



ARC · 2016

An Introduction to DPLR

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What is Aerothermodynamics?

- ◆ **Accurate and conservative prediction of the heating environment encountered by an Earth or planetary entry vehicle**
- ◆ **Aerothermal modeling is completely coupled and entwined with Thermal Protection System (TPS) design**
 - The TPS is designed to withstand the predicted environment with risk-appropriate margin
 - The flowfield and TPS interact with each other in non-reversible manner; the physics themselves are coupled
- ◆ **At its core, aerothermodynamics becomes the study of an energy balance at the surface of the material**
 - Experimental - ground and flight testing
 - Engineering approximations
 - **Computational fluid dynamics**
 - Shock layer radiation transport
 - Direct Simulation Monte-Carlo for rarified flows



Principles of Aerothermal Models

Planetary Atmospheres

Mars&Venus: CO₂/N₂
Titan: N₂/CH₄
Giants: H₂/He
Earth: N₂/O₂

Hot Shock Layer (up to 20000 K)

Thermochemical nonequilibrium, Ionization, Radiation

Boundary Layer (2-6000 K)

Transport properties, Ablation product mixing, Radiation blockage

V

"Cool" Surface (2-3000 K)

Surface kinetics, Ablation

Thermal Protection System (TPS)

Afterbody Flow
Unsteady non-continuum vortical flowfield

Surface Energy Balance

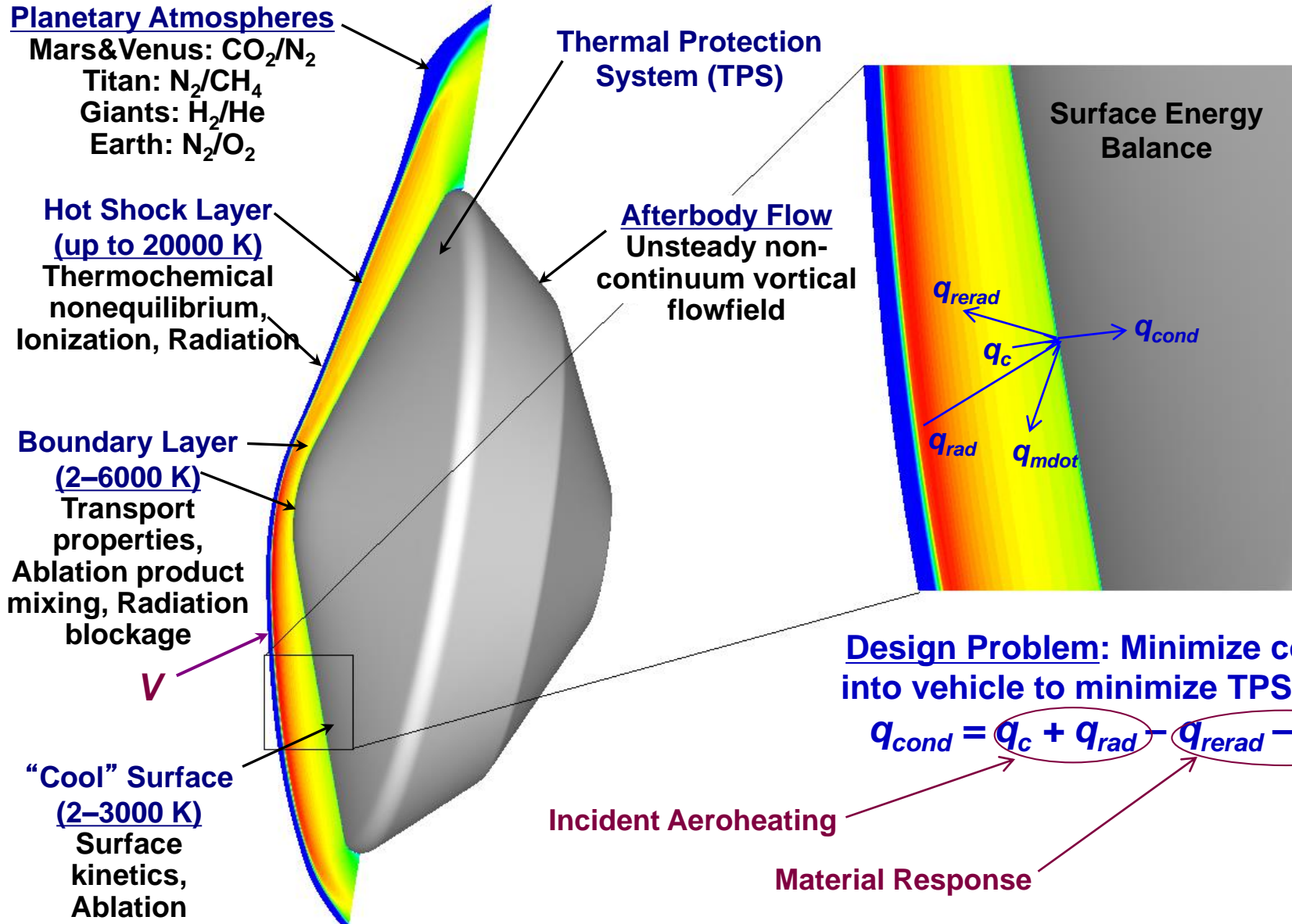
q_{rerad}
 q_c
 q_{rad}
 q_{mdot}
 q_{cond}

Design Problem: Minimize conduction into vehicle to minimize TPS mass/risk

$$q_{cond} = q_c + q_{rad} - q_{rerad} - q_{mdot}$$

Incident Aeroheating

Material Response





Why is Aerothermal Modeling Important?

- Heat flux (with pressure & shear) used to select TPS material
- Heat load determines TPS thickness

Can't we just 'cover up' uncertainties in aerothermal modeling with increased TPS margins?

- Sometimes, but:
 - Margin increases mass; ripple effect throughout system
 - Without a good understanding of the environment risk cannot be quantified; benefits of TPS margin cannot be traded with other risk reduction strategies
 - Margin cannot retire risk of exceeding performance limits
 - For some missions (i.e. Neptune aerocapture, Jupiter polar probe), improved aerothermal models may be enabling

Can't we retire all uncertainties via testing?

- No!
 - No ground test can simultaneously reproduce all aspects of the flight environment. A good understanding of the underlying physics is required to trace ground test results to flight.
 - Flight testing should be reserved for model and system validation, after we have good physics-based models of the expected environment



Extended Navier-Stokes Equations for Nonequilibrium Reacting Flows

• Species Continuity (ns equations):

$$\frac{\partial \rho_s}{\partial t} + \frac{\partial}{\partial x_j} (\rho_s u_j + \rho_s v_{sj}) = \dot{w}_s$$

• Momentum (3 equations)

$$\frac{\partial}{\partial t} (\rho u_i) + \frac{\partial}{\partial x_j} (\rho u_i u_j + p \delta_{ij}) + \frac{\partial \tau_{ij}}{\partial x_j} = 0$$

• Total Energy Conservation (1 equation)

$$\frac{\partial E}{\partial t} + \frac{\partial}{\partial x_j} ((E + p)u_j) + \frac{\partial}{\partial x_j} \left(q_j + \sum_k q_{kj} \right) + \frac{\partial}{\partial x_j} (u_i \tau_{ij}) + \sum_s \frac{\partial}{\partial x_j} (v_{sj} h_s) = -\nabla \cdot Q_R$$

• Species Energy (ne equations)

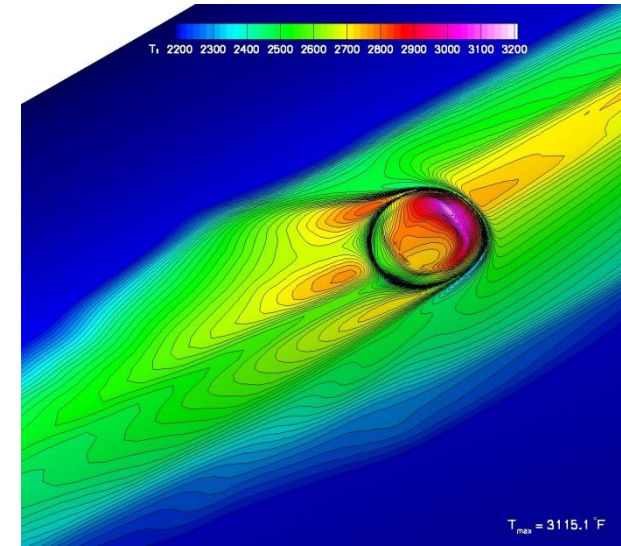
$$\frac{\partial}{\partial t} (\rho e_k) + \frac{\partial}{\partial x_j} (\rho e_k u_j) + \frac{\partial}{\partial x_j} (\rho e_k v_{sj} + q_{kj}) = \dot{Q}_k$$



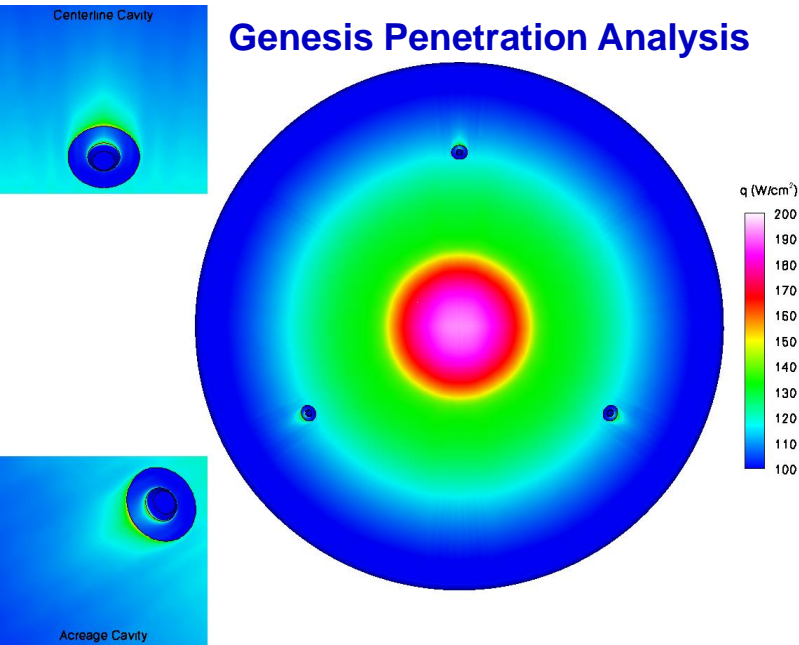
CFD Process for Entry Vehicle Design

- High fidelity CFD tools based on 20-year old methodologies
- Recent advances in parallel computing, efficient implicit algorithms have enabled rapid turnaround capability for complex geometries
- Full body three-dimensional CFD is an integral part of the design of all planetary and Earth entry TPS

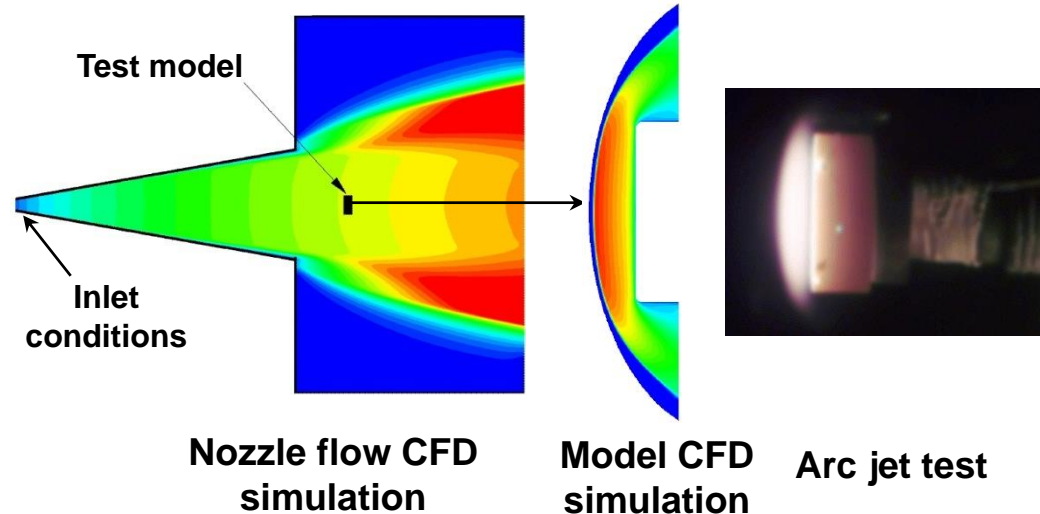
Shuttle RCC Repair
Concept Evaluation



Genesis Penetration Analysis



Arc Jet Model Simulation



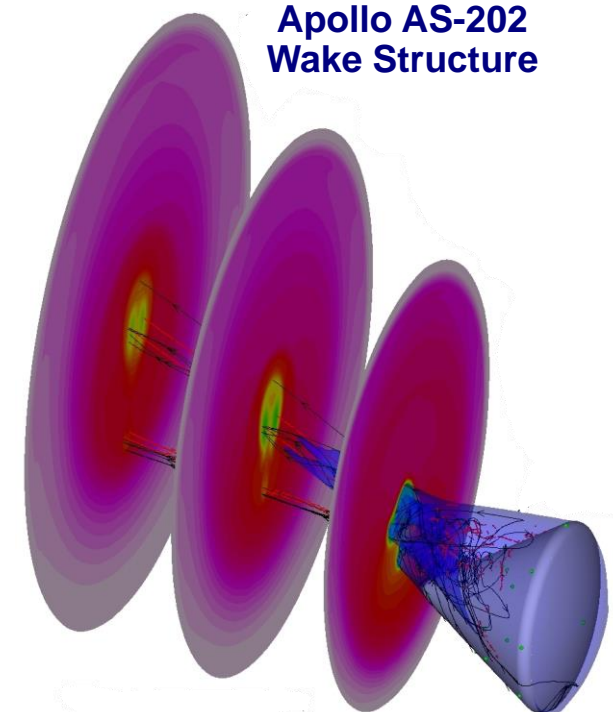
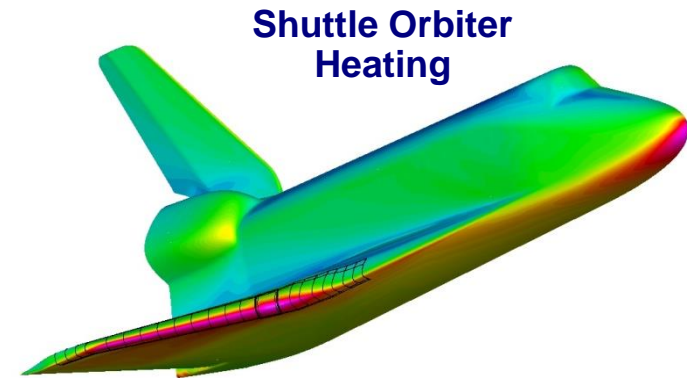


CFD Process: Status and Development for Planetary Entry

What are the “long poles” in the current state-of-the-art?

- **Winged Vehicles (High L/D, orbital entry velocity)**
 - geometry driven; ~80% of design time to convert CAD files to volume grids
 - RTF demonstrates rapid turnaround capabilities
 - acreage environment reasonably well understood - conservative predictions are possible

- **Planetary Probes (Low to Mid L/D, hyperbolic velocity)**
 - physics driven: complex flow modeling required to simulate high velocity entries
 - fluid dynamics, radiation, material response, shape change can all be physically coupled
 - understanding these processes is necessary to quantify/reduce uncertainty and increase payload of future science and exploration missions





What DPLR is

- **Ames-Developed Hypersonic Continuum CFD Code**
 - Physical models sufficient for high speed Earth and planetary entry
 - Massively parallel efficient algorithm permits rapid turnaround times
 - In house development allows source-control
 - Generality makes incorporation of new physics models straightforward
 - Validation is ongoing (Fire-II, Apollo, Shuttle)
 - Calibration with heritage codes (GASP, LAURA) permits leveraging of extensive validation of those codes

Co-Winner of NASA Software of the Year (2007)

**>40 unique installations at NASA centers, gov' t labs,
contractors, and universities**



What DPLR isn't

- **DSMC (can only solve problems in continuum regime)**
 - Slip wall boundary conditions in place to allow limited extension to transitional flows
- **Unstructured (fully point-matched structured grids are required)**
 - Overset grid capability as of v4-01-0
 - US3D is an unstructured grid solver
- **Radiation or material response solver**
 - Hooks are provided for external analysis by other tools (NEQAIR, FIAT)
 - Coupled optically thin radiation analysis does exist
 - Generalized Gas-surface interaction framework and some models for carbon materials are available



The DPLR Package

- **Four Codes:**
 - **DPLR2D:** axisymmetric/2D solutions
 - **DPLR3D:** three-dimensional solutions
 - **FCONVERT:** grid pre-processor
 - **POSTFLOW:** solution post-processor

- **Provided Utilities:**
 - *dpinputs:* update old input decks
 - *zbconvert:* convert format of zonal interface data
 - *seqinput:* sequence an input deck

- **“Third Party” Utilities:**
 - *Outbound:* grid alignment and reclustering
 - *Template:* input deck setup
 - *BLAYER:* extraction of boundary layer data
 - **Radial Interp**



DPLR: The Saga

Version	Released	Improvements
DPLR v3-05-0	6-2006	Software of the year!
DPLR v4-01-0 Denali	2-2009	Major fixes since v3-05-0 hiatus
DPLR v4-01-1 Arcadia	6-2009	Dual-time and Overset grids
DPLR v4-01-2 DryTortugas	-	Moved into v4-02-0, TSA only
DPLR v4-02-0 Yosemite	9-2009	Free-format input, revamped time accuracy and statistics, better grid smoothing, point extraction
DPLR v4-02-1 HotSprings	4-2010	Reduced memory footprint, dpinputs utility
DPLR v4-02-2 Zion	1-2011	Usability improvements, time accurate and statistics fixes Spallart-Almaras DES
DPLR v4-03-0 BigBend	3-2012	GSI (finite rate surface chemistry), PETSc/GMRES solver, reduced dual-time memory footprint
DPLR v4-03-1 Roosevelt	12-2012	preliminary HDF5 support format, usability improvements
DPLR v5-00-0 Yellowstone	TBD	NEQAIR coupling, BC API, Fluid structure interaction, numerical Jacobians?



DPLR Implementation

- **Parallel implementation**
 - **Requires MPI for implementation, even on single processor**
 - **Can be run on shared memory computers, distributed memory cluster**
 - **Implicit method optimized for parallel performance**

- **Fortran 90**
 - **About 55,000 lines of source for all four programs**

- **Optional links to BLAS, Tecplot®, XDR libraries**

- **Optional Overset grid capability with SUGGAR & DiRTLIB.**

- **Some (intentional) superficial similarity to GASP®**
 - **BC numbering, interface file format**

- **Full users manual**
 - **Hands on training still required**



DPLR - Numerical Modeling

- **Parallel generalized multiblock finite-volume code**
- **3rd-order accurate modified Steger-Warming Euler fluxes**
- **2nd-order accurate central-differenced viscous fluxes**
- **2nd-order accurate in time with dual time stepping**
- **Data-Parallel Line Relaxation for implicit time advancement**
- **Efficient numerical methods and parallelism lead to significant (> order of magnitude) speedups over traditional solvers**
- **Built in routine to adapt grid to bow shock location**

- **In-house development of source allows for rapid modifications to handle new physical models or boundary conditions**



DPLR - Physical Modeling

- **Reacting Navier-Stokes equations**
 - **Finite-rate (nonequilibrium) chemistry or perfect gas**
 - **Generalized chemistry modeling makes new mechanism import simple**
- **Laminar or turbulent flow models**
 - **Baldwin-Lomax, Spalart-Allmaras, and SST models all in place**
 - **User-specified transition maps**
- **2D, axisymmetric, and 3D flows**
 - **Separate driver for 2D flows allows for rapid solution turnaround**
 - **1D space-marching option for shock-tube simulations**
- **Thermal equilibrium or nonequilibrium**
 - **Vibrational and/or rotational nonequilibrium can be selected at runtime**
- **Accurate collision-integral based transport models, including multicomponent diffusion (SCEBD)**
- **Fully coupled solution for optically thin radiation**
- **Hooks for loose coupling to radiation or material response codes**



DPLR - Boundary Conditions

- **All boundary conditions can be (optionally) specified as pointwise during problem setup**
 - profiles, wall temperatures
 - material maps, transition maps
- **Solid walls**
 - viscous/inviscid walls
 - isothermal/radiative equilibrium
 - material-specific finite rate catalycity and emissivity
 - slip walls and mass blowing
 - input material map option permits modeling of material splitlines
- **Supersonic inflow/outflow, planes of symmetry**
- **Singular axes**
- **Characteristic based subsonic inflow/outflow**
- **Boundary conditions implemented implicitly for maximum robustness and convergence**



DPLR - Process

- 1. Generate structured multiblock volume grid**
 - Third-party grid generator, plot3d format
- 2. Run FCONVERT to convert grid for DPLR use**
 - Either hand-compute interfaces or use auto-detect feature
 - Select number of processors to run use and decompose accordingly
- 3. Setup DPLR input deck**
 - Specify physical models, numerical models, BC's, freestream conditions
 - Input deck is set up according to number of master blocks
- 4. Run DPLR solution**
 - One or more grid adaptations may be required using OutBound or inline procedure
- 5. Perform quality/sanity checks as appropriate**
- 6. Extract desired output quantities using POSTFLOW**
- 7. View result using Tecplot® or favorite visualization tool**



How Fast is DPLR?

The answer is strongly dependent on the physics of the problem and the available computer, however as a general rule:

- **Axisymmetric forebodies:** **seconds to minutes**
 - 3000 Mars cases are run overnight on 8 CPU to support Monte-Carlo sensitivity analysis
 - **Axisymmetric afterbodies:** **minutes to an hour**
 - Stardust cases required about one hour on 10 CPU
 - **3D forebodies:** **minutes to an hour**
 - Mars Science Laboratory cases run in 40 min on 8 CPU
 - **3D afterbodies:** **hours**
 - Apollo cases with 1.5 million grid points run in about 12 hours on 16 CPU
 - **Lifting vehicles:** **see final chart for Orbiter examples**
- ⇒ **In all cases more processors = faster turnaround**

**In general far more time is spent in setting up the problems,
understanding the solutions, turning them into useful
design data and performing sensitivity studies to help with TPS design**

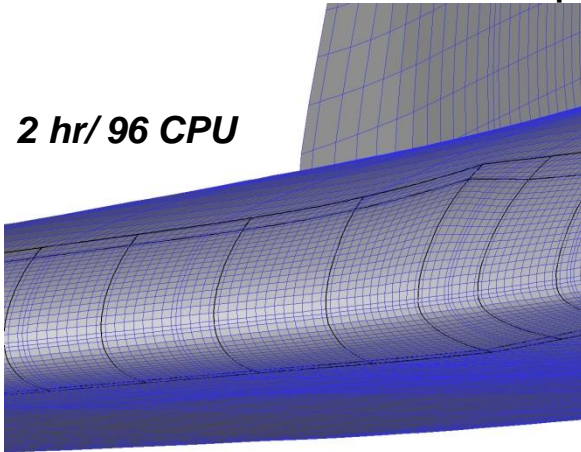


Scalability for Large Complex Problems

- DPLR ported to NAS Altix in support of Shuttle Return to Flight
- Three calculations completed demonstrating grid resolution on wing leading edge:

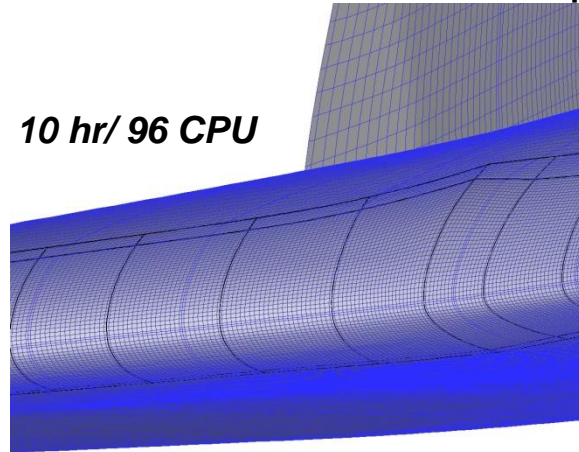
Coarse: 2.03 million pts.

2 hr/ 96 CPU



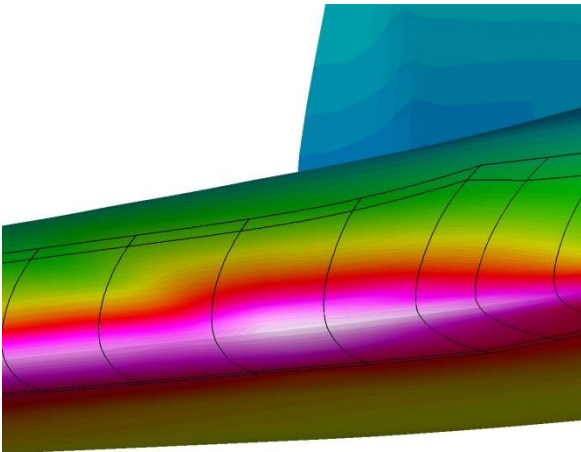
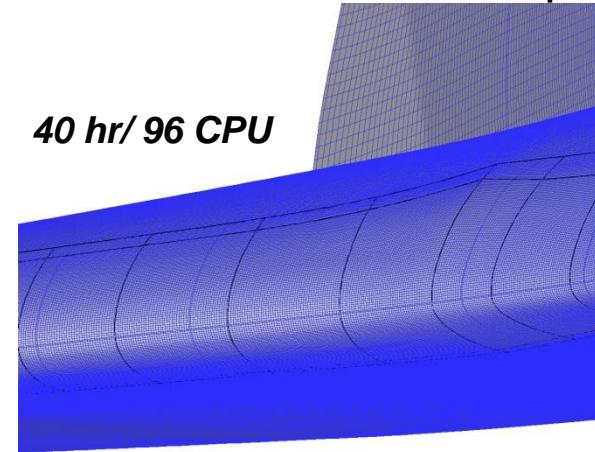
Medium: 7.62 million pts.

10 hr/ 96 CPU

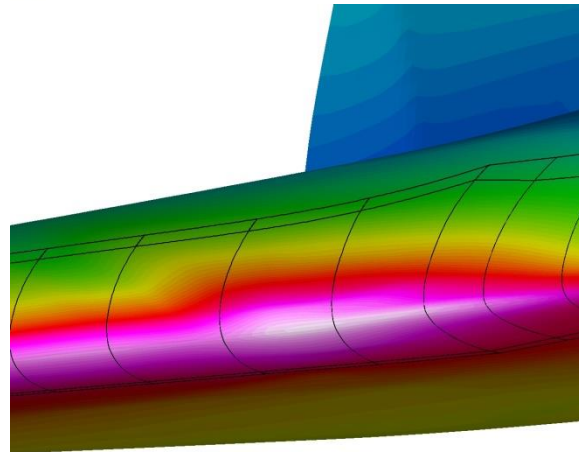


Fine: 29.5 million pts.

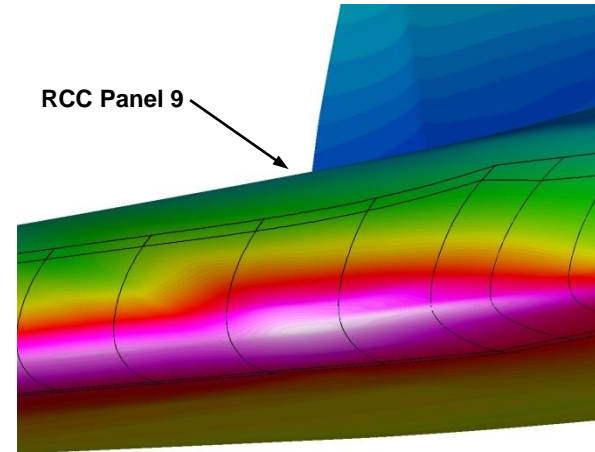
40 hr/ 96 CPU



T, K
200 360 520 680 840 1000 1160 1320 1480 1640 1800



T, K
200 360 520 680 840 1000 1160 1320 1480 1640 1800



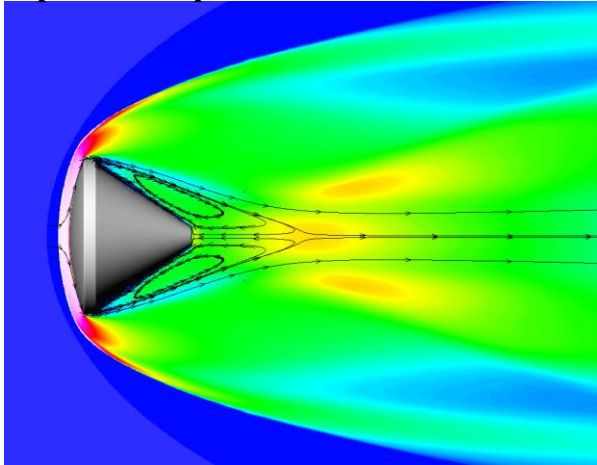
RCC Panel 9

T, K
200 360 520 680 840 1000 1160 1320 1480 1640 1800

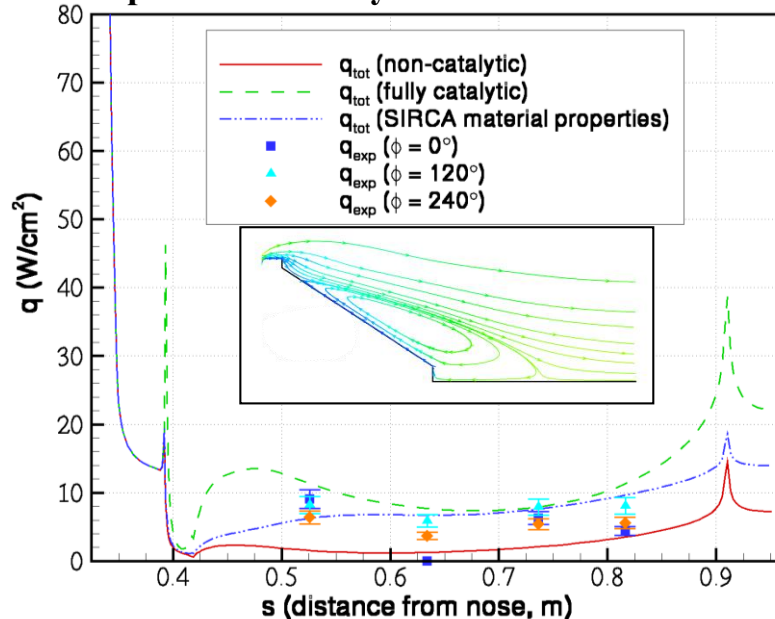


Applications: Fire II Reentry Vehicle

Pitch plane temperature contours at $t = 1634$ s

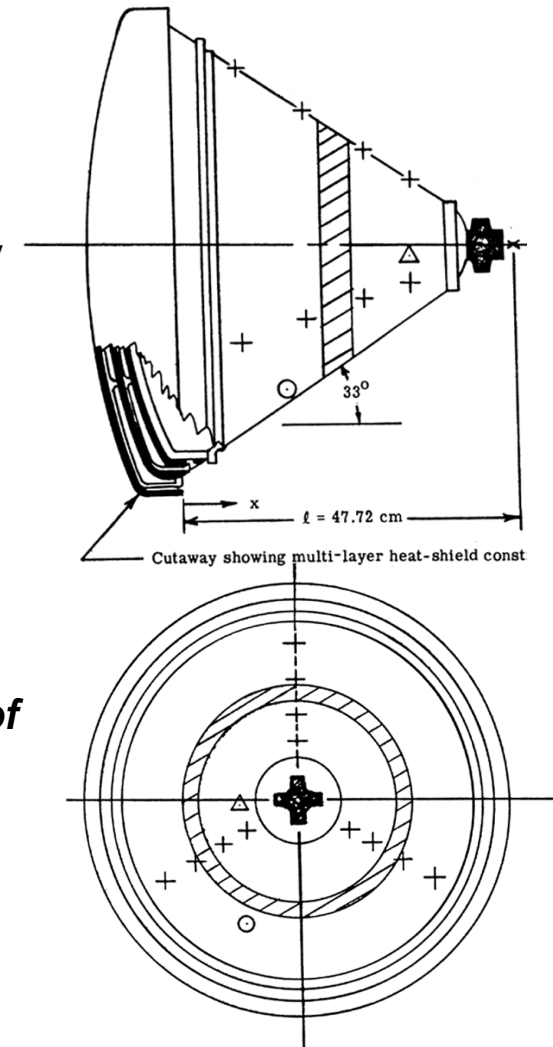


Computed Afterbody Heat Transfer at $t=1634$ s



- Goal: reduce uncertainty levels by validation with flight data
- Excellent agreement between CFD and flight data for laminar flows without afterbody TPS blowing
- Published: *Journal of Thermophysics and Heat Transfer*, Vol. 17, No. 2, 2003

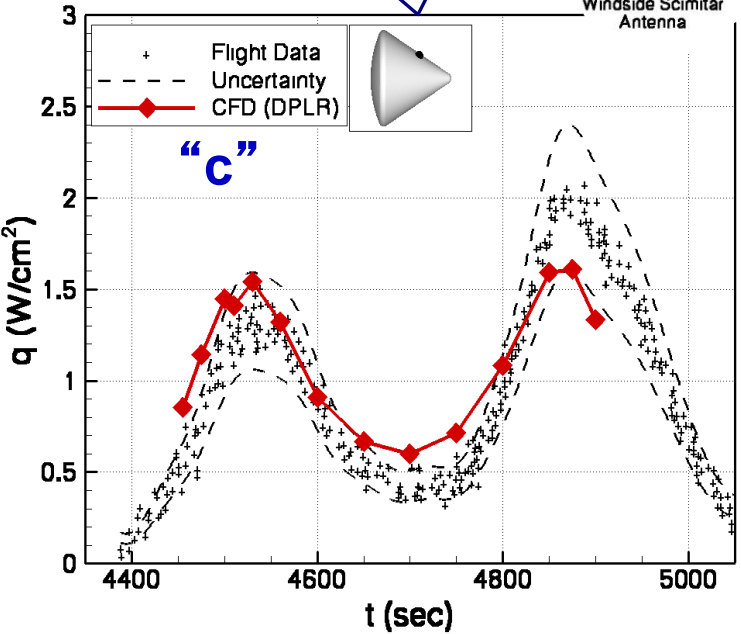
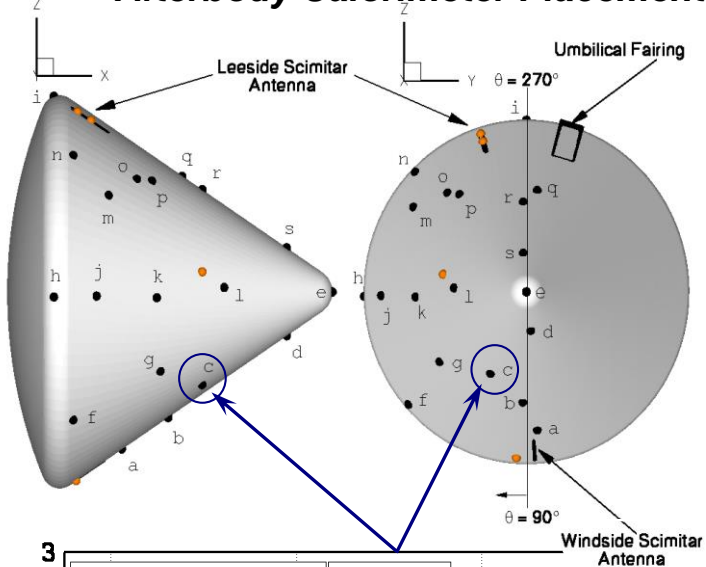
Fire-II Instrumentation





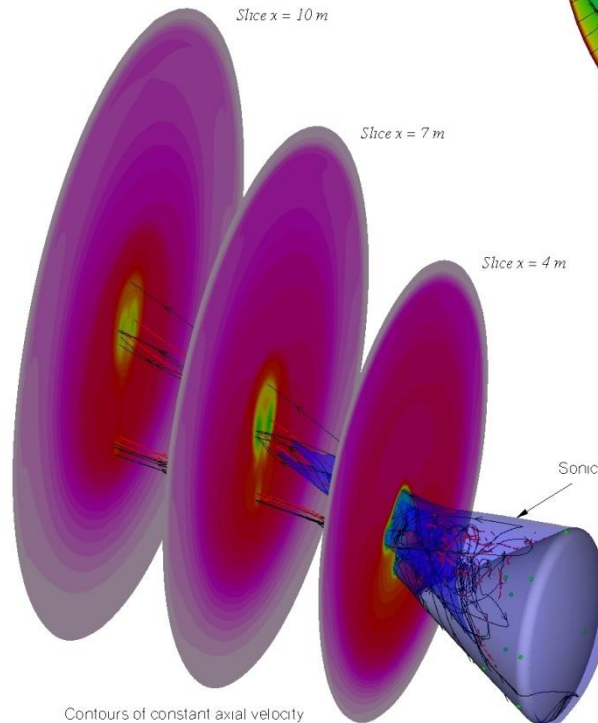
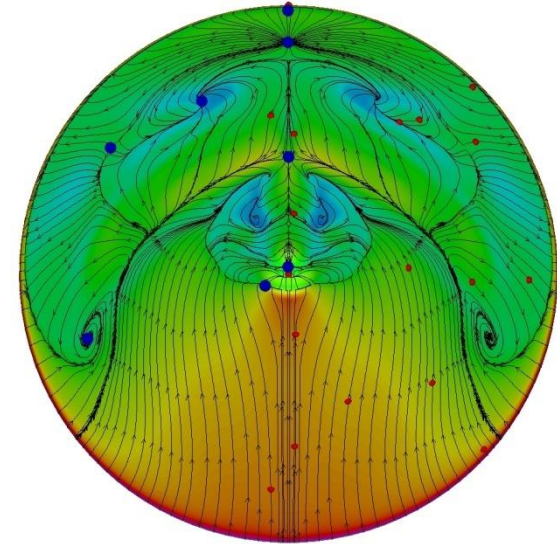
Afterbody Heating Apollo AS-202: Validation with Flight Data

Afterbody Calorimeter Placement



- **Problem:** Current uncertainty on afterbody heating predictions is very high
- **Goal:** reduce uncertainty levels by validation with flight data

Surface Oilflow
 $t = 4900 \text{ s}, Re_D = 7.6 \times 10^5$



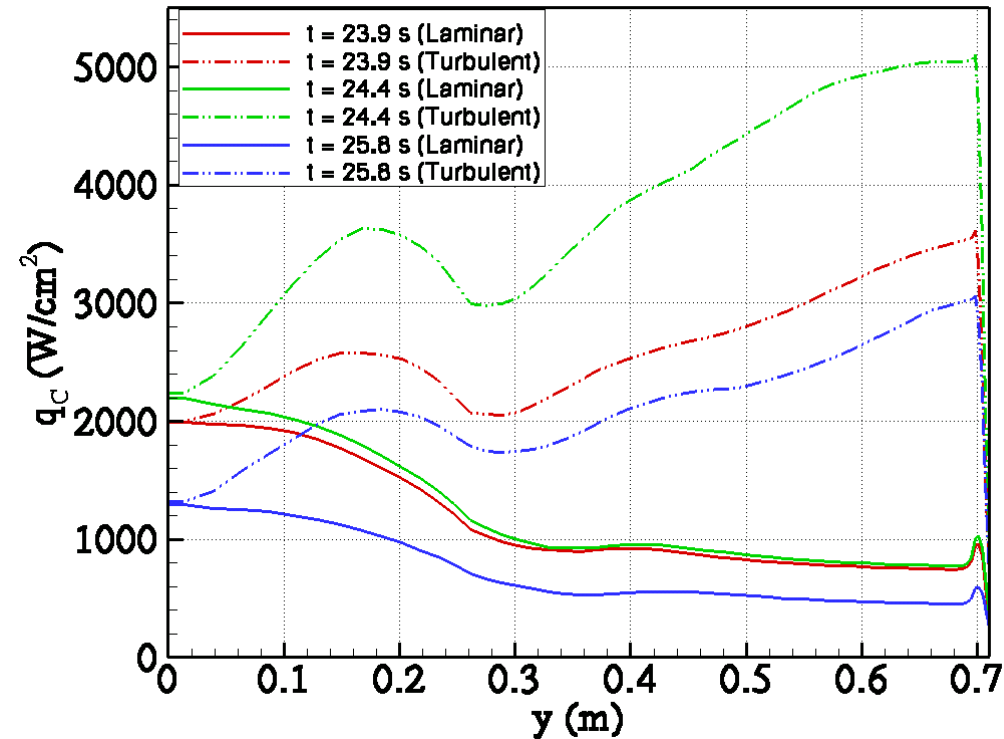
T_w, K
 200 300 400 500 600 700 800 900 1000 1100 1200

⇒ Computations generally agree with flight data to within $\pm 20\%$ uncertainty at 15 of 19 calorimeter locations.

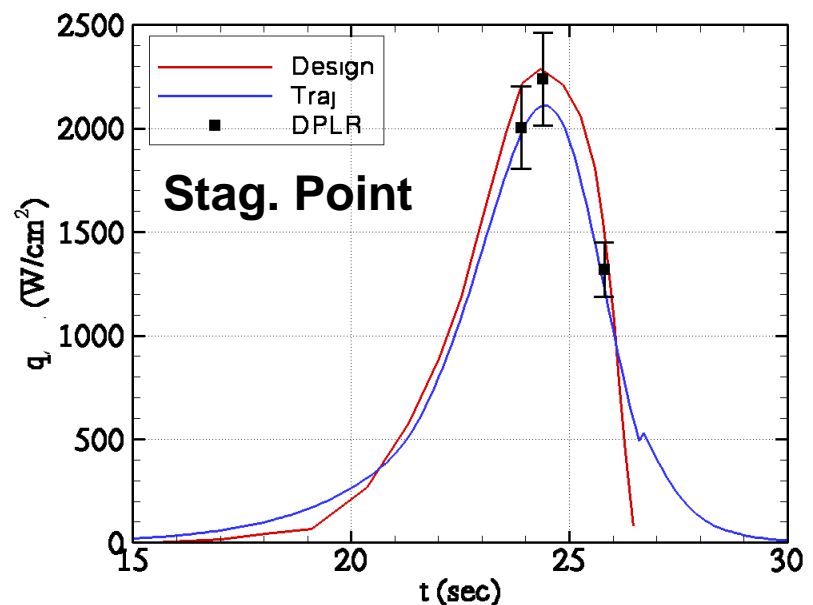
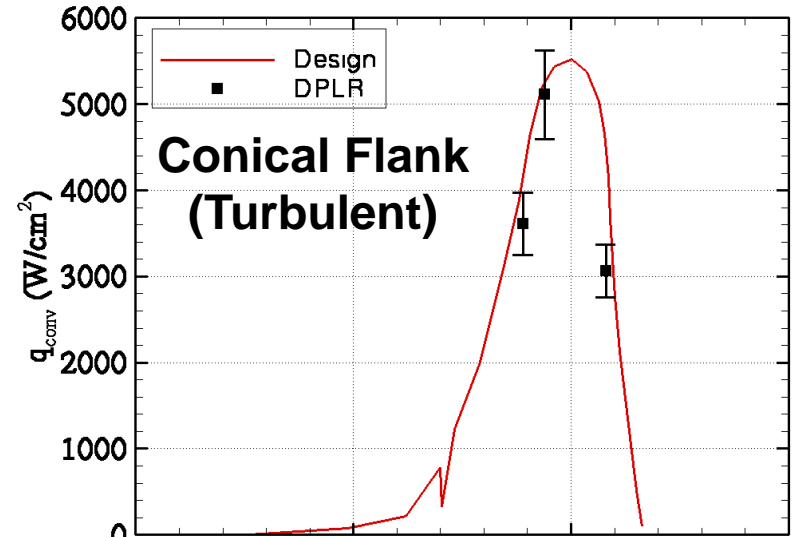


Applications: Pioneer Venus Large Probe

PV Large Probe Laminar & Turbulent DPLR Solutions



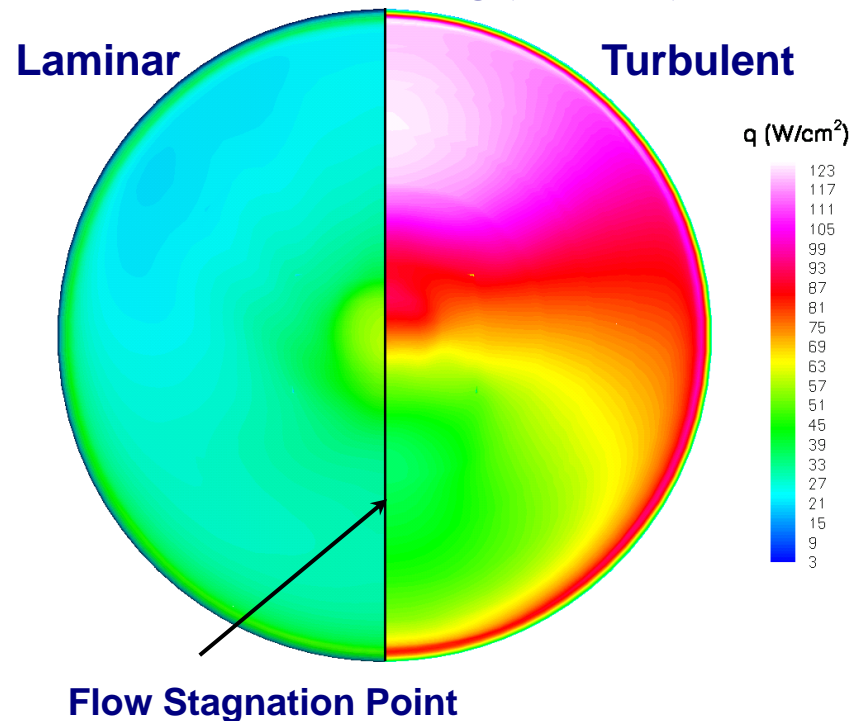
- **Design Data** : scanned from PV CDR report
- **Traj Results** : 3DoF reconstruction of design trajectory
- **DPLR Results** : fully catalytic (“error” bars show modeling variability)





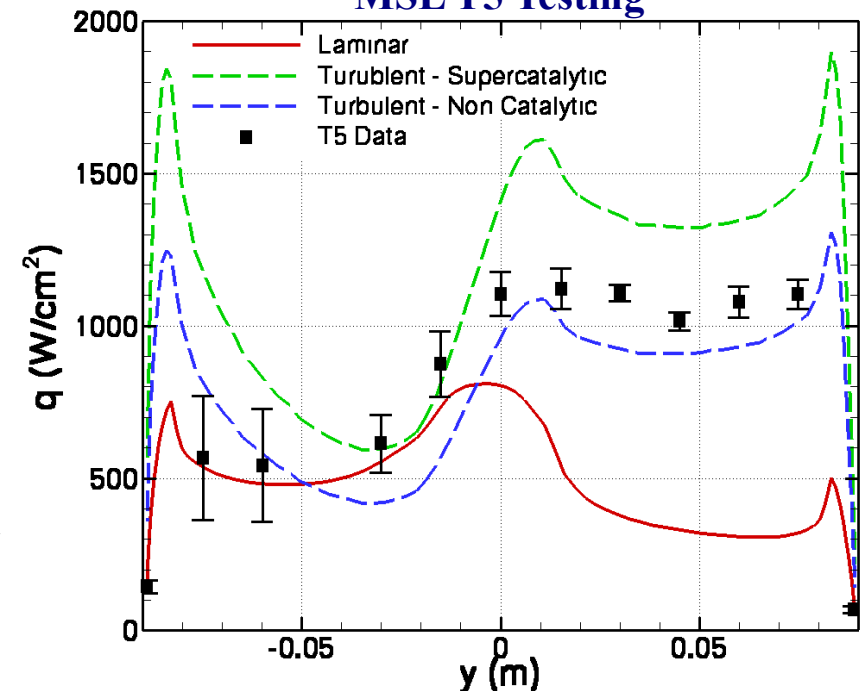
Applications: Mars Science Laboratory

MSL Peak Heating ($\alpha = 16^\circ$)



- 70° sphere-cone flying at angle of attack
- Leeside turbulent heating levels dominate aeroheating environment - design to stag. point heating would not be conservative
- High heating levels drive TPS material selection and thickness

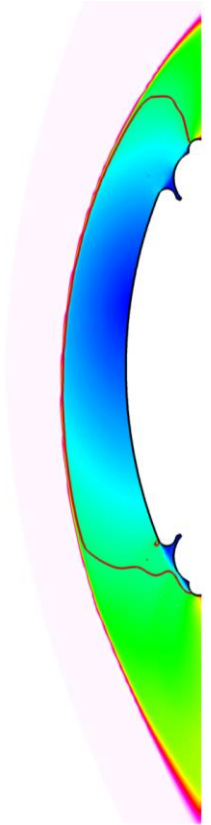
MSL T5 Testing



- Testing in shock tunnels at T5 and LENS to understand turbulent augmentation factors and enable validation of CFD at flight enthalpy



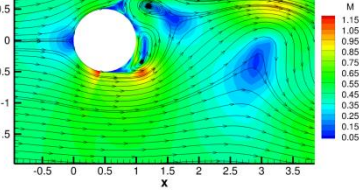
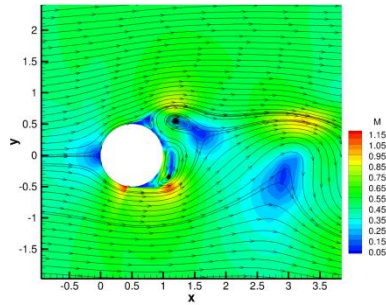
Applications: Beyond Blunt Bodies



HEATSHIELD+SIAD

Unusual blunt-body shape and topologies (SIAD, Dinesh)

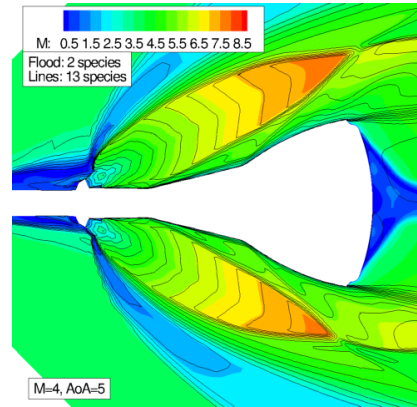
Low speed flows (vortex shedding test, Todd)



Flood: 2 species
Lines: 13 species

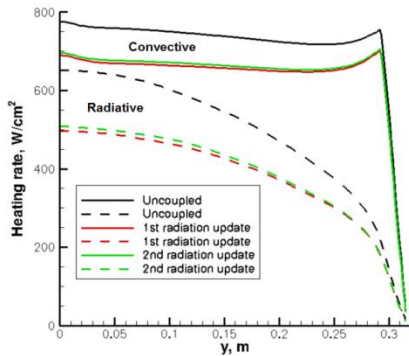
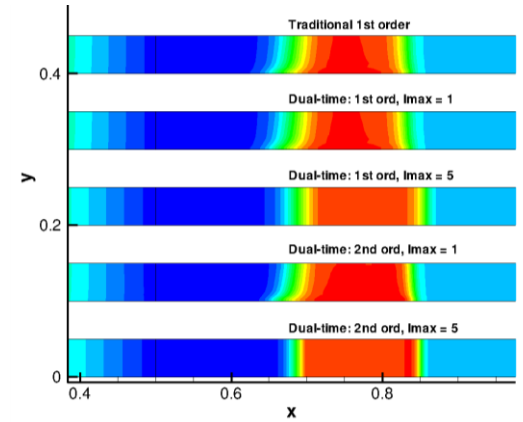
M=4, AoA=5

Low speed flows (vortex shedding test, Todd)



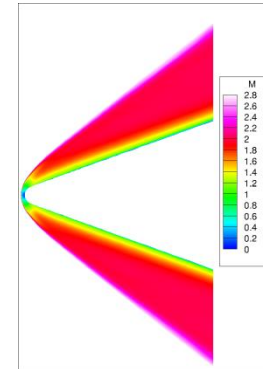
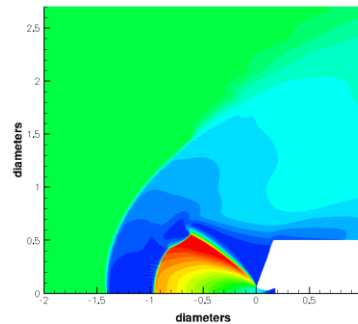
Large grids & complex geometries (LAV, Emre)

Time accuracy (Shock tube, Mike B.)

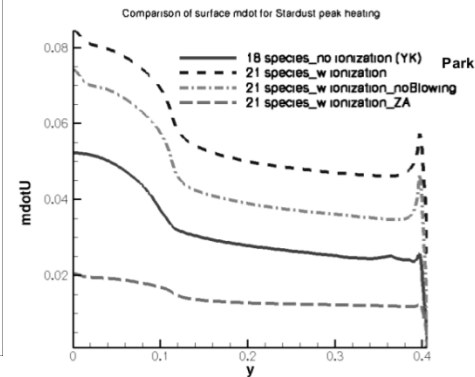


Coupled flowfield & radiation (Fire II, Grant)

Supersonic Retropropulsion w/ Overset (SRP, Kerry)



Gas-surface interaction and blowing (Matt M., Dave D., Ioana)





Credit Where Credit Is Due

Michael Wright:

Matt MacLean:

Dave Saunders:

Jim Brown:

Ryan McDaniel:

Grant Palmer:

Chun Tang:

David Boger:

Matt Bartkowicz:

Mike Barnhardt:

Nancy Mangini:

Todd White:

Creator

Automatic Interface Detection

Spalart-Allmaras Turb. Model

Automatic Grid Adaption

SST Turb. Model

Baldwin-Lomax Turb. Model

Chapman Viscosity Model

User training

Overset Grid

Subsonic BCs

Dual-time and Flow statistics

Users Manual

Development PM

Developers Wanted -- Please Add More Features!



Getting Started with DPLR

What do I need to run DPLR?

- 1. A Linux workstation or cluster with a Fortran 90/95 compiler: Intel Fortran, Portland, gfortran, ...**
- 2. A working implementation of MPI: recommend OpenMPI**

How can I get DPLR?

- 1. Contact Kim Chrestenson at NASA ARC to setup a NASA SUA: Kim.L.Chrestenson@nasa.gov & dplr-requests@lists.nasa.gov**
- 2. Access DPLR source, documentation, and test cases online at nsckn.nasa.gov**

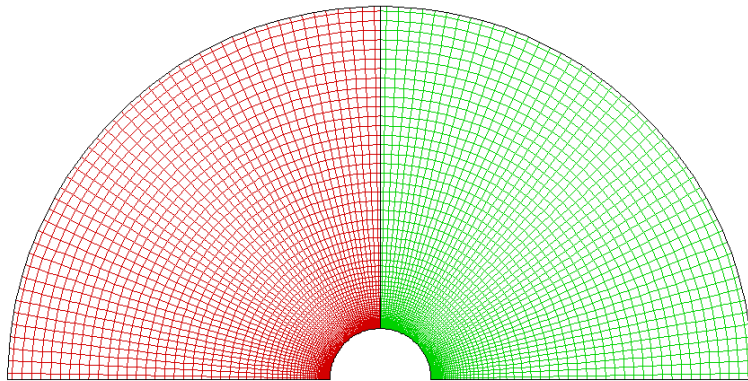
What if I have questions?

- 1. The DPLR manual has installation tips and detailed description of flags and options.**
- 2. Help is available by email: dplr-support@lists.nasa.gov & Todd.R.White@nasa.gov**

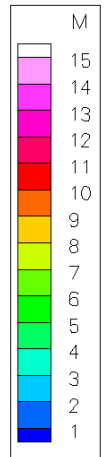
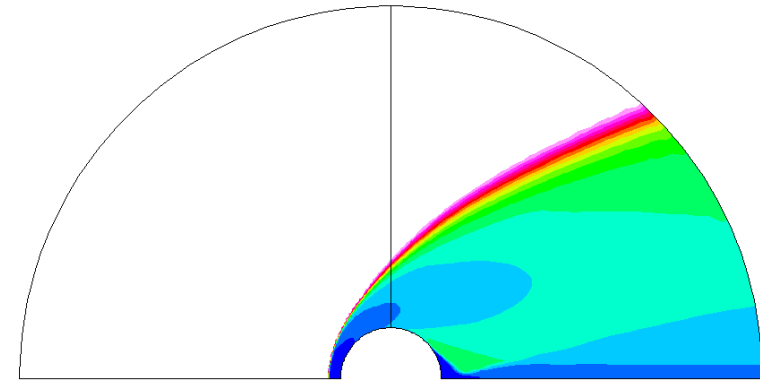


DPLR simulation on a 2D cylinder

Grids for 2D Cylinder



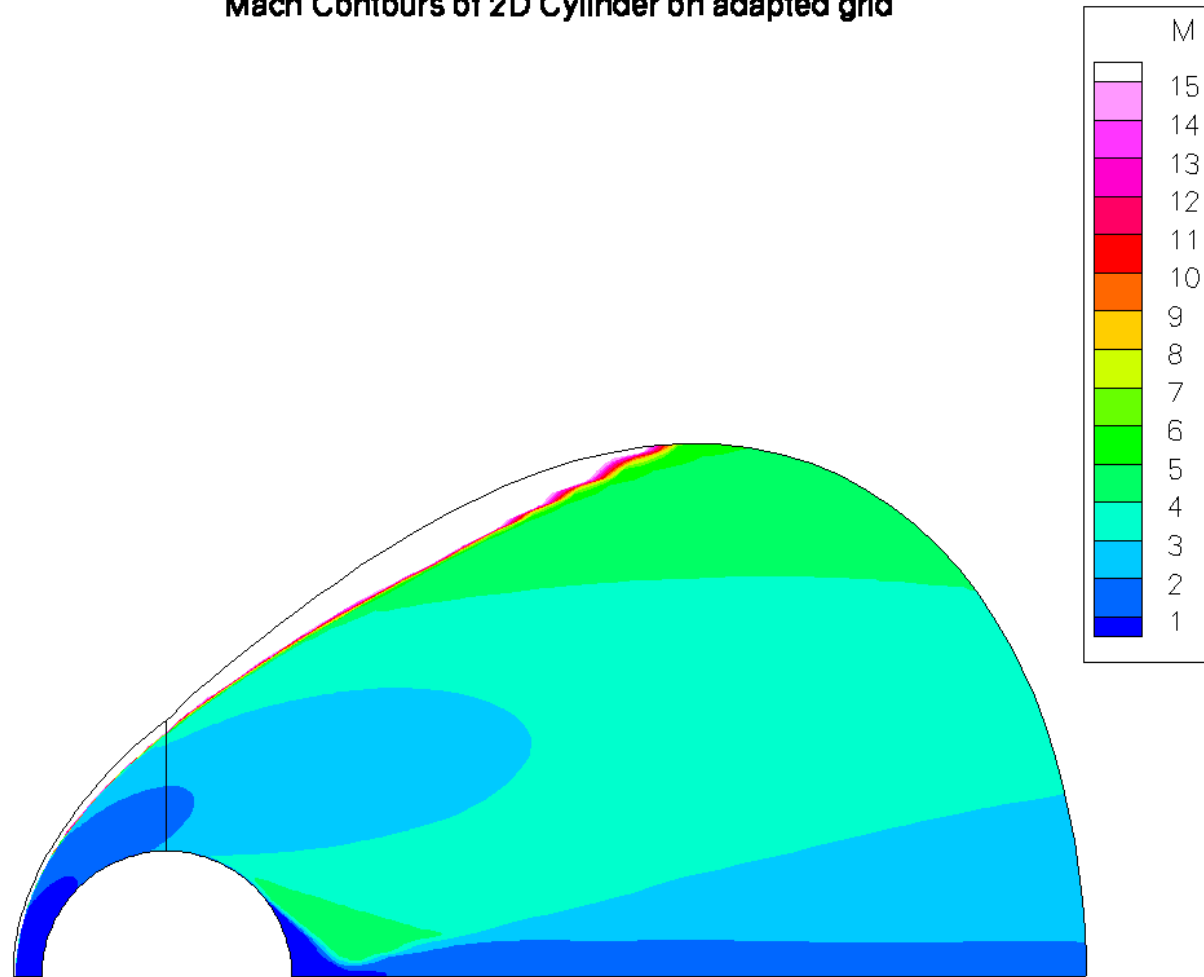
Mach Contours for 2D Cylinder





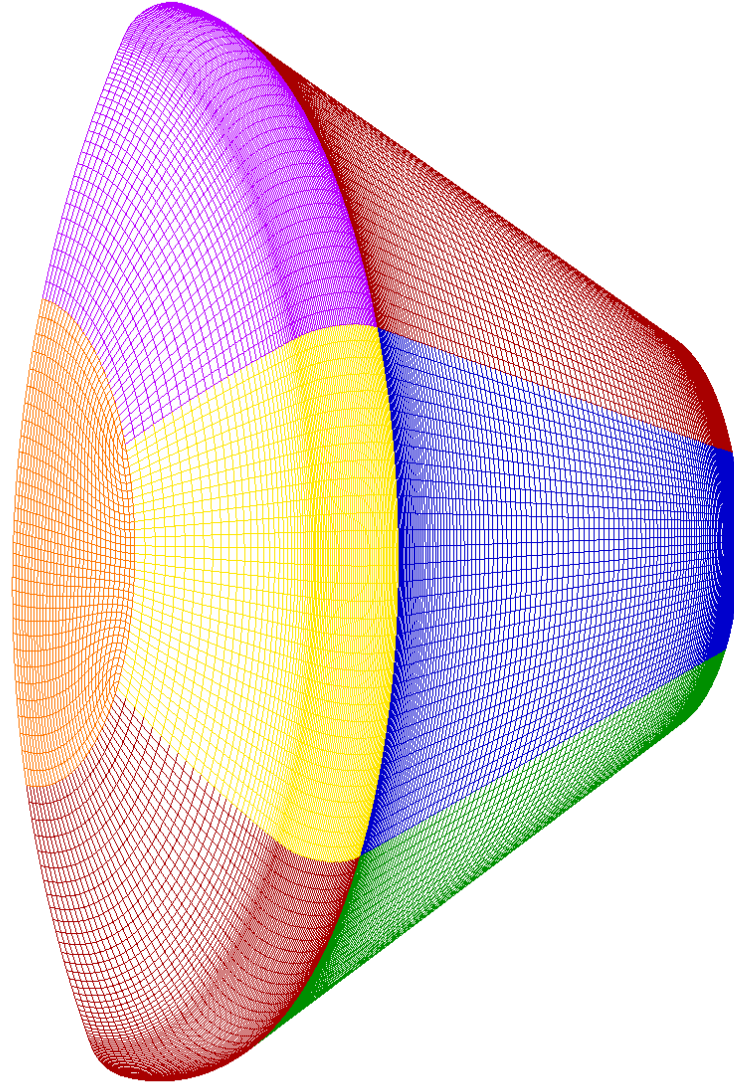
DPLR simulation on a 2D cylinder

Mach Contours of 2D Cylinder on adapted grid



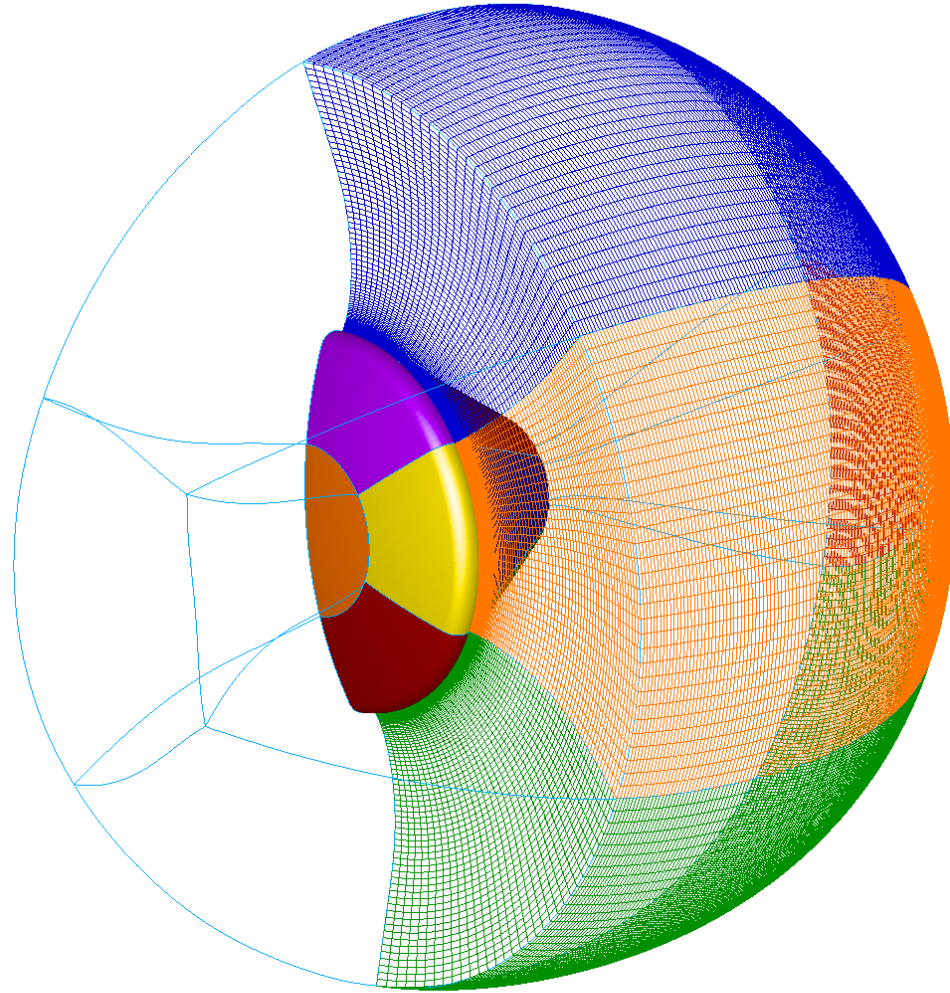


Hyperbolic Grid using Gridgen



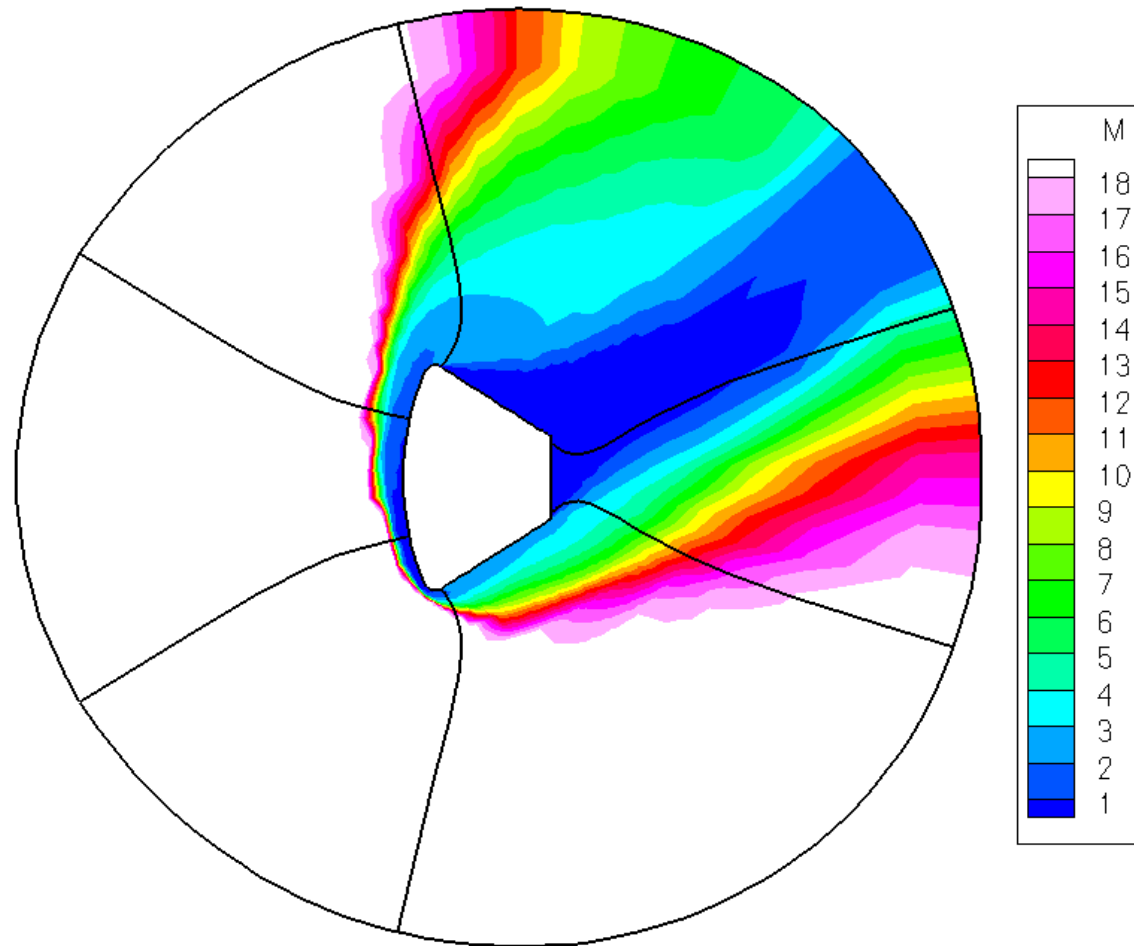


Hyperbolic Grid using Gridgen



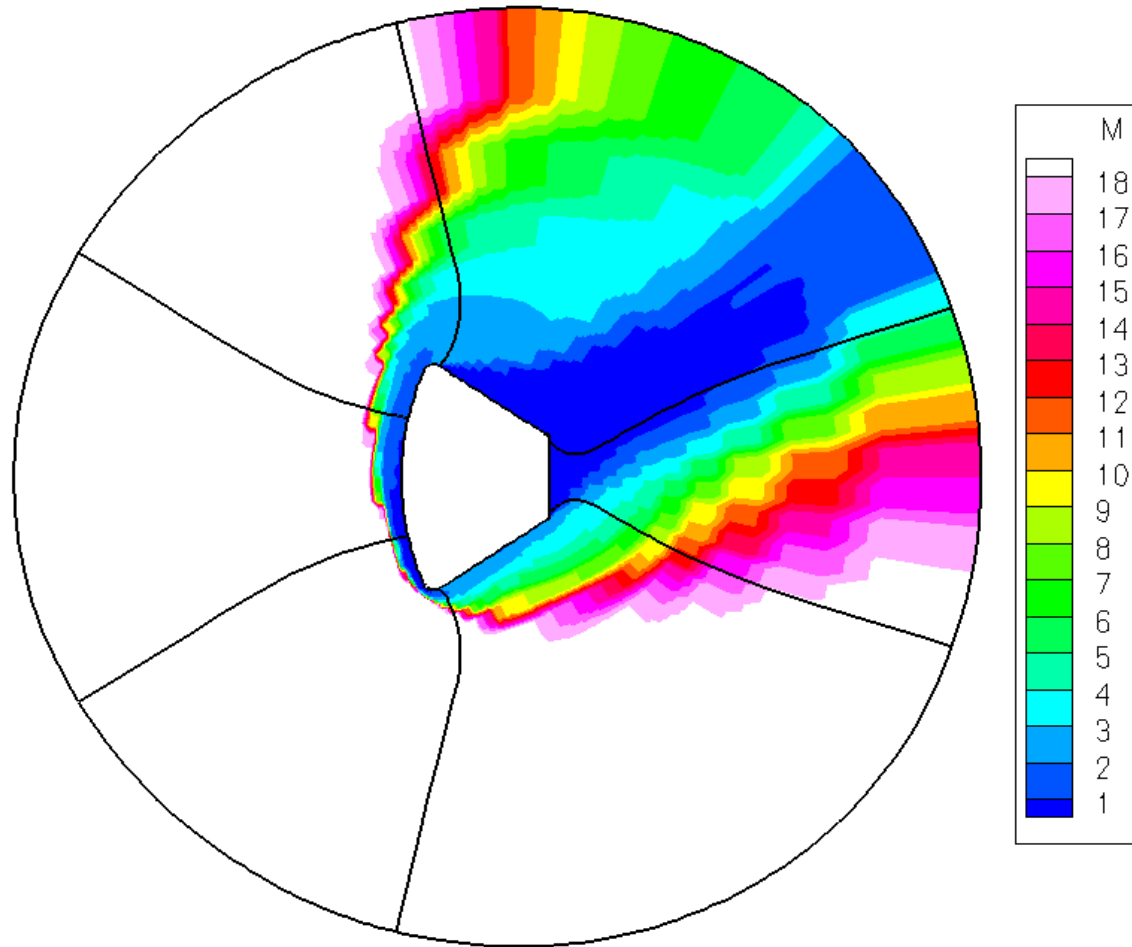


Mach Contours on pitch plane (coarse grid)



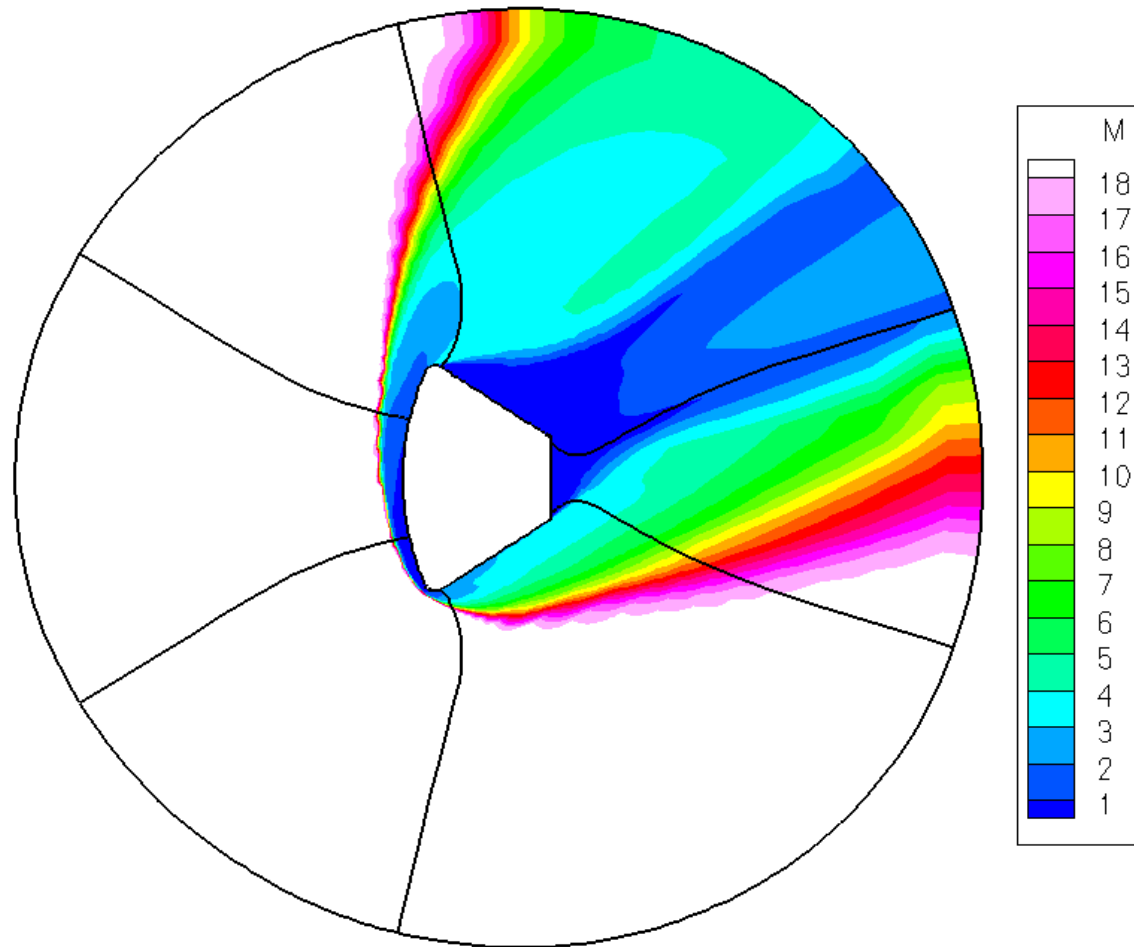


Up-sequenced Mach contours (medium grid)



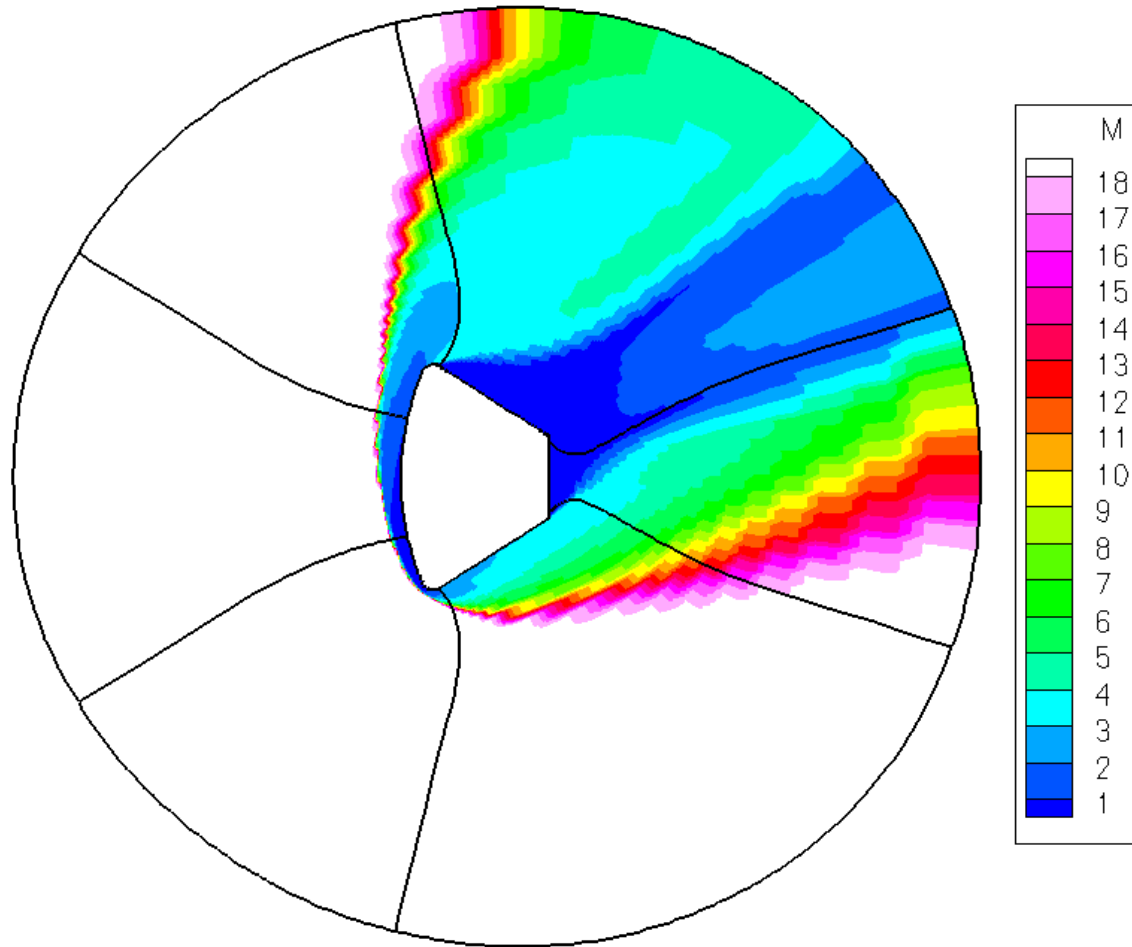


Mach contours on pitch plane (medium grid)



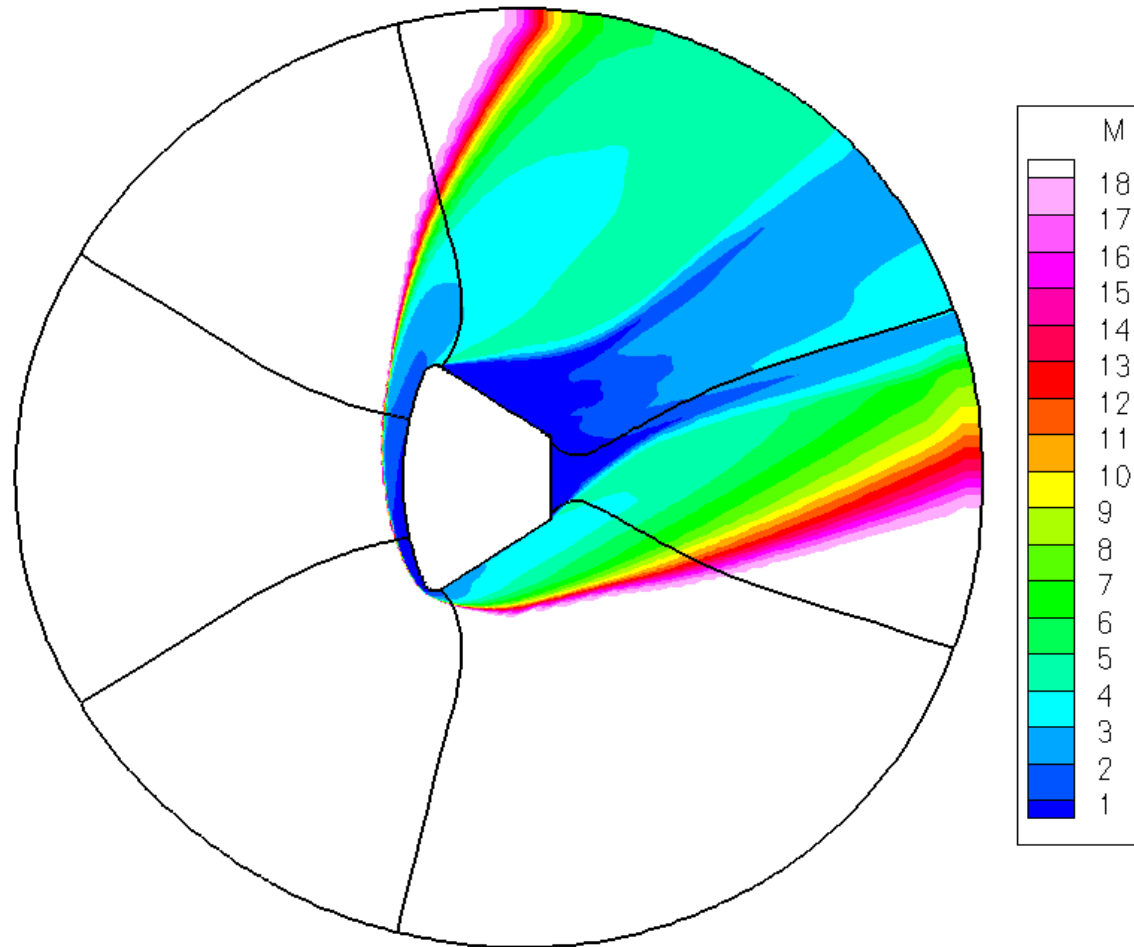


Up-sequenced Mach contours (fine grid)



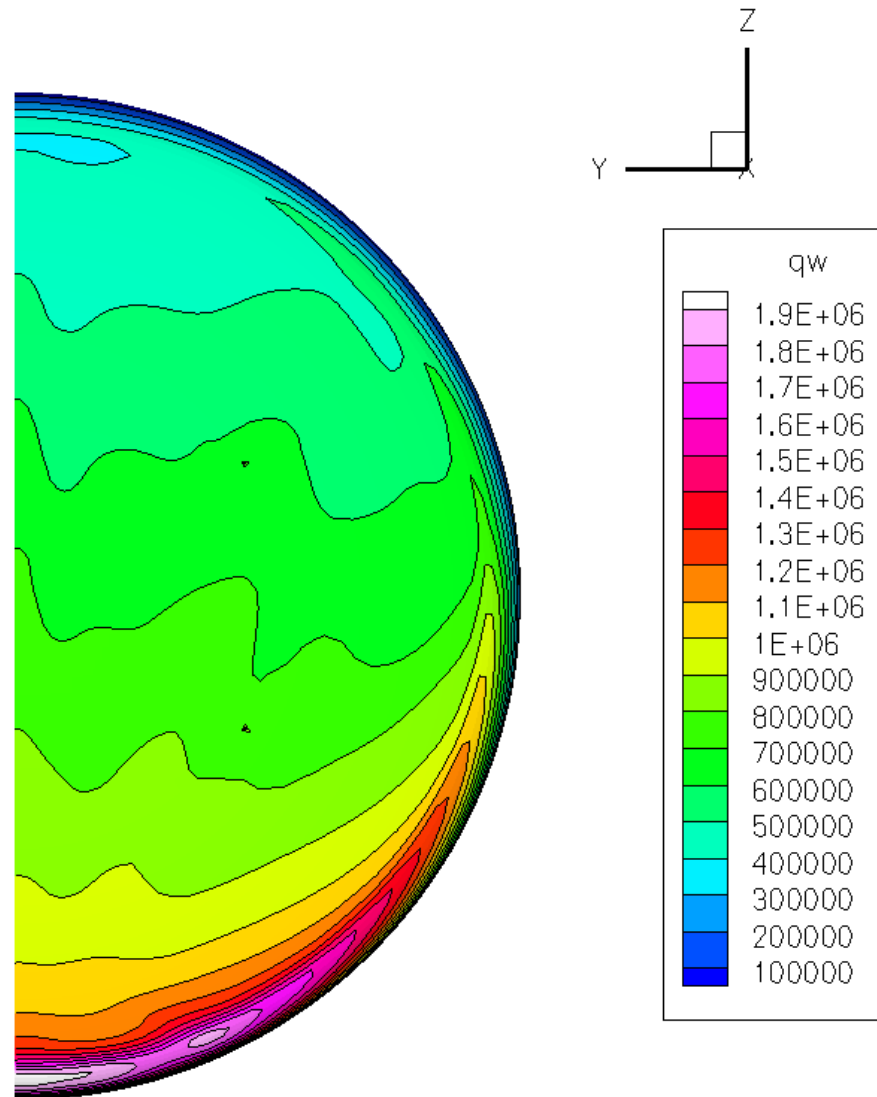


Mach contours at pitch plane (fine grid)



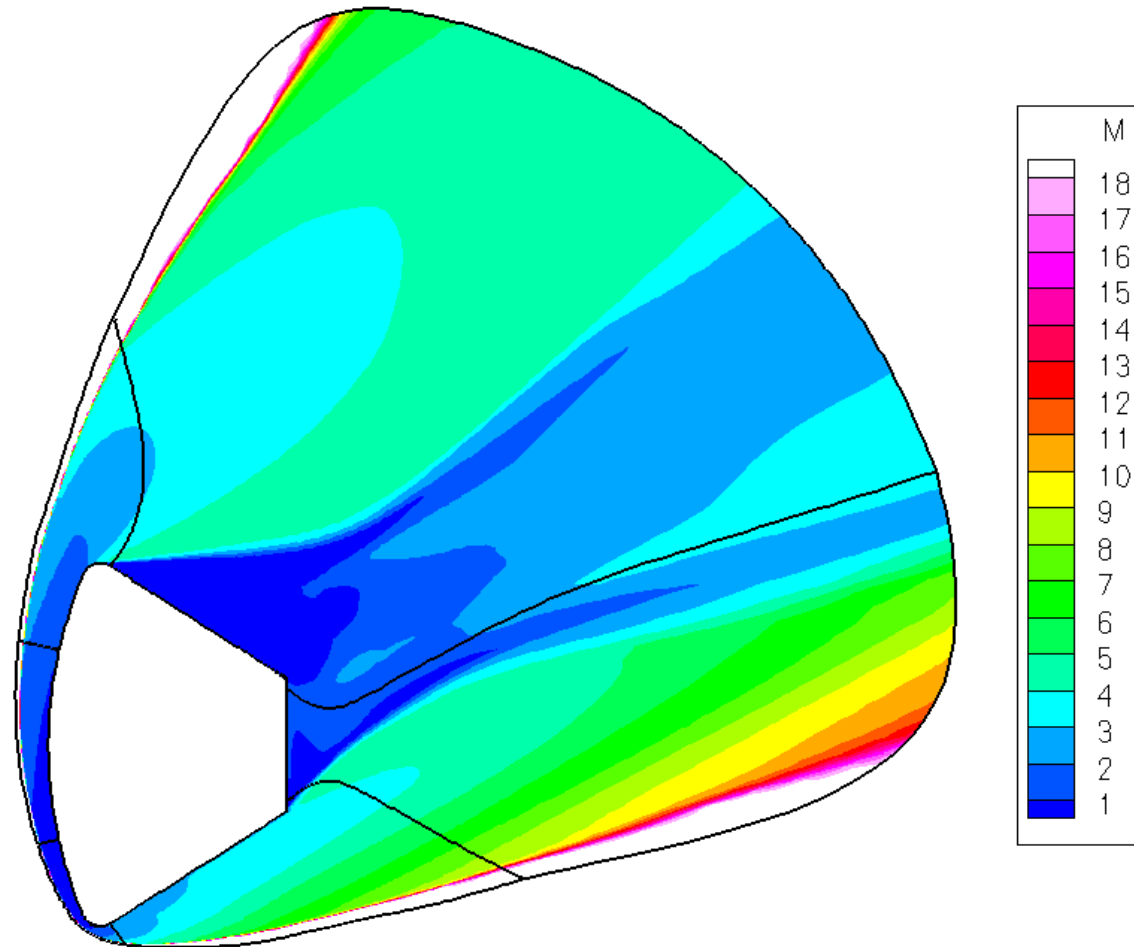


Surface heat flux contours on heatshield





Mach contours on adapted grid (fine grid)





Comparison of heat flux contours on heatshield

