Modeling Hypersonic Vehicles With Computational Fluid Dynamics (CFD)

Prepared for:

Siemens Digital Industries Software Webinar

13290 Evening Creek Drive S, San Diego CA 92128

Date:

16th February 2022

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Agenda:

- Adam Green (ATA Engineering)
  ATA & STAR-CCM+ Overview.

- Chris Ostoich (ATA Engineering)
  CFD and Hypersonics.

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Who We Are

We are an **employee-owned** small business with a **full-time staff of over 190**, nearly 150 of whom are degreed engineers

34 Ph.D.

91 M.S.

24 B.S.

14
Registered Professional Engineers

Subject matter experts recognized by
- National Academy of Engineering
- Society of Experimental Mechanics
- AIAA & ASME

14
Average years of experience

ATA ENGINEERING, INC.

What We Do

ATA Engineering's **high-value engineering services** help solve our customers' toughest product design challenges

ATA is an Employee-Owned Small Business

Employee ownership benefits you because our owners:



- Take your project personally
- Are empowered to make decisions
- Are efficiency minded
- Recognize the direct link between your satisfaction and their success
- Strive for customer delight

ATA ENGINEERING, INC.

Our Commitment to Excellence

We have been recognized by numerous organizations for our **outstanding customer support** and **work environment**

NASA JPL
Thomas H. May Legacy of Excellence

NASA
George M. Low Award

SBA
Tibbetts Award

SNC
Small Business Excellence Award

NASA JPL
Small Business Subcontractor of the Year

Wall Street Journal
Top 15 Small Workplaces

NCEO
Innovations in Employee Ownership

SDBJ
San Diego's Fastest Growing Companies

NRO
Commander Commemoration

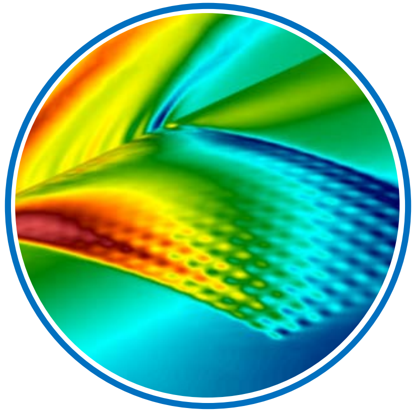
More than 90% of our clients rate our technical work and customer support "**Excellent**"

Our Services

We provide our customers with **complete, integrated solutions**

Design

From initial concept development to detailed structural design

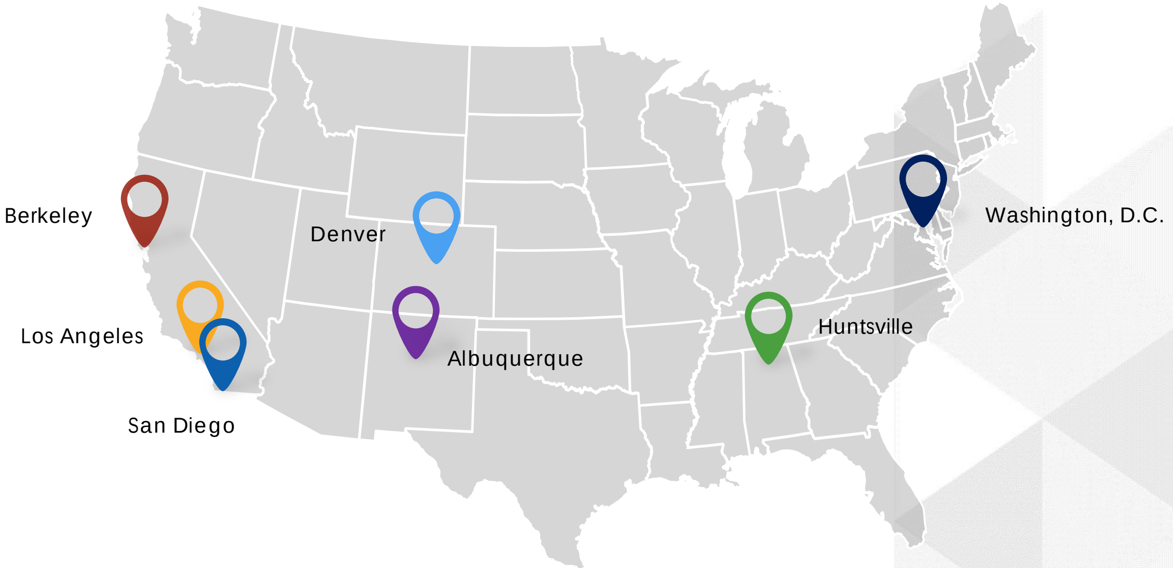


Analysis

Comprehensive structural, fluid, acoustic, and thermal analysis services

Test

Industry-leading structural test services for extreme loading environments



ATA Engineering - Timeline

- A Legacy of Engineering Excellence:

1975 | 2000 | 2002 | 2007 | 2009 | 2010 | 2018 | 2020

SDRC

SDRC was an early pioneer of PLM tools starting in 1967.

After a series of acquisitions, SDRC was purchased by Siemens and their I-DEAS software was integrated with Unigraphics into the well known NX product line.

PLM Software SIEMENS NX

ATA Engineering was formed in April 2000 after a management buyout from SRDC of the Advanced Test and Analysis Division.

Given this shared corporate heritage, ATA maintains its strong relationship with Siemens today

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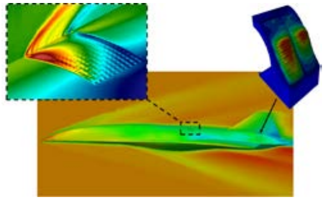


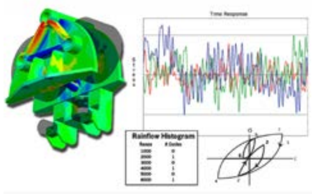
ATA opens Eastern regional Office (ERO) in Herndon VA

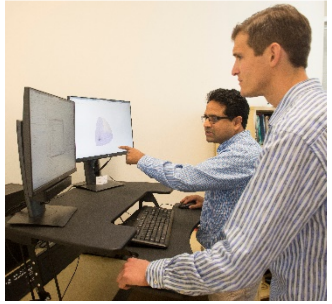
2005

ATA opens LA office in the heart of the Southern California Aerospace Industry

2007

ATA opens Denver office and labels it RMO: Rocky Mountain Office

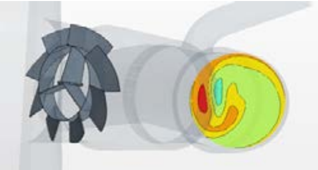




2009

ATA opens Huntsville Office to service South Eastern Aerospace clients

ATA becomes a full VAR for Siemens selling NX, Femap and Nastran

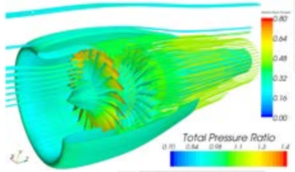


2018

ATA extends Siemens VAR relationship to include STAR-CCM+ & HEEDS

ATA opens Berkeley, California Office

SIEMENS Ingenuity for life



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Our Software Services

ATA is a **Platinum** value-added reseller for **Siemens PLM Software**
http://www.ata-plmsoftware.com/

Siemens Value Added Reseller

Hotline Support

Nastran Training Material

Software Implementation

Preferred Training Provider

Software Integration

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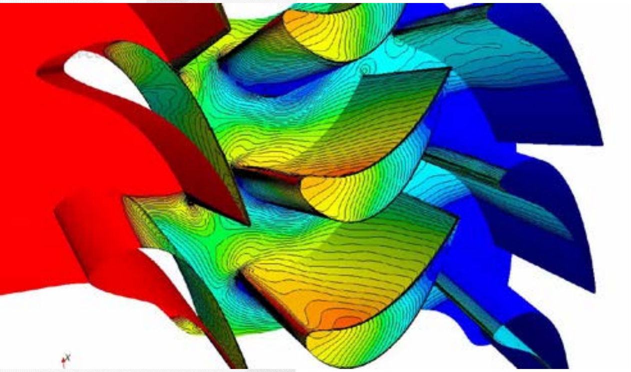
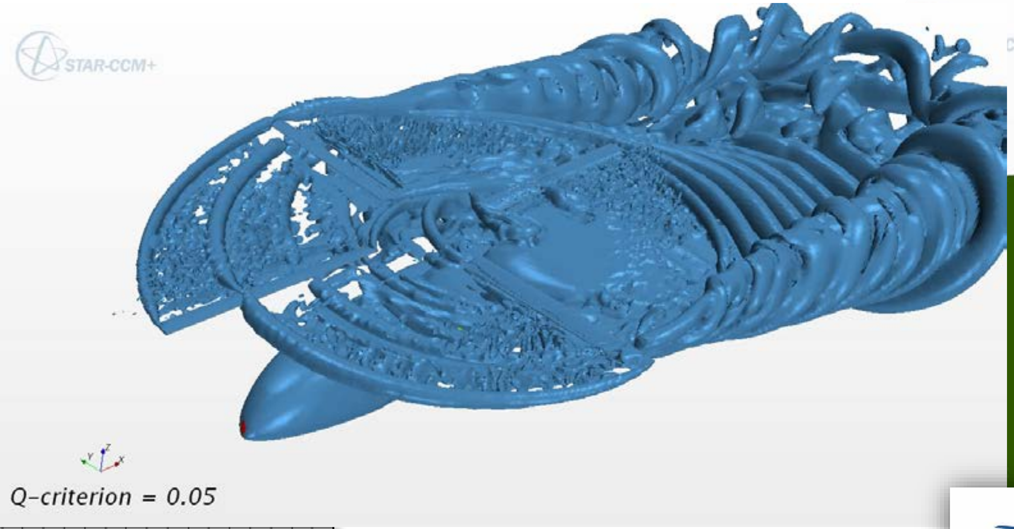
Solution Partner PLM SIEMENS

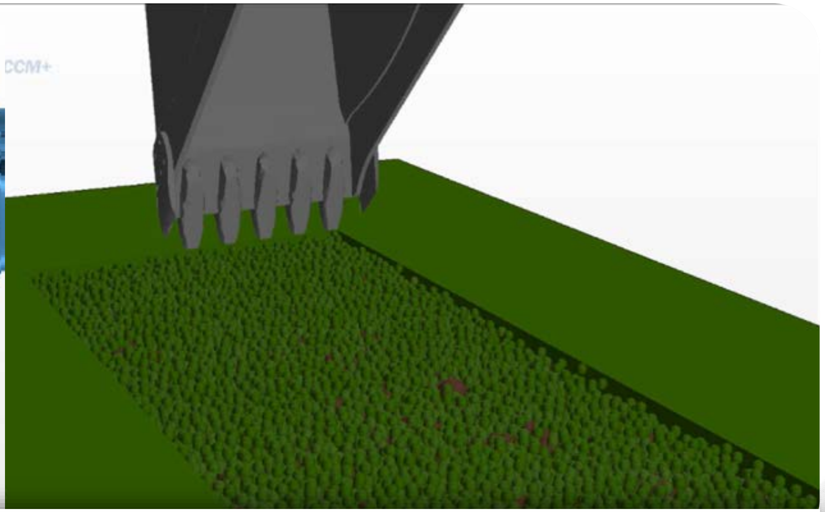
Loci/CHEM and STAR-CCM+ Both Used By ATA Engineering for Hypersonic Flows

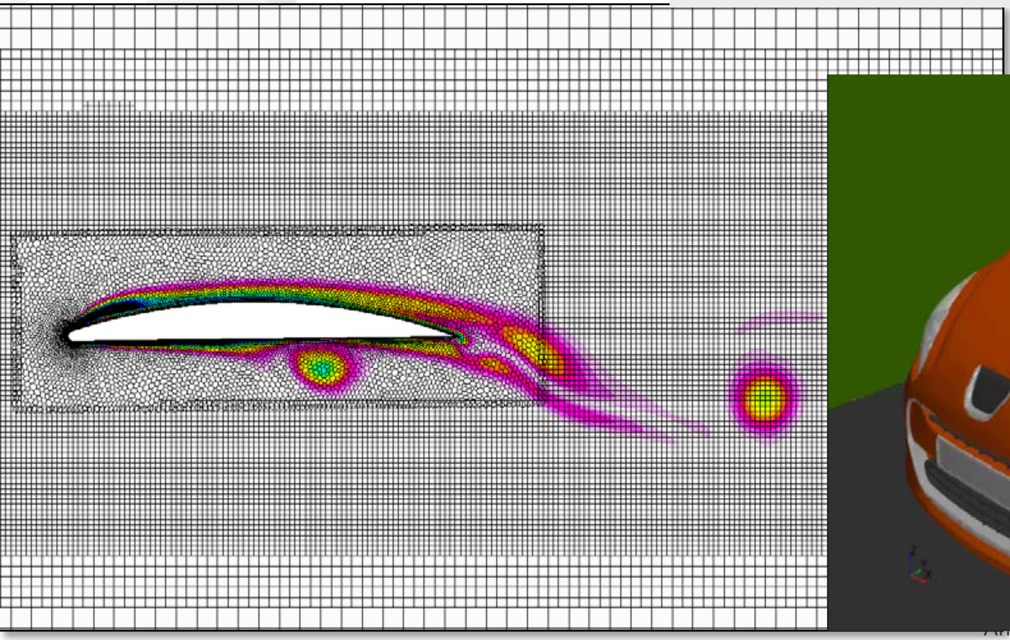
- Loci/CHEM
  - University code developed at Mississippi State by Prof. Ed Luke
  - ATA Engineering among contributing developers
  - Flexibility to modify source/add modules makes Loci/CHEM good for research and development
- STAR-CCM+
  - Multiphysics commercial package produced by Siemens
  - **General CFD/multiphysics solver emphasizing efficient workflow, automation, and high-fidelity**
  - Continued development towards hypersonics capabilities

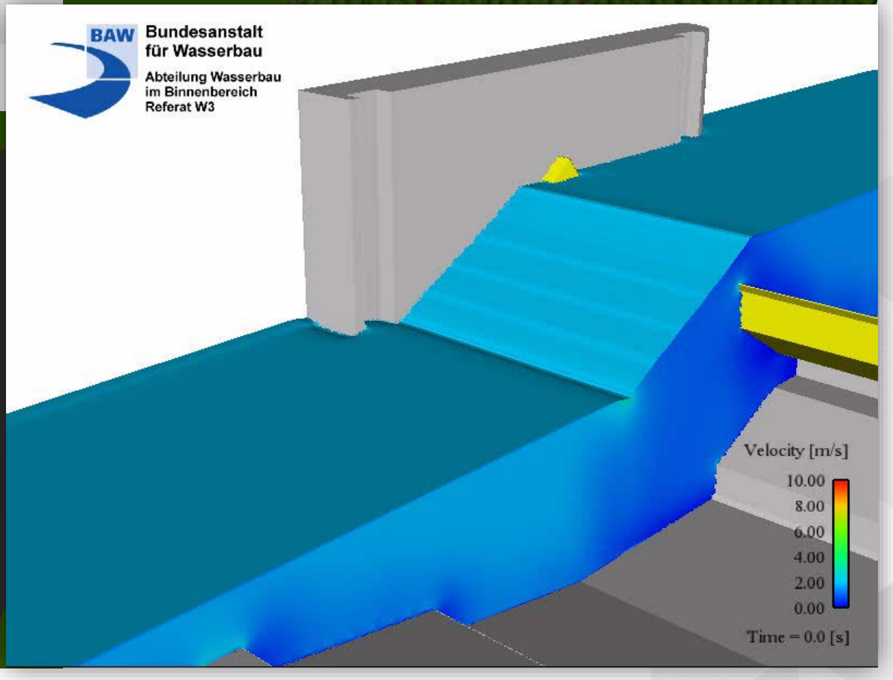
STAR-CCM+®




STAR-CCM+
Q-criterion = 0.05

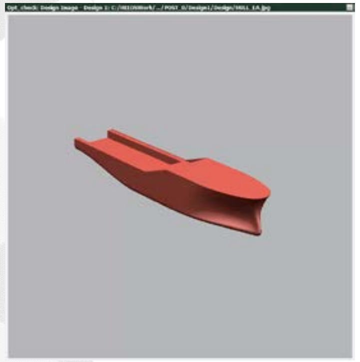





BAW
Bundesanstalt für Wasserbau
Abteilung Wasserbau im Binnenbereich Referat W3
Velocity [m/s]
10.00
8.00
6.00
4.00
2.00
0.00
Time = 0.0 [s]

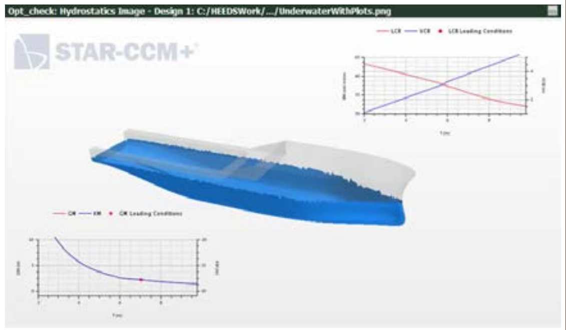
Design Space Exploration

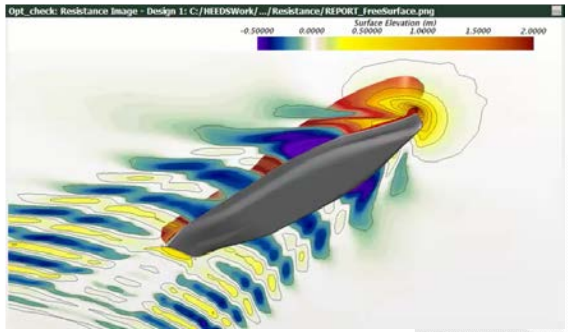
Update Ship Geometry



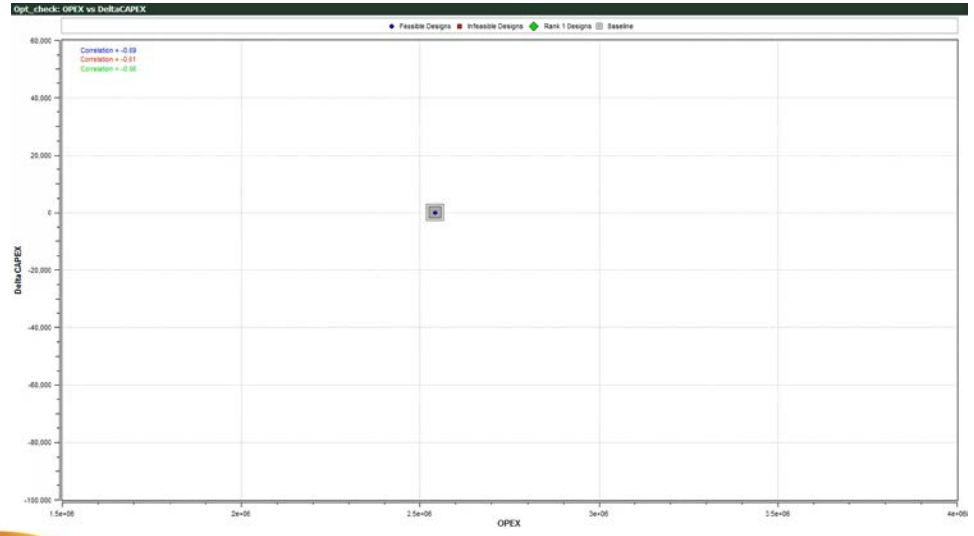
Calculate Steel Weight

Calculate Hydrostatics & Resistance





Directed Modification



HEEDS' intelligent search method

- SHERPA Search Framework

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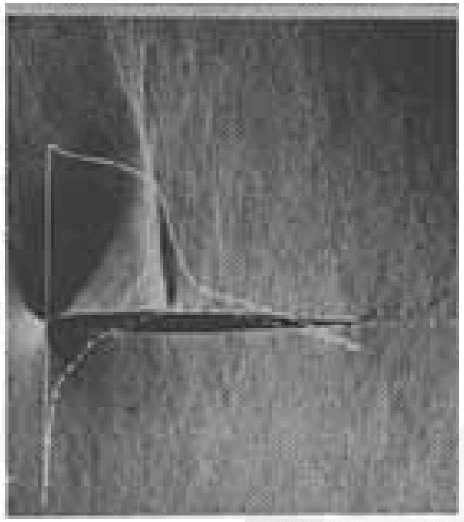
Transonic Flight Development

- Large drag increase near speed of sound
  - Significant difficulty accelerating past Mach 1
- Schlieren images showed standing shocks on wings leading to wave drag
- Significant breakthrough – Whitcomb Area Rule
  - Cross-sectional area to have smooth streamwise variation
  - Fuselage to narrow in vicinity of wings
    - "Coke Bottle" shape
- Area rule a product of decades-long study due to difficulties with transonic experimentation and understanding!



NACA 64A006 Airfoil in Mach 0.79 flow
(Beker, J. "The High-Speed Frontier")

HEEDS Optimization

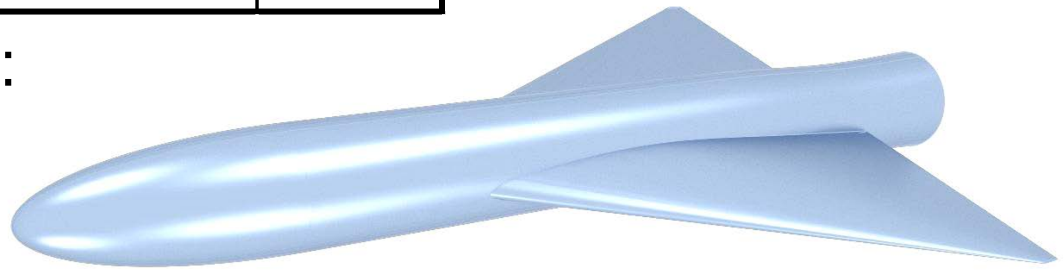
- HEEDS SHERPA design space exploration intelligently searches radii ranges to determine minimum drag configuration

Parameters	Range		Resolution
	Minimum	Maximum	
r1	0.5 m	2 m	101
r2	0.5 m	2 m	101
r3	0.5 m	2 m	101
r4	0.5 m	2 m	101
r5	0.5 m	2 m	101

Response	
Variable	Objective
$C_D = \frac{Drag}{1/2\,\rho_\infty U_\infty^2 A}$	Minimize

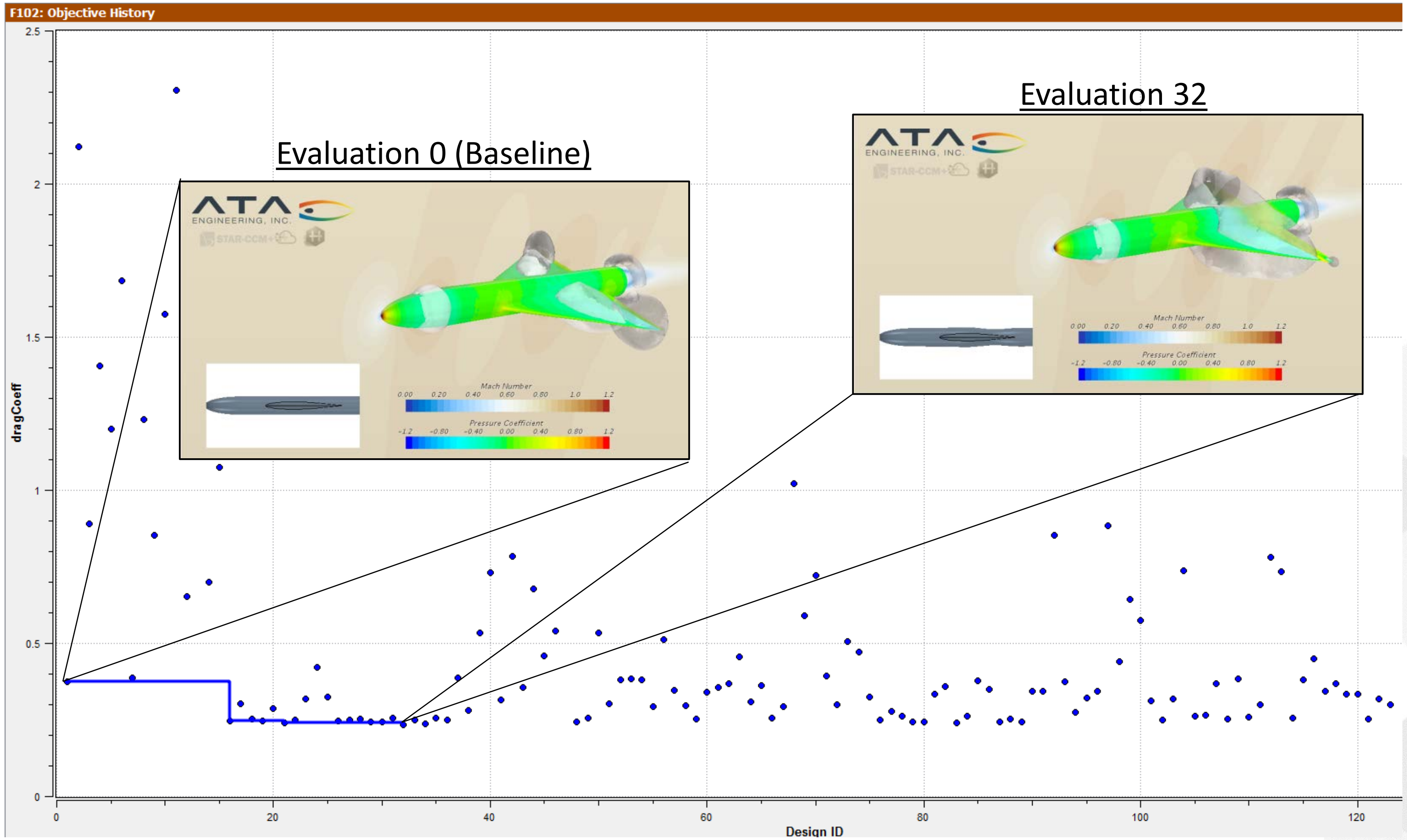
- Exhaustive search of this design space: 101^5=10.5 billion simulations

- SHERPA finds improved solution after 150 realizations



HEEDS Design Optimization

- HEEDS SHERPA explores design space to drive towards objective
- Evaluation 32 (out of 150) found to have the lowest drag coefficient
- Improved fuselage results in 38% reduction in drag



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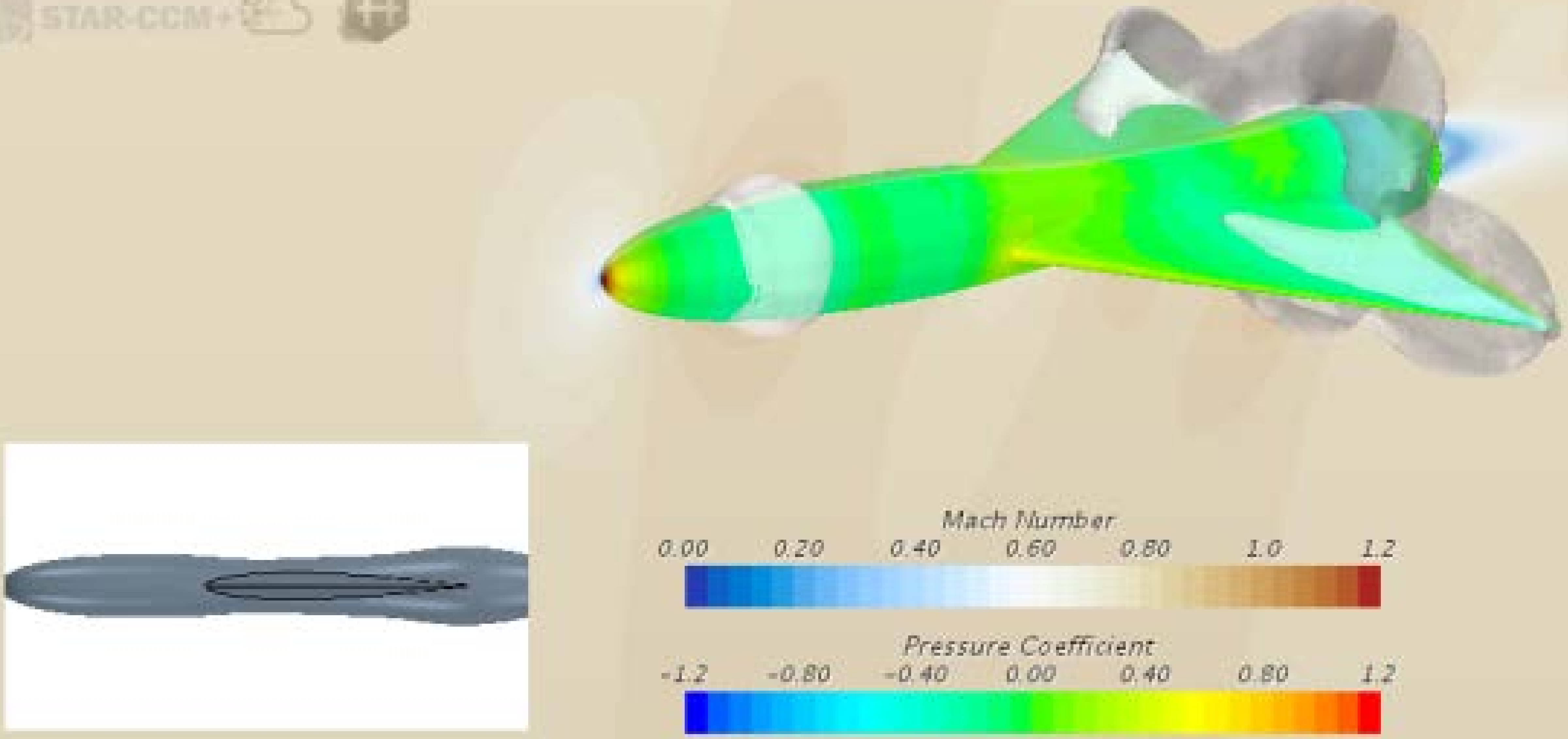

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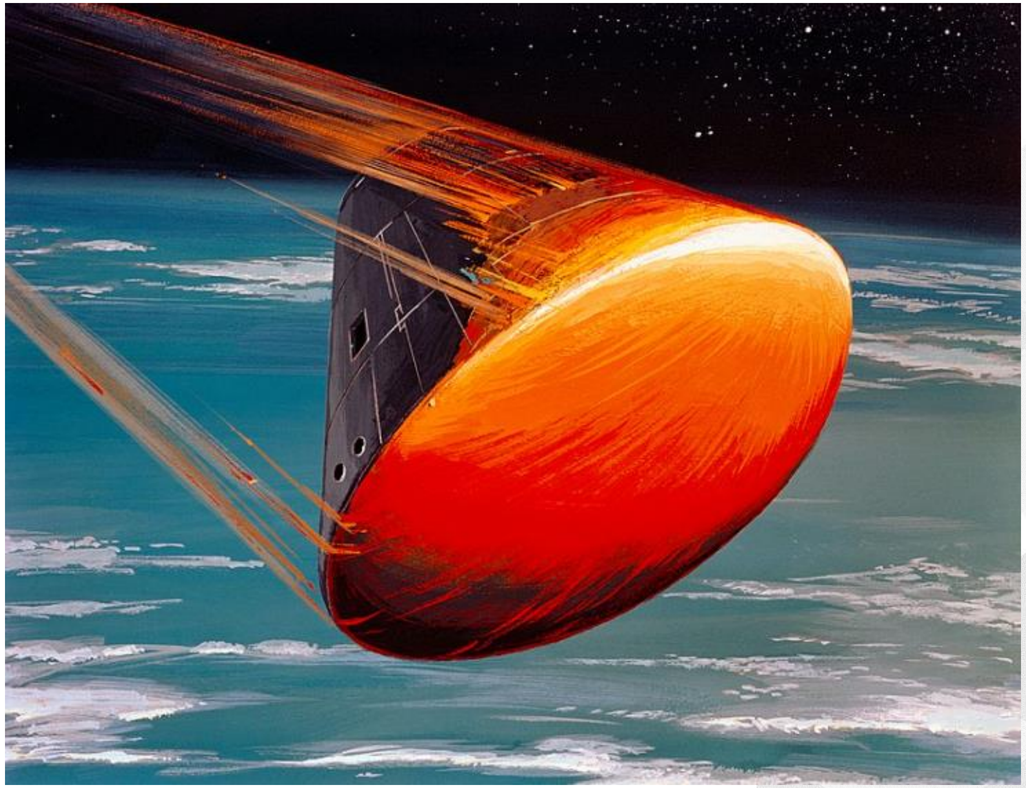
Modeling in the Hypersonic Environment

- This webinar will review some issues in CFD for hypersonics
- Will give some best practices
  - Meshing
  - Turbulence modeling
  - Initialization and convergence acceleration
  - Physics modeling
- Demonstration of automation in STAR-CCM+

Hypersonic flows characterized by certain effects becoming increasingly important

From Anderson "Hypersonic and High-Temperature Gas Dynamics"

- High temperatures
  - Vehicle thermal effects
  - Energy storage mechanisms, chemical reactions and ionization
- Low-density flow
  - Velocity-slip and temperature slip become significant
  - Continuum equations become invalid
- Viscous interaction
  - High temperatures lead to fast growing BL, significant change in aerodynamic shape
- Entropy layer
  - Strong wall-normal entropy gradient in boundary layer
- Thin shock layer



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Continuum CFD

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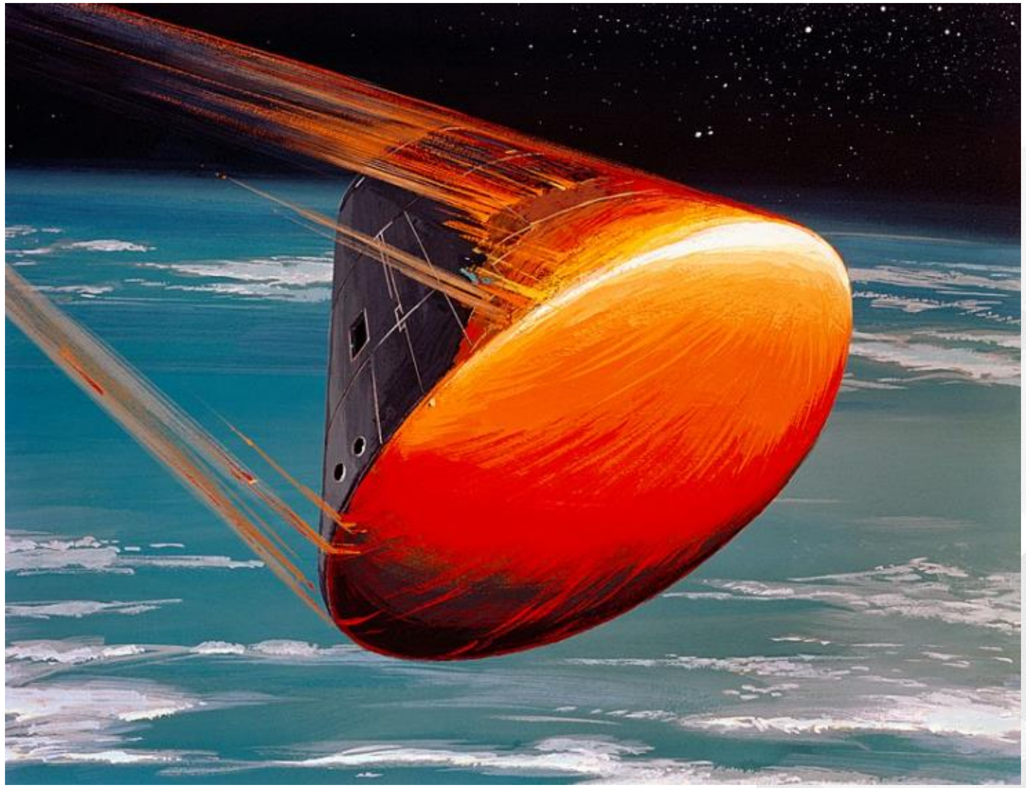
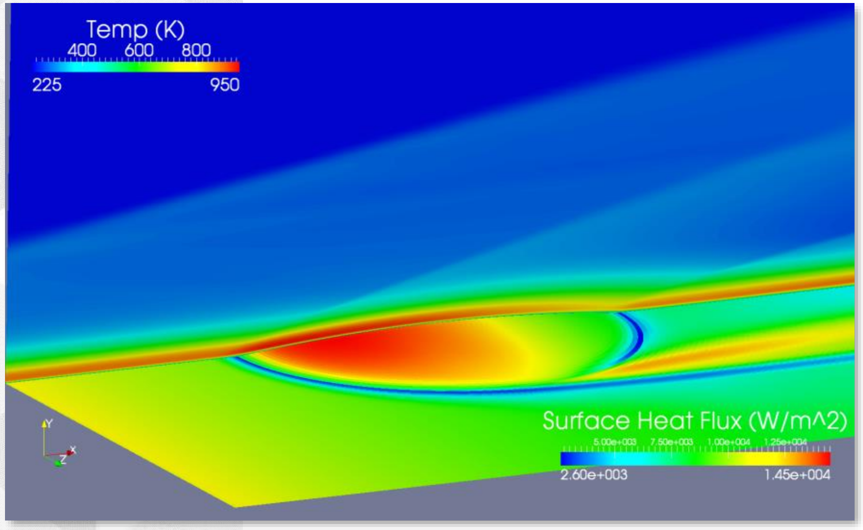
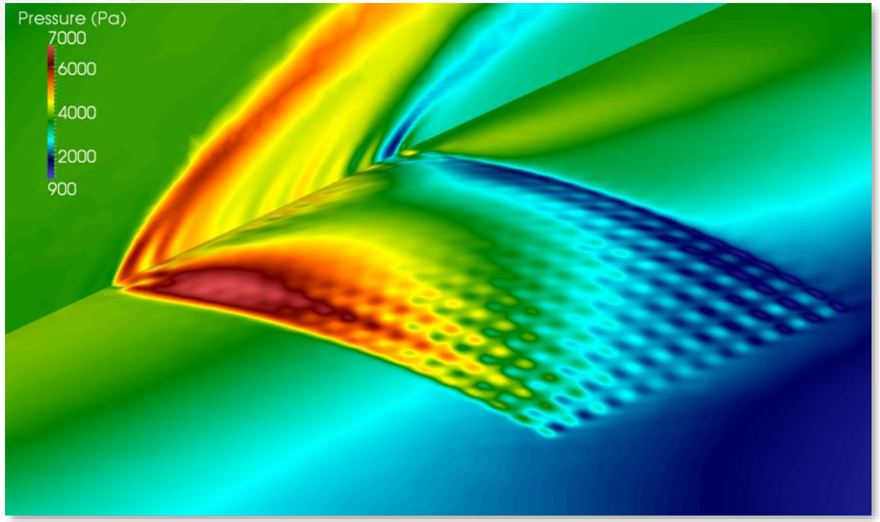


Hypersonics at ATA Engineering

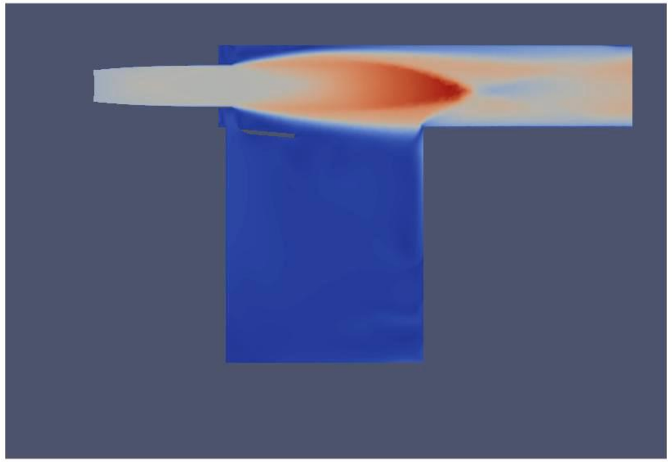
Aerothermal Modeling



Hypersonic Panel FTSI

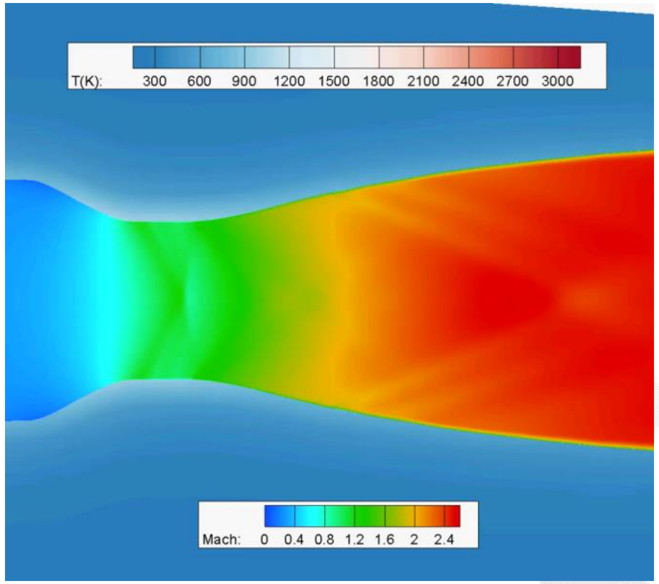


Wind Tunnel Transient Airload Prediction

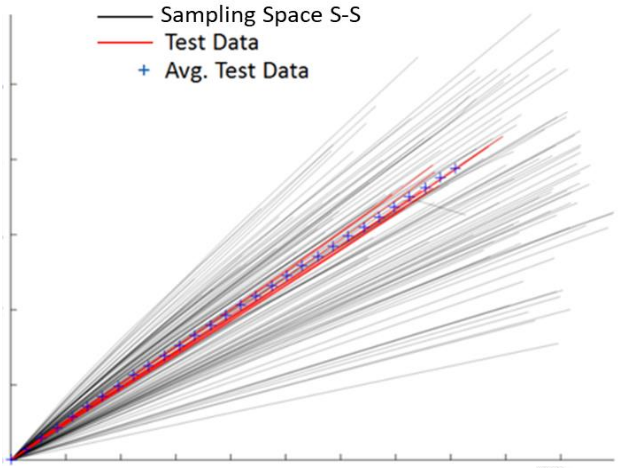


References:
AIAA 2013-1746
AIAA 2017-5021
AIAA 2022-2334

Nozzle Throat Ablation



Advanced Composites Modeling



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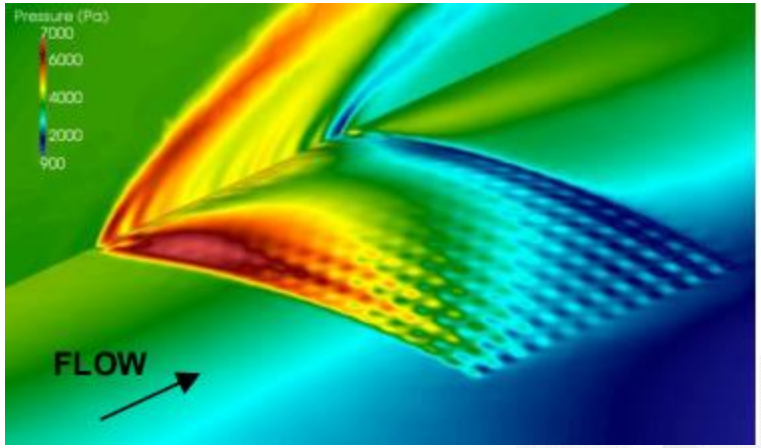
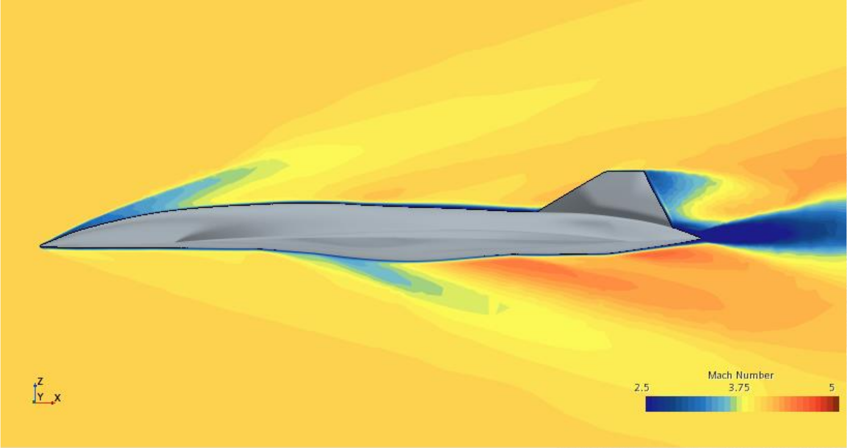
Loci/CHEM and STAR-CCM+ Both Used By ATA Engineering for Hypersonic Flows

- Loci/CHEM
  - University code developed at Mississippi State by Prof. Ed Luke
  - ATA Engineering among contributing developers
  - Flexibility to modify source/add modules makes Loci/CHEM good for research and development

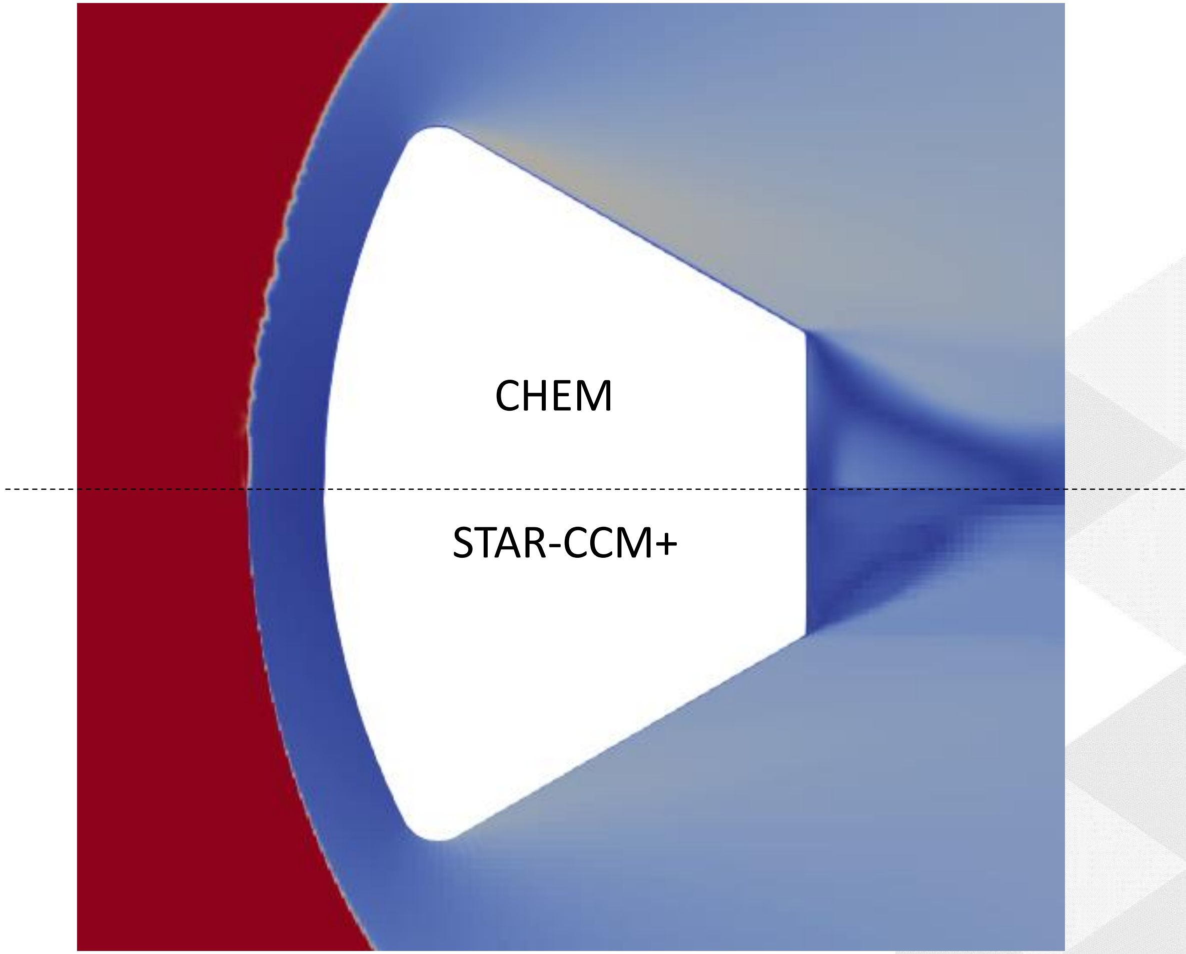


- STAR-CCM+
  - Multiphysics commercial package produced by Siemens
  - General CFD/multiphysics solver emphasizing efficient workflow, automation, and high-fidelity
  - Continued development towards hypersonics capabilities



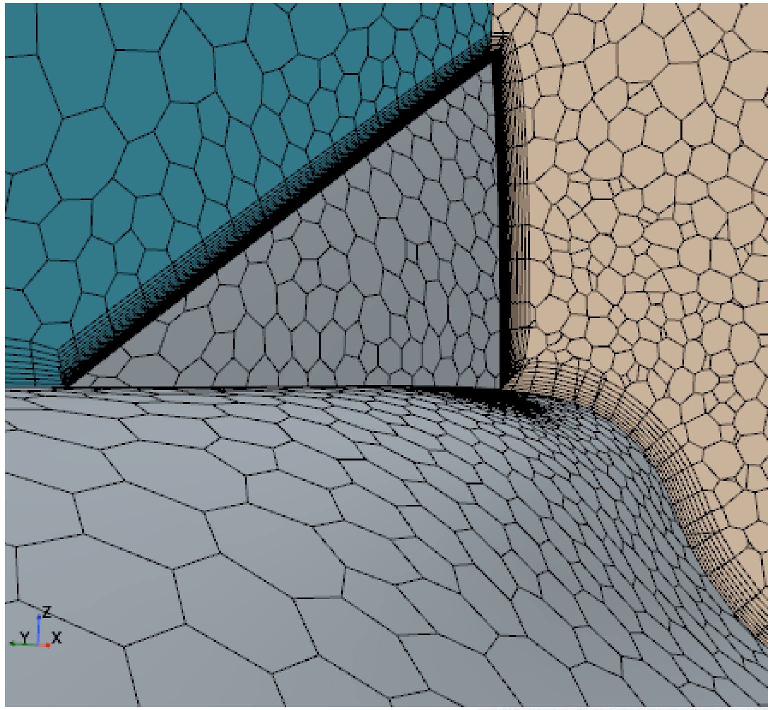
Flow Over Re-entry Capsule

- Example Mach 10 case run with both Loci/CHEM and STAR-CCM+
- Both tools produce perform well in the hypersonic regime
- Use of Loci/CHEM allows ATA to implement enhancements to develop tools to attack specific research problems
- Use of STAR-CCM+ enables efficient workflow and access to large suite of varied physics models



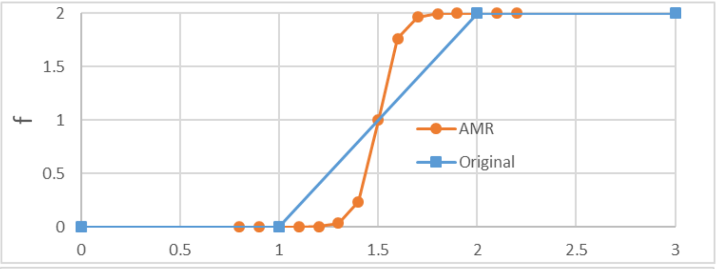
Meshing and Adaptive Mesh Refinement

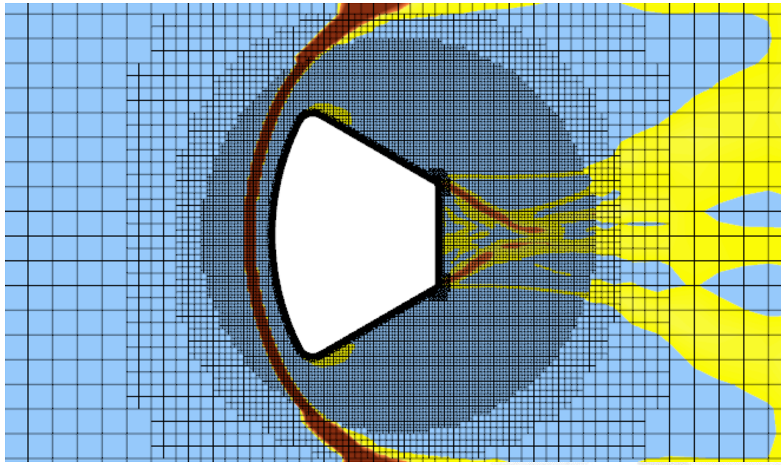
- Surface heating a large concern in design of vehicles for hypersonic environment
  - Prism layers at solid boundaries should accurately capture heat flux
  - Thicken prism layers to envelope shock to ameliorate Carbuncle
  - Wall Y+ << 1 recommended
- Shock waves are characteristic of supersonic and hypersonic flows
  - Position not known a-priori, based on solution
- Adaptive mesh refinement (AMR) places cells where needed based on user field function



Adaptive Mesh Refinement to Locally Resolve High Solution Gradients

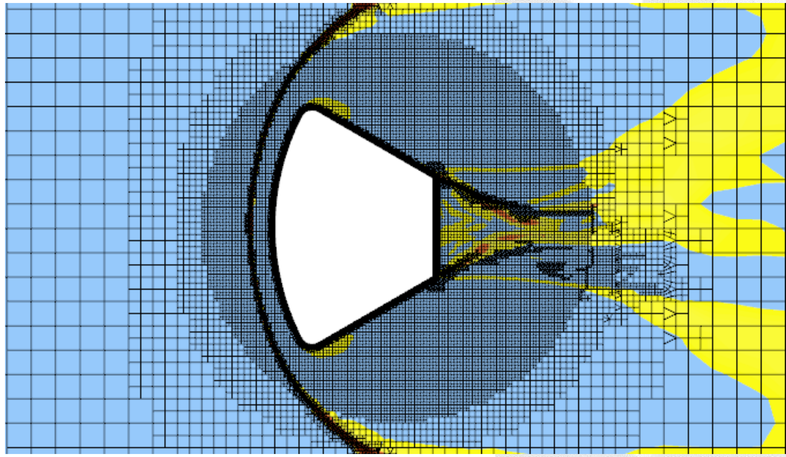
- AMR responds to user-defined metric to identify unresolved gradients
- Effective function quantifies gradient of flow field across cell: G=$|\nabla f| \cdot \Delta x$
  - Flow gradient times cell size
  - Use AMR to limit gradient





AMR Function on Coarse Grid

- Example AMR function in STAR-CCM+: mag(grad(${MachNumber}))*(${AdaptionCellSize})
- STAR-CCM+ AMR
  - Blue (G<0.2) – Coarsen towards original grid
  - Yellow (0.8>G>0.2) – Maintain size
  - Red (G>0.8) – Subdivide cell to specified limit



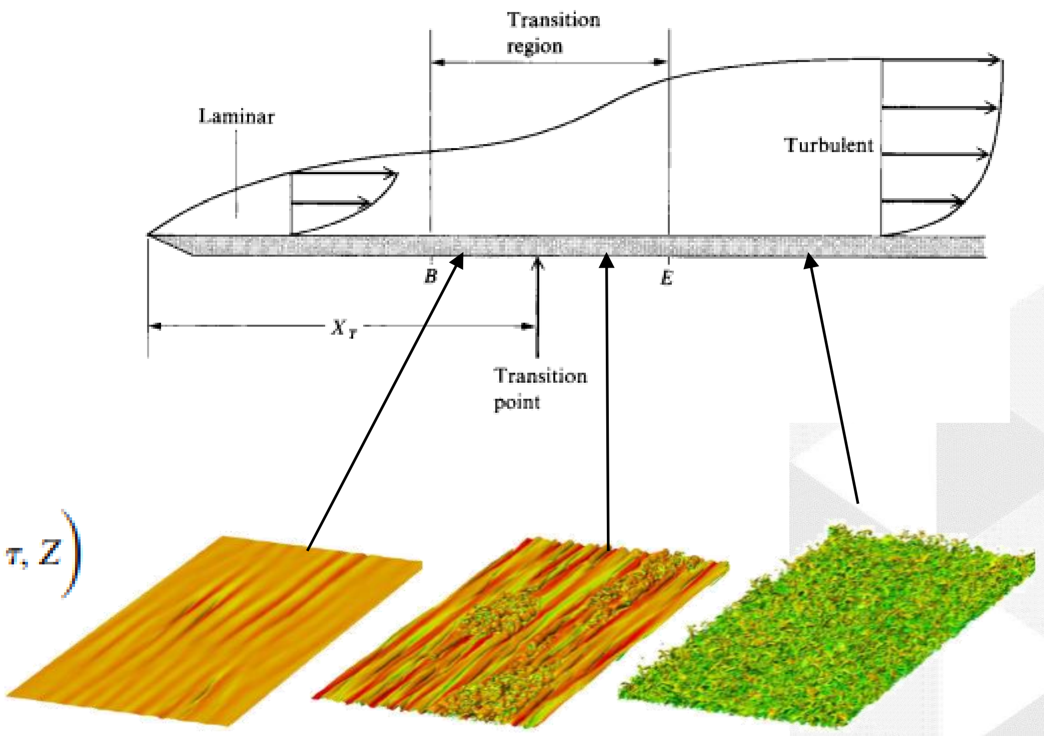
AMR Function on Refined Grid

Turbulence in Hypersonic Flows

- BL transition is complicated in hypersonic flows
- Incompressible flat plate BL Re_T~5e5
- In hypersonics, transition Re is complicated function of multiple parameters

$$Re_T = f\left(M_e, \theta_c, T_w, \dot{m}, \alpha, k_R, E, \frac{\partial p}{\partial x}, R_N, Re_\infty/\text{ft}, \frac{x}{R_N}, V, C, \frac{\partial w}{\partial z}, T_0, d^*, \tau, Z\right)$$

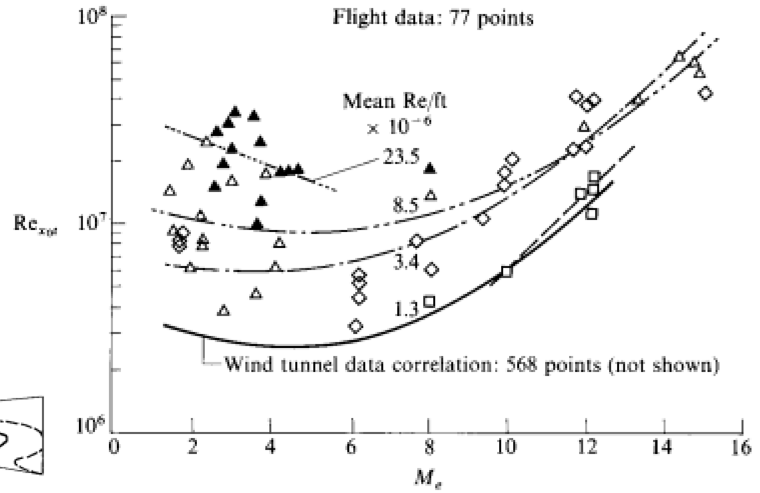
- Transition location is very problem specific, and often not consistent with lower speed observations



Three stages of a boundary layer during transition. Vorticity isosurface colored by streamwise velocity. (AIAA, 2013)

Some Hypersonic BL Transition Observations

- Transition Re observed to be delayed at high Mach numbers
  - Case dependent
  - Example above roughly Mach 4, Re_T increases rapidly
- Re_T increases with unit Re
- Strong 3D effects
  - At AoA, windward side delayed transition
- Blunt nosetip may delay transition
  - But not too blunt!
- Cold wall may delay *or* advance transition!



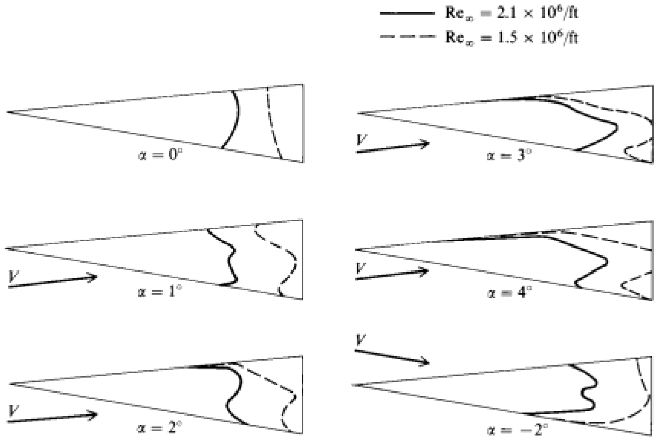
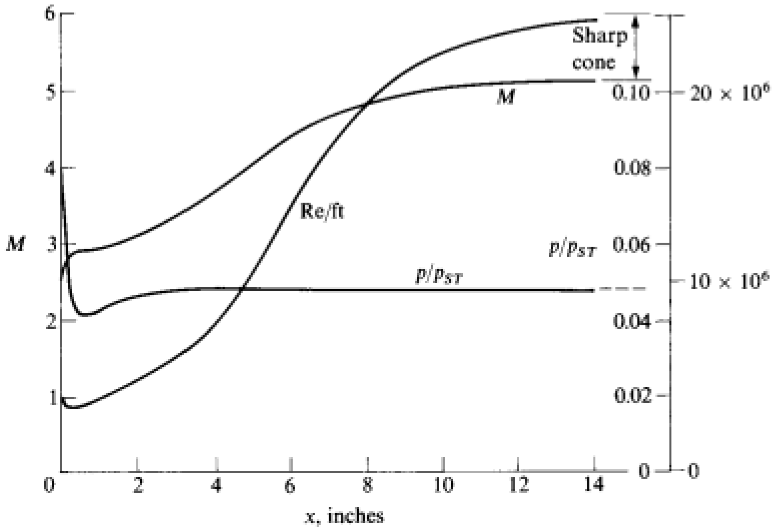


Fig. 6.26 Effect on angle of attack on boundary-layer transition on a sharp cone; θ_c = 8 deg (from DiCristina, [102]).



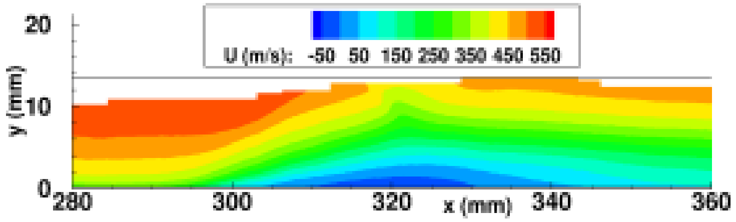
Turbulent BL not always present

Anderson "Hypersonic and High-Temperature Gas Dynamics"

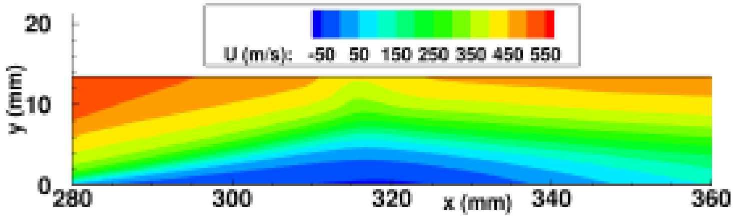
Recommended Settings for Turbulence Modeling

- Recommended turbulence model k-w SST with some non-standard changes
  - a_1 coefficient should be set to 0.355
  - Best for shock separated flows
- Quadratic constitutive relation (QCR)
  - Better accounts for anisotropy, secondary flows
- Specify k and w explicitly in initial conditions and in regions
  - $k = 1 \times 10^{-6} U_\infty^2$
  - $\omega = \frac{5U_\infty}{L}$

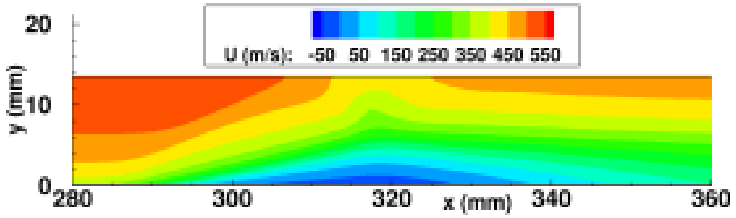
	Mach 10@70 kft L = 1 m	Default
k	9.2414	1.0E-03
ω	1.5E+04	1.0E-04



(a) Experiment



(b) SST



(d) SST, $a_1 = 0.355$

Georgiadis, Nicholas J., and Dennis A. Yoder. "Recalibration of the Shear Stress Transport Model to Improve Calculation of Shock Separated Flows." (2013).

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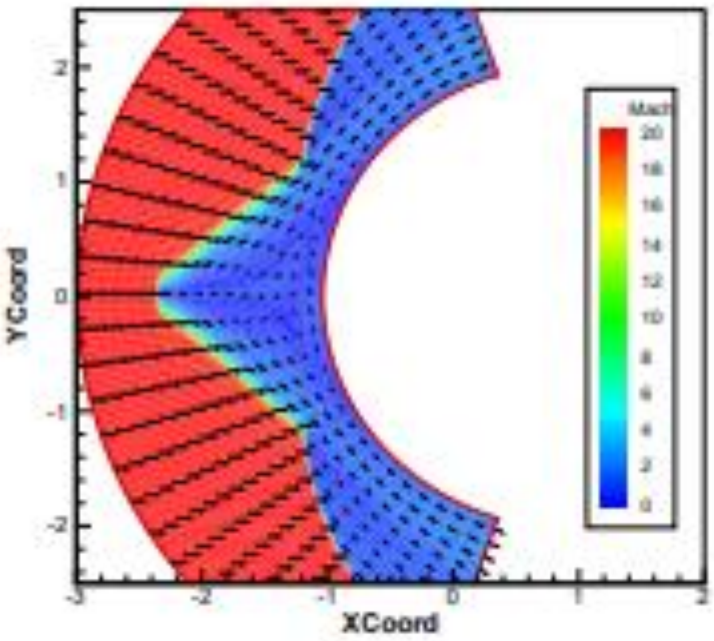
Solver Settings to Mitigate Inaccuracies and the Carbuncle Phenomenon

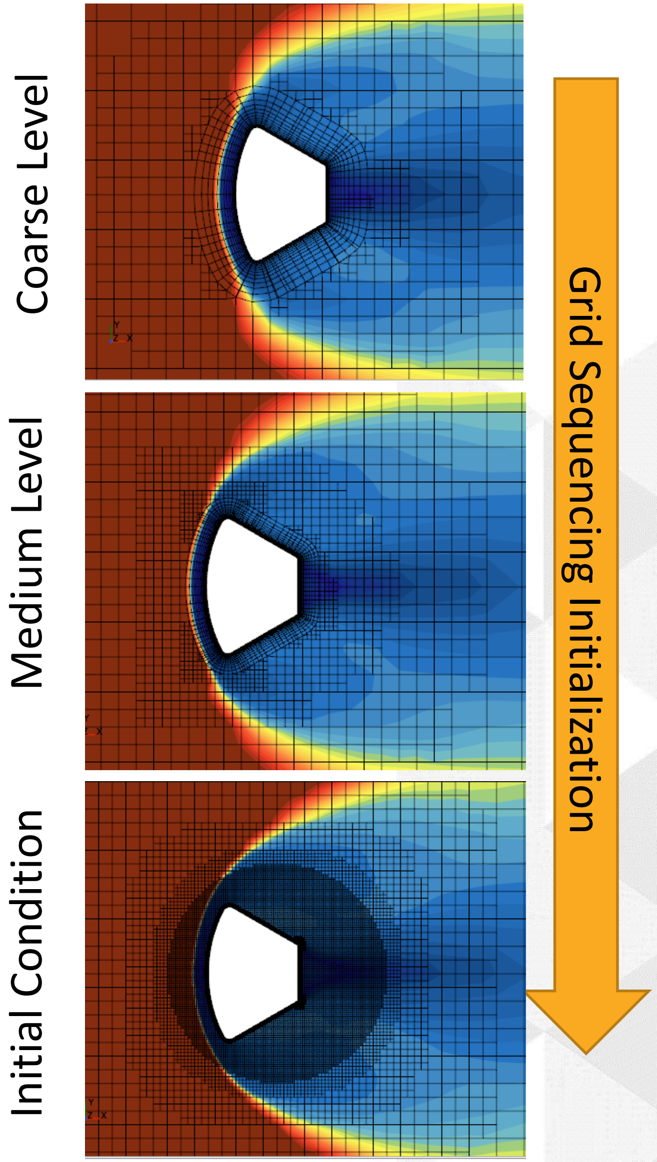
- Use AUSM+ flux vector splitting
  - Mesh misalignment with flow solution can produce spurious vorticity and shock-wave deformations
  - These can materialize as uneven wall heat flux and shear stress downstream
  - AUSM+ formulated to correct for mesh misalignments that lead to Carbuncle phenomenon
- Use MUSCL 3rd order differencing scheme
- Reduce AMG solver tolerance to 0.001 to avoid error stack-up
  - Will impact runtime
- Use ILU under-relaxation instead of constant value



An instance of the Carbuncle phenomenon
Ismail, et al., 2006

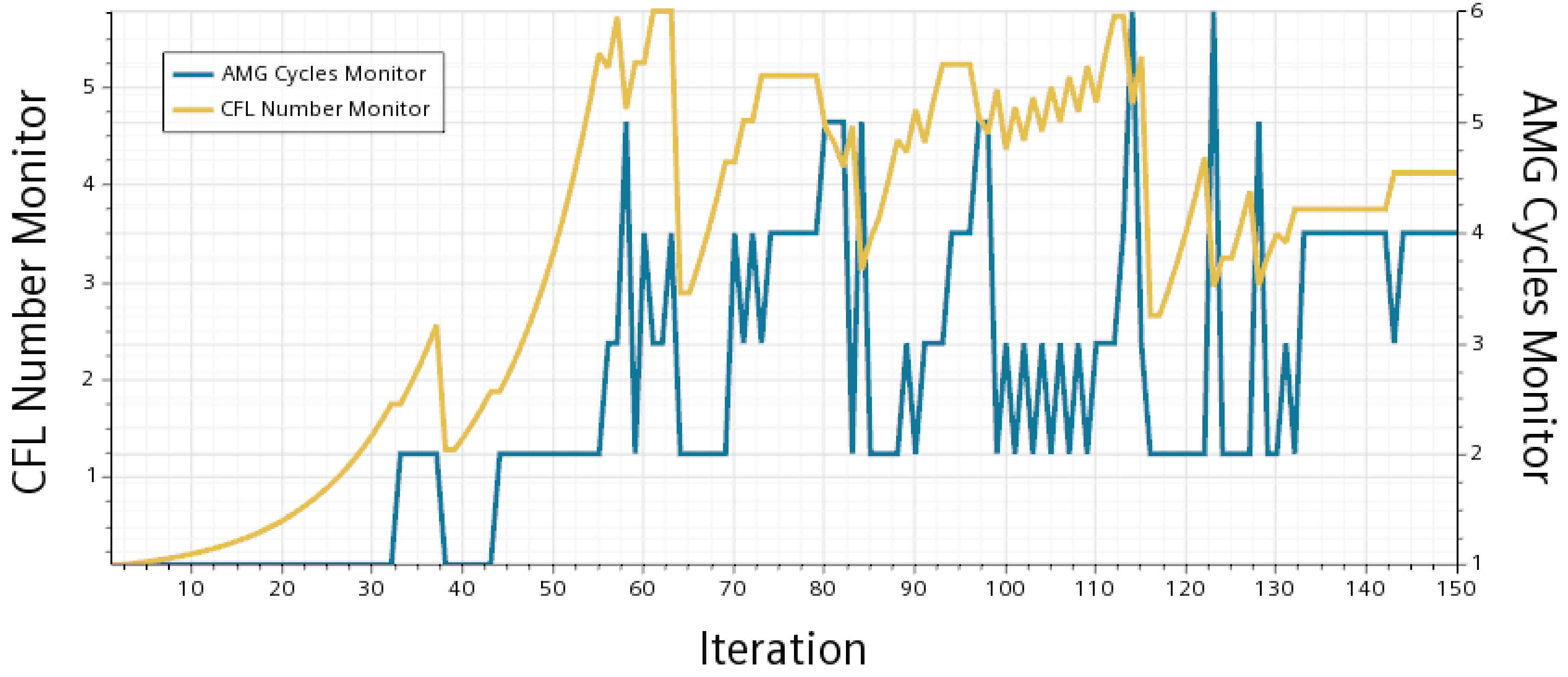
Grid Sequence Initialization Provides Higher Quality Initial Condition

- Bad initial guess of flow field can severely slow convergence or lead to divergence
- Grid sequencing expert initialization uses a multi-grid technique to provide good initial condition
  - Series of course meshes generated
  - Approximate solution is computed on coarsest grid, then interpolated to next finer grid
  - Process ends with initial condition on target mesh
- Higher wavenumber signals damped quickly on coarse grids



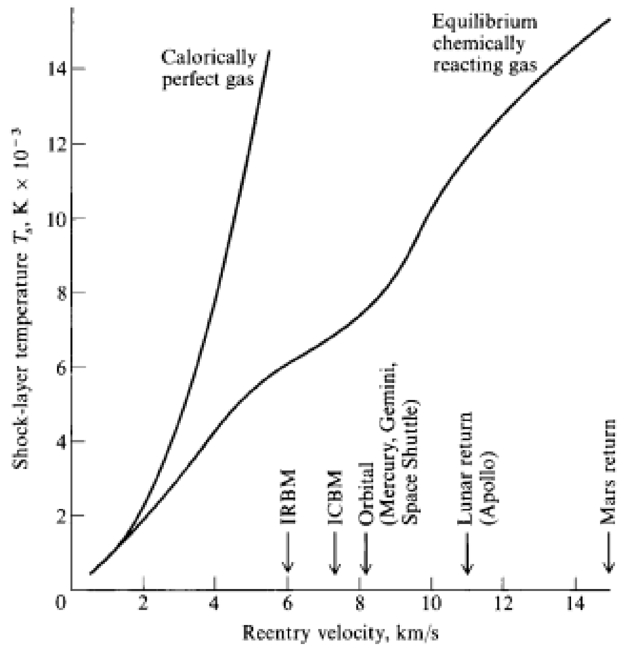
Automatic CFL Encourages Quicker Convergence

- The Automatic CFL method aggressively adjusts CFL number
  - Works in response to linear algebraic solver convergence, seeks balance between cost of forming linear system and cost of solving
- Accelerates convergence while preserving stability
- Line search under-relaxation may be helpful in difficult cases



High Temperature Hypersonic Flows

- At high temperatures the effects of molecular dissociation, internal energy excitation, and ionization become significant
  - Around 800 K the vibrational energy storage, $C_p/C_v=f(T)$
  - Above 2000 K, oxygen dissociation ($O_2 \rightarrow 2O$)
  - Above 4000 K, nitrogen dissociation ($N_2 \rightarrow 2N$)
  - Above 9000 K, ionization begins
- STAR-CCM+ Equilibrium Air model is recommended
  - Does not explicitly solve for dissociation and ionization
  - Curve fits account for chemical reactions and ionization



Anderson "Hypersonic and High-Temperature Gas Dynamics"

- Reaction chemistry unimportant unless in non-equilibrium or species needed for surface reactions, i.e. ablation
- If modeling ablation, detailed information about surface composition is needed, which is often unknown

For flow hypersonic flow predictions, STAR-CCM+ works well.
ATA uses Loci/CHEM coupled with in-house advanced material models for ablation

ENGINEERING, INC.

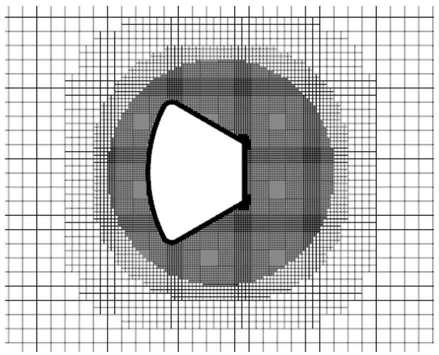
STAR-CCM+ is Built for Automation

- End-to-end workflow in a single environment
- Automate creation of aero databases without needing any user-driven customization

Native CAD and Software Links

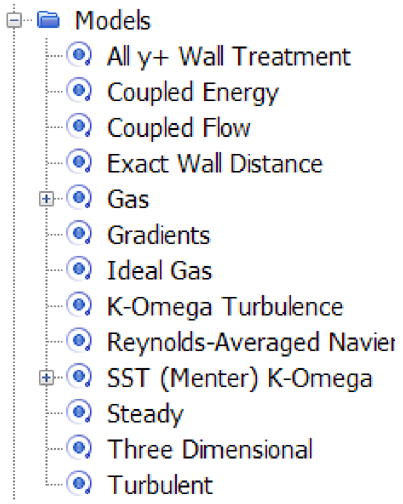
CAD

Robust and Intelligent Meshing



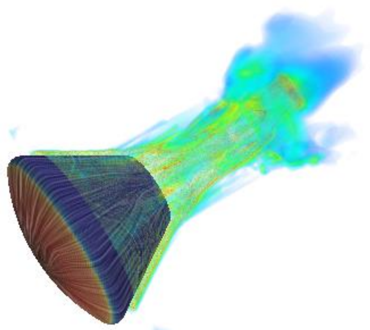
Mesh

Comprehensive High-Fidelity Physics Models



Solution

Powerful Solvers and Post Processing Tools

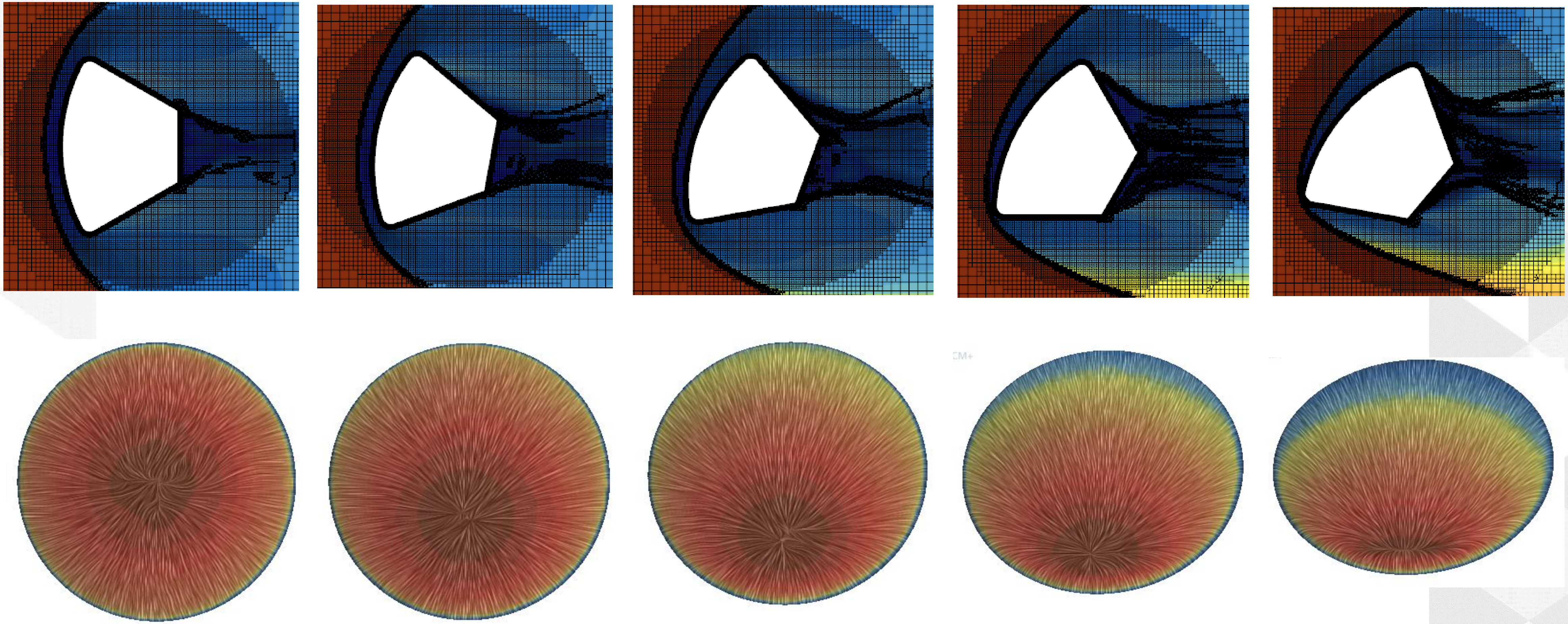


Analysis

ATA ENGINEERING, INC.

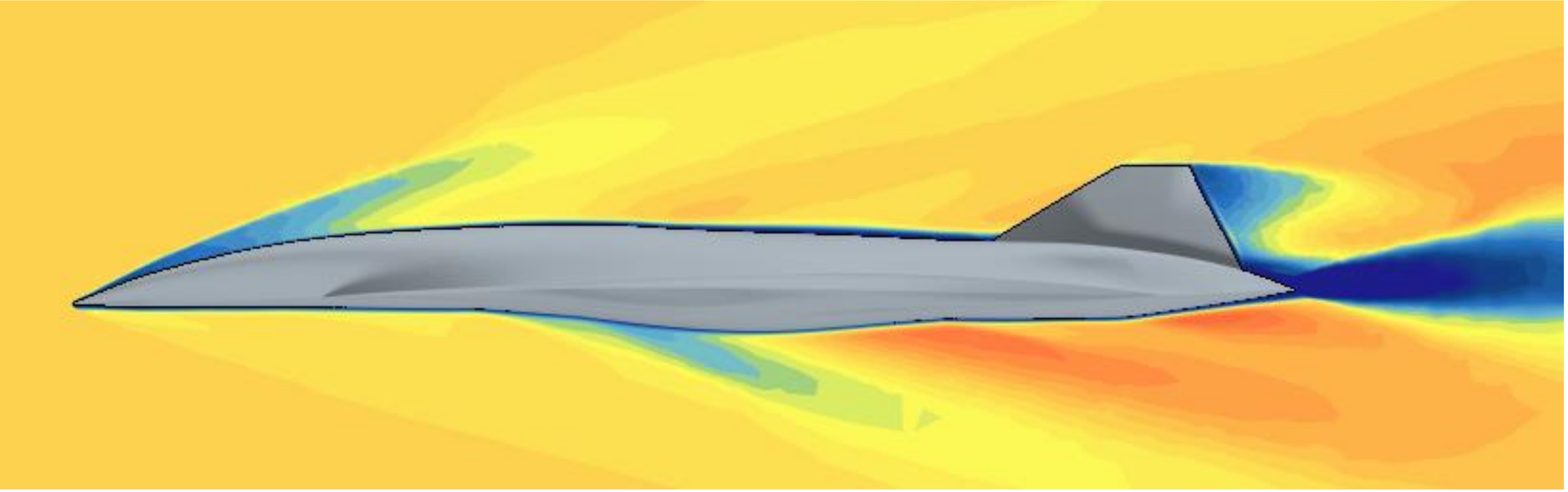
Automation Allows Engineer to Analyze Results While Computer Takes Care of Tedious Workflow

AoA sweep run on weekend on desktop computer



Modeling in the Hypersonic Environment

- ➢Review of issues in hypersonic modeling
- ➢Recommended best practices
- ➢Introduced how automation in STAR-CCM+ can save analyst time



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