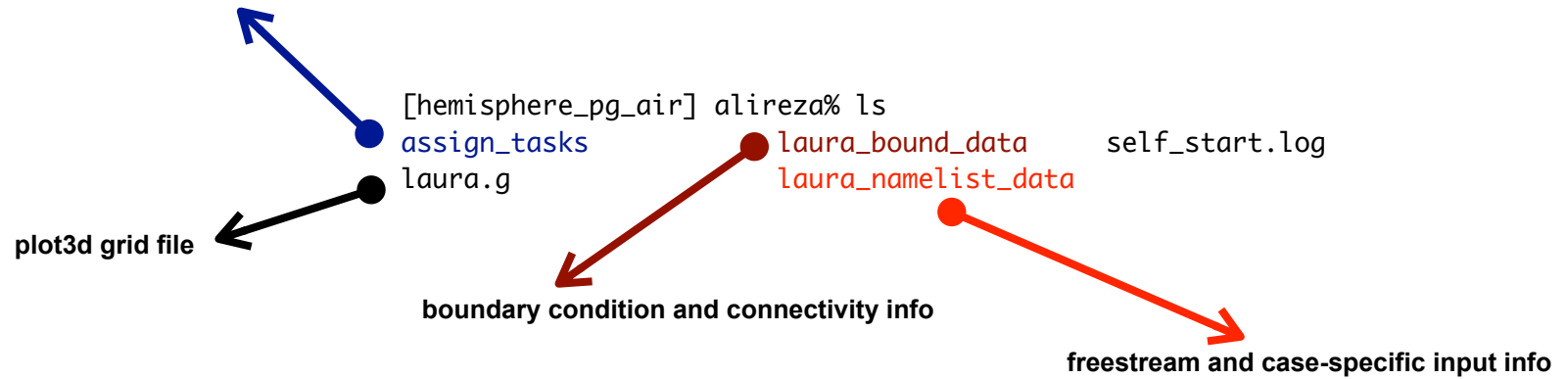
Part 4: Live Examples



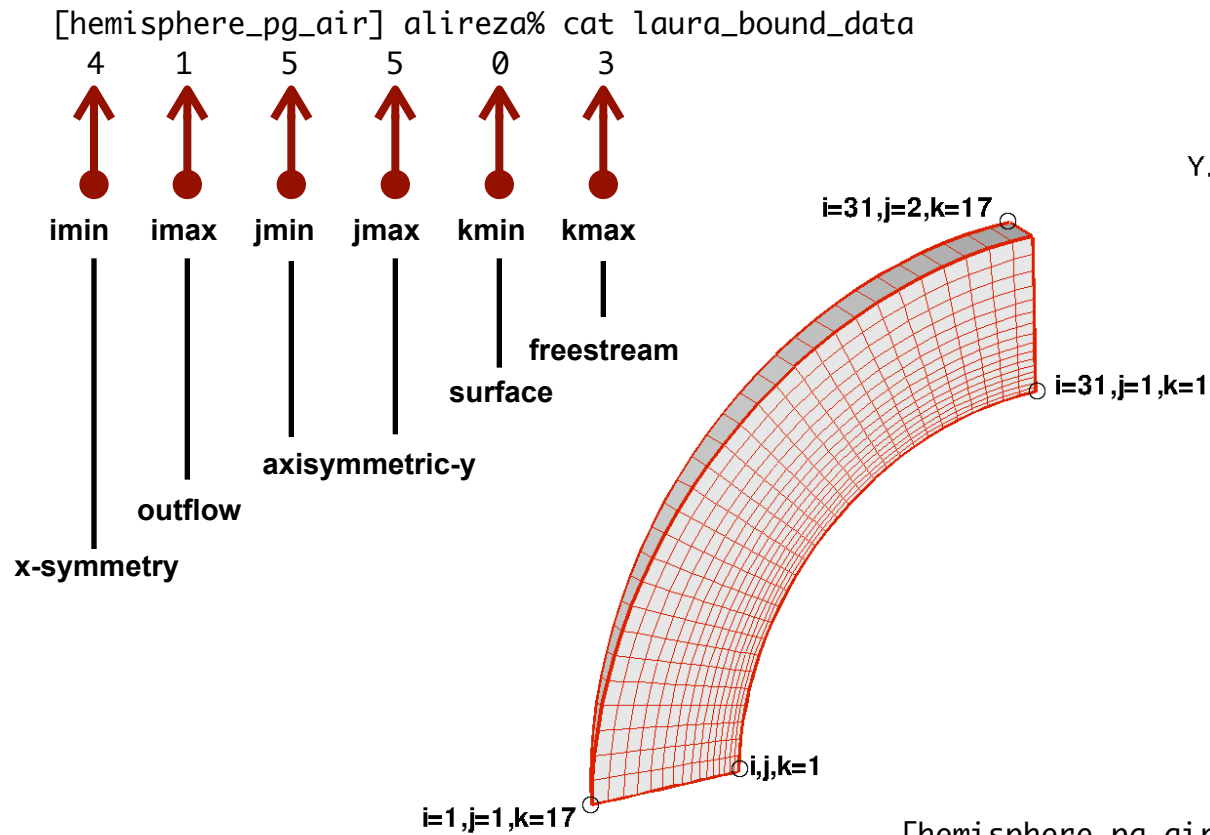
- **run *self_start* to create a grid:**

```
[hemisphere_pg_air] alireza% ./self_start
Select dimensionality:
1 = Axisymmetric
2 = Two-dimensional
3 = Three-dimensional
1
1 axisymmetric body
Select geometry:
1 = Conic (cone/wedge, paraboloid, etc.).
2 = Aerobrake (includes AFE without axis singularity).
2
2 aerobrake
Select aerobrake type:
0 = AFE
1 = hemisphere
2 = customized aerobrake
1
1 hemisphere
Enter radius (m) {      1.000000}:
1
1. radius (m)
Select number of cells along symmetry plane.
30
30 cells along symmetry plane
Enter number of cells in k direction, prior to any doubling
16
16 k-direction cells prior to doubling
```

relaxation and sweep directions info



Part 4: Live Examples



[hemisphere_pg_air] alireza% cat assign_tasks

blk#	sweep.dir	relax.dir	istart	iend	not used
1	3	0	1	0	1

- Modify the *laura_namelist_data* file:

```
&laura_namelist
```

```
velocity_ref = xxxx ! reference velocity, m/s
density_ref  = xxxx ! reference density, kg/m^3
tref         = xxxx ! reference temperature, K
alpha        = xxxx ! pitch angle, degrees
twall_bc     = xxxx ! initial wall temperature, K
```

```
chem_flag = 0 ! 0 chemically frozen, 1 chemical source on
therm_flag = 0 ! 0 thermally frozen, 1 thermal source on
irest      = 0 ! 0 for fresh start, 1 for restart
```

```
ncyc = 5000 ! global steps
```

```
jupdate = 4 ! steps between update of jacobian
ntran    = 4 ! steps between update of transport properties
nitfo    = 1500 ! number of 1st-order relaxation steps
iterwrt  = 200 ! steps between saves of intermediate solution
rf_inv   = 3.0 ! inviscid relaxation parameter
rf_vis   = 1.0 ! viscous relaxation parameter
```

```
movegrd = 350 ! number of steps between calls to align_shock
maxmoves = 0 ! maximum number of calls to align_shock
```

```
re_cell = 0.1 ! target cell reynolds number at wall
```

```
fsh = 0.6 ! target bow shock position arc length fraction
```

```
kmax_error = 0.01 ! error norm triggering k-cell increase
```

```
kmax_final = 64 ! final number of k-cells
```

```
nexch = 2 ! steps between exchange of info in mpi
```

```
frac_line_implicit = 0.7 ! fraction of line by block tri-dia
```

```
surface_temperature_type_0 = 'constant'
```

```
catalysis_model_0 = 'super-catalytic'
```

```
emiss_a_0 = 0.89
```

```
ept = 0.010 ! relaxation factor on read eq wall bc
```

```
dimensionality = 'axisymmetric'
```

```
xmc = 0.0000
```

```
ymc = 0.0000
```

```
zmc = 0.0000
```

```
grid_conversion_factor = 1.0000
```

```
sref = 0.43633E-01
```

```
cref = 2.0000
```

```
/
```

change to

```
velocity_ref = 5000.
density_ref = 0.01
tref = 200.
alpha = 0.
twall_bc = 300.
```

change to

```
ncyc = 7000
```

change to

```
maxmoves = 15
```

change to

```
fsh = 0.8
```

- At this point LAURA does not know anything about the gas model ... tdata file defines the gas model:

```
[hemisphere_pg_air] alireza% cat tdata  
perfect_gas
```

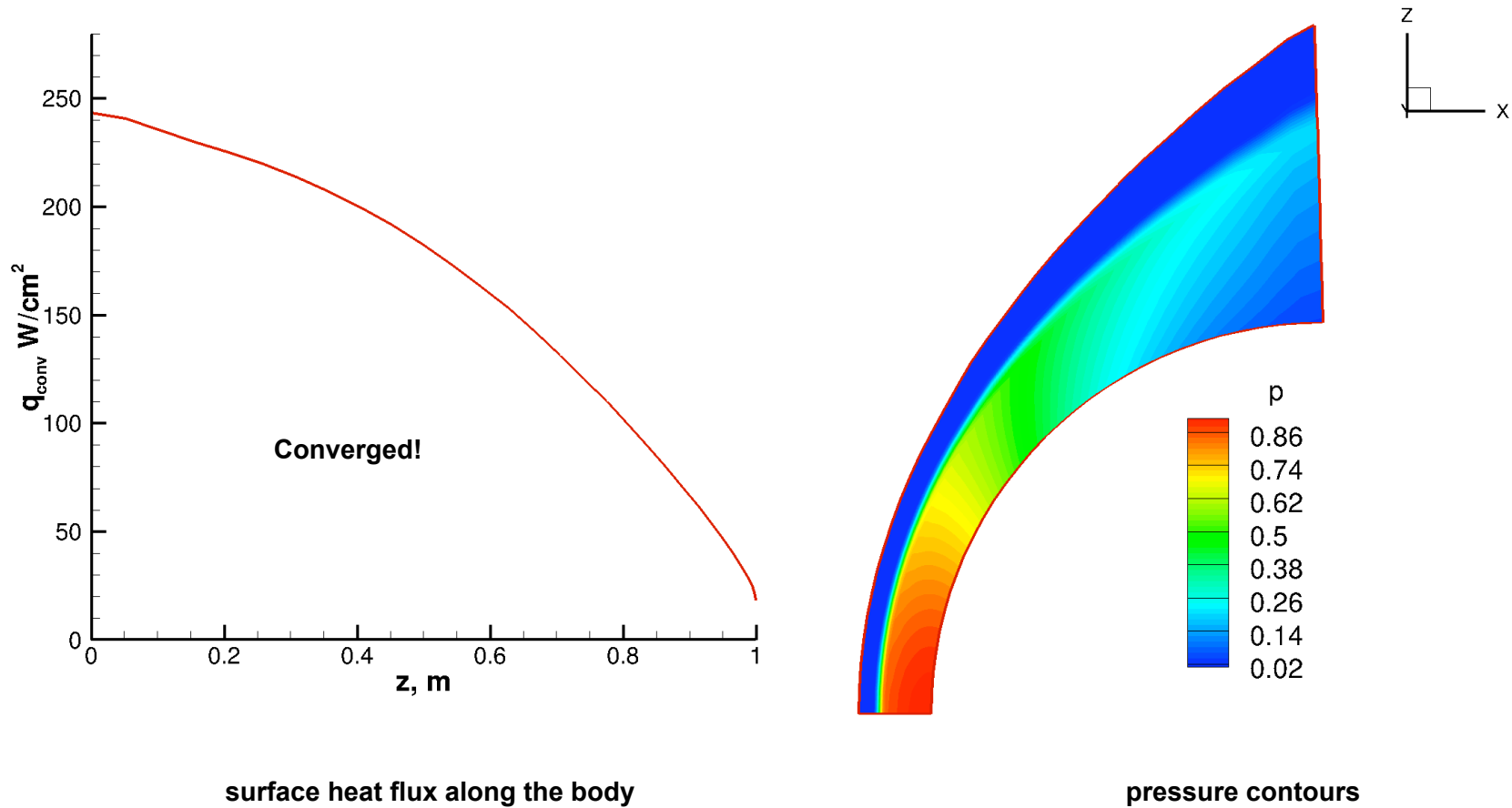
```
&species_properties  
gamma = 1.4  
mol_wt = 28.0  
suther1 = 0.1458205E-05  
suther2 = 110.333333  
prand = 0.72  
/
```

This portion of the file is optional!

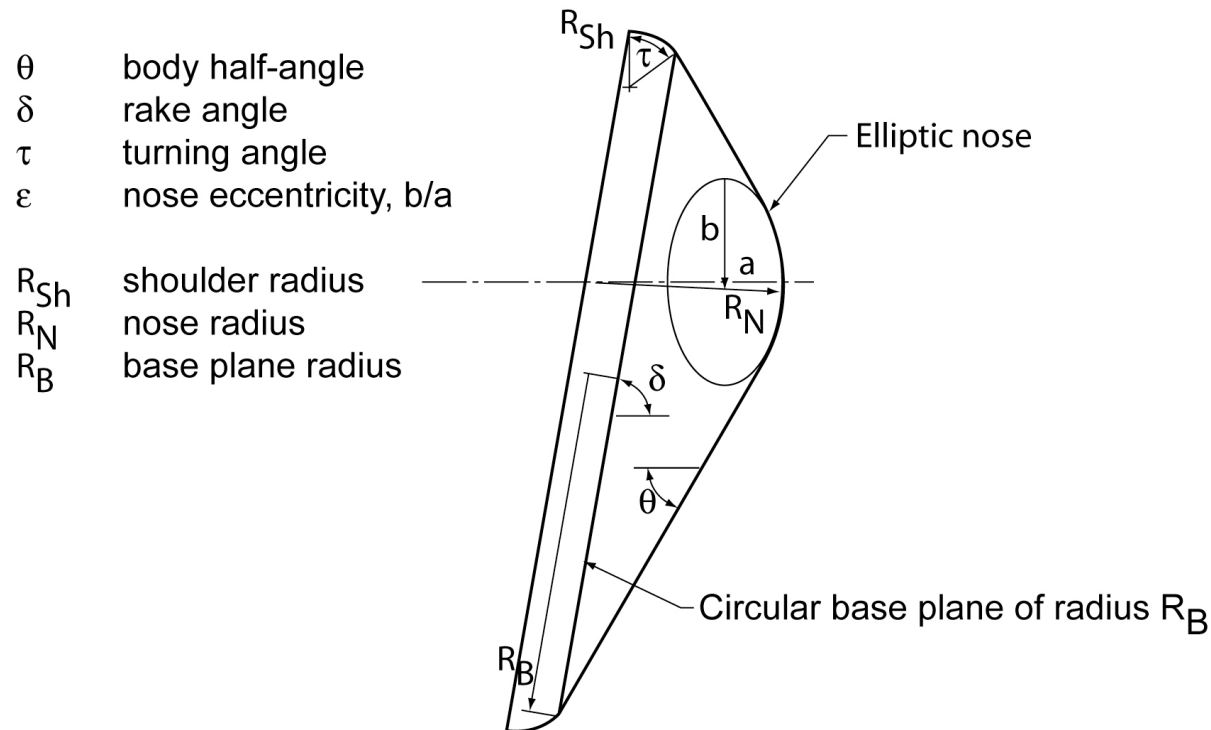
$$\mu = s_1 \frac{T^{3/2}}{T + s_2}$$

Solutions to perfect gas axisymmetric hemisphere

(results after total of 10,000 iterations--residual 1E-10)



self_start utility:





Suggest a geometry to be solved in the class!



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