Design Optimization of a Supersonic Natural Laminar Flow Business Jet

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Outline

- Quick explanation of laminar flow and transition prediction
- Design of various laminar flow experiments
  - small blade under F-15
  - airfoils for lengthened blade
  - rocket-propelled sled test
- Full aircraft configuration aerodynamic optimization

Natural Laminar Flow Supersonic Business Jet

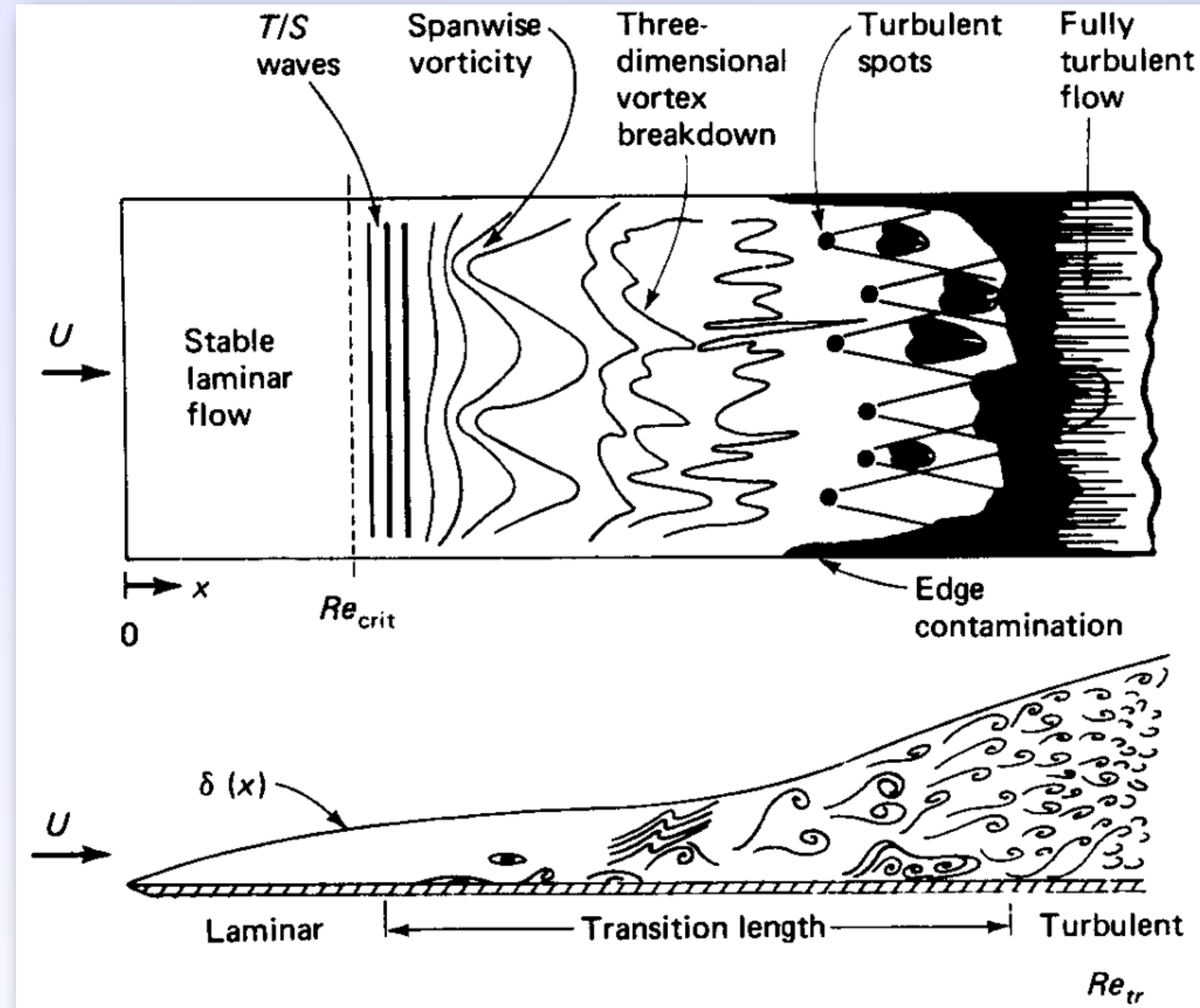
- Conventional supersonic designs minimize wave drag
  - wing/body shaping (traditional "area ruling")
  - propulsion integration
- Alternately can minimize skin friction
  - natural laminar flow
  - Aerion Corporation (Richard Tracy)

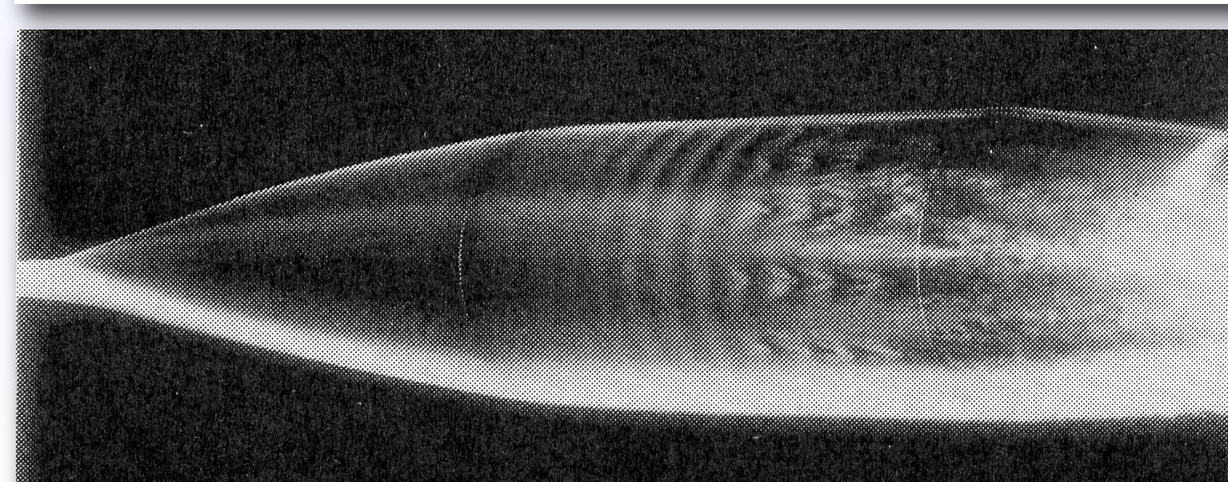
AERION corporation

www.aerioncorp.com

Laminar to Turbulent Transition

- ✦ Viscous boundary layer near surface begins in laminar state
- ✦ Laminar flow becomes unstable
  - initially instabilities behave as linear waves
  - various types of instabilities exist
- ✦ Turbulent flow bad for drag
  - skin friction increases 5 to 10-fold (depending on flight conditions)
  - very little laminar flow in today's jet aircraft





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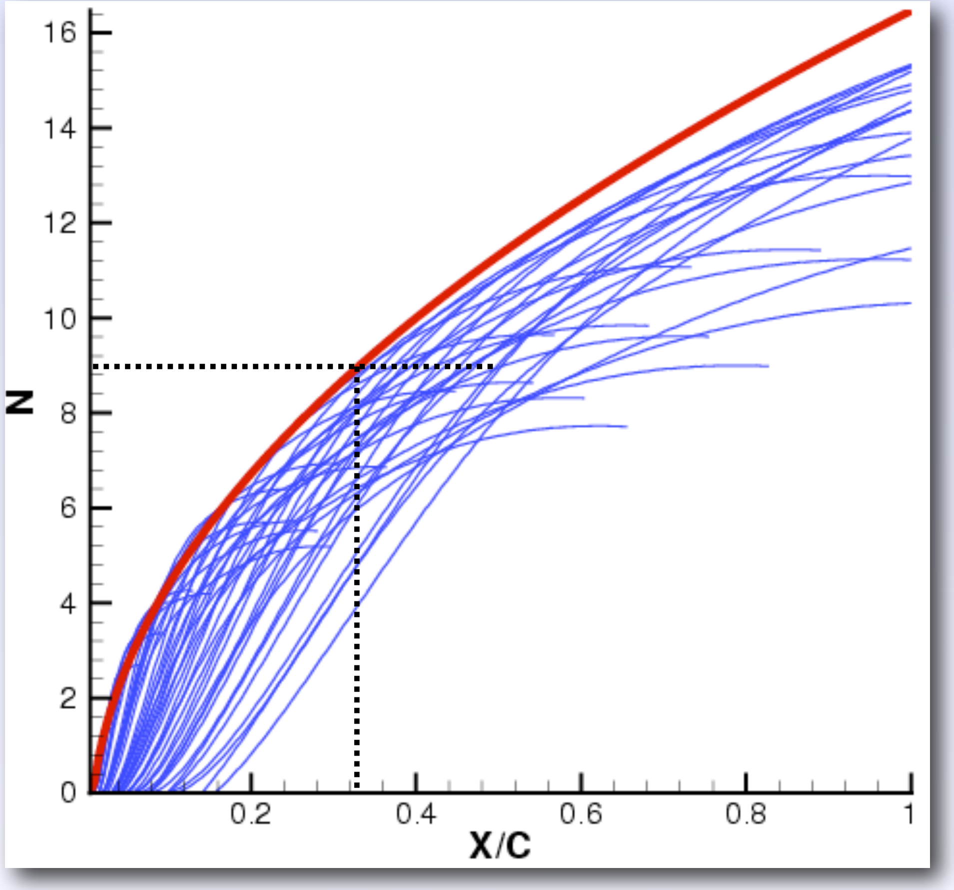
Design for Laminar Flow

- Current aviation industry practice very limited
  - 2-D airfoil section design based on pressure distribution
  - Beech did 3-D inverse design to a specified pressure distribution (Alonso & Reuther SYN-107)
  - interest in laminar flow increasing for transonic aircraft
- For Aerion, laminar flow drives entire configuration
  - strong coupling between supersonic wave drag and laminar flow
  - need transition modeling for conceptual design

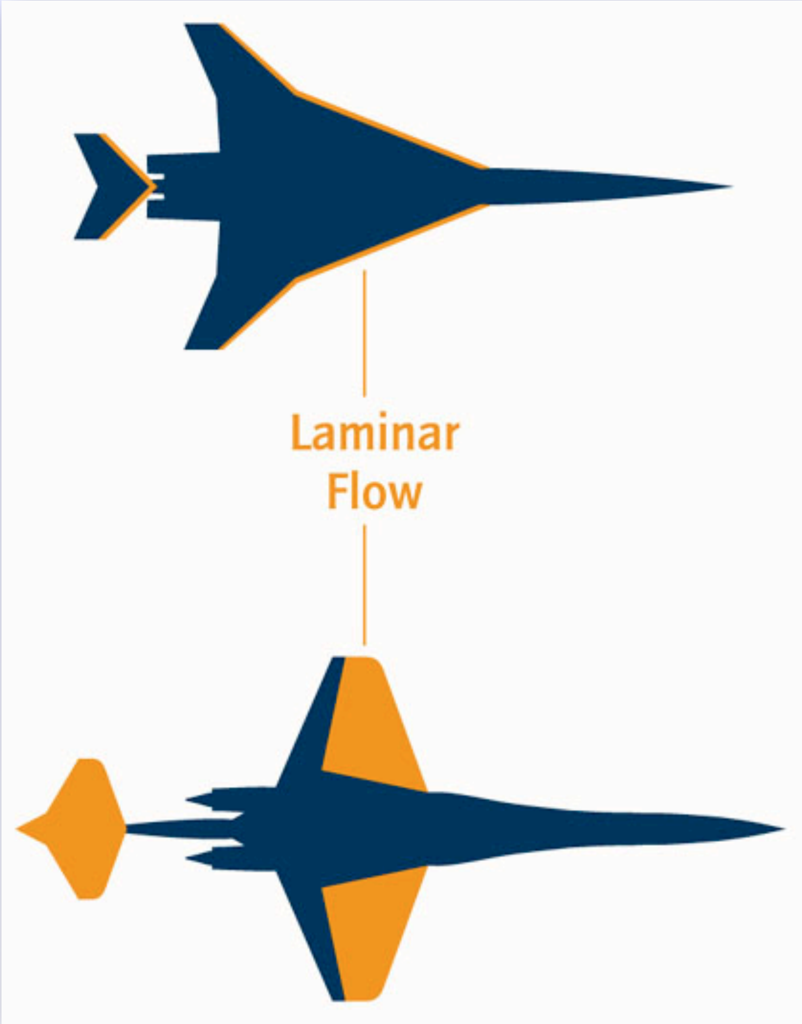
Modeling Transition

- Direct computation of transition still not practical
- Relatively high-fidelity transition prediction available since the '80s
  - computationally intensive, even the semi-empirical "e^N" method
  - human intervention required: "massaging" and "baby sitting"
  - not suited for numerical optimization
- Database or parametric models used instead
  - very fast
  - less accurate, but
  - can be focused around particular characteristics of aircraft of interest



Aerion Concept

- Supersonic flight stabilizes laminar flow
- Low wing sweep
  - delay crossflow transition
- Sharp leading edge
  - decrease wave drag
  - eliminate attachment line transition
  - favorable pressure gradient delays TS transition
- Thin wing
  - minimize wave drag
  - fuselage area ruling
  - structural and fuel volume trade
- Optimization necessary



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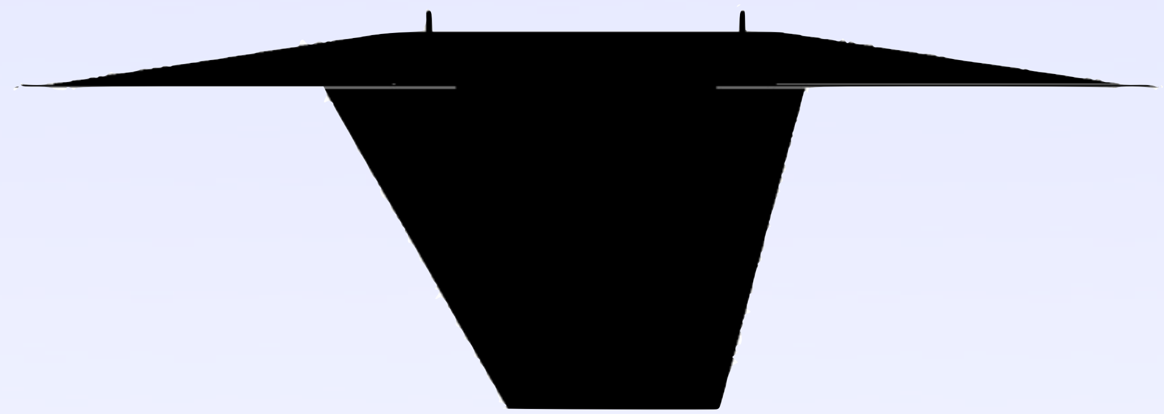
Does it Really Work?

- V-2 nose cone in 1950
  - Demonstrated 90 million Re_{tr} at Mach 2.7
- F104 test in 1959
  - Demonstrated 8 million Re_{tr} at Mach 2
  - Difficult to analyze due to lack of geometry model
- Most other tests on high Mach reentry bodies

Does it really work?

- Flight test under F-15B
- Aerion-like wing
  - Span: 80 cm
  - Sweep: 30° or 15°
  - Thickness: 3.5% root, 2.5% tip



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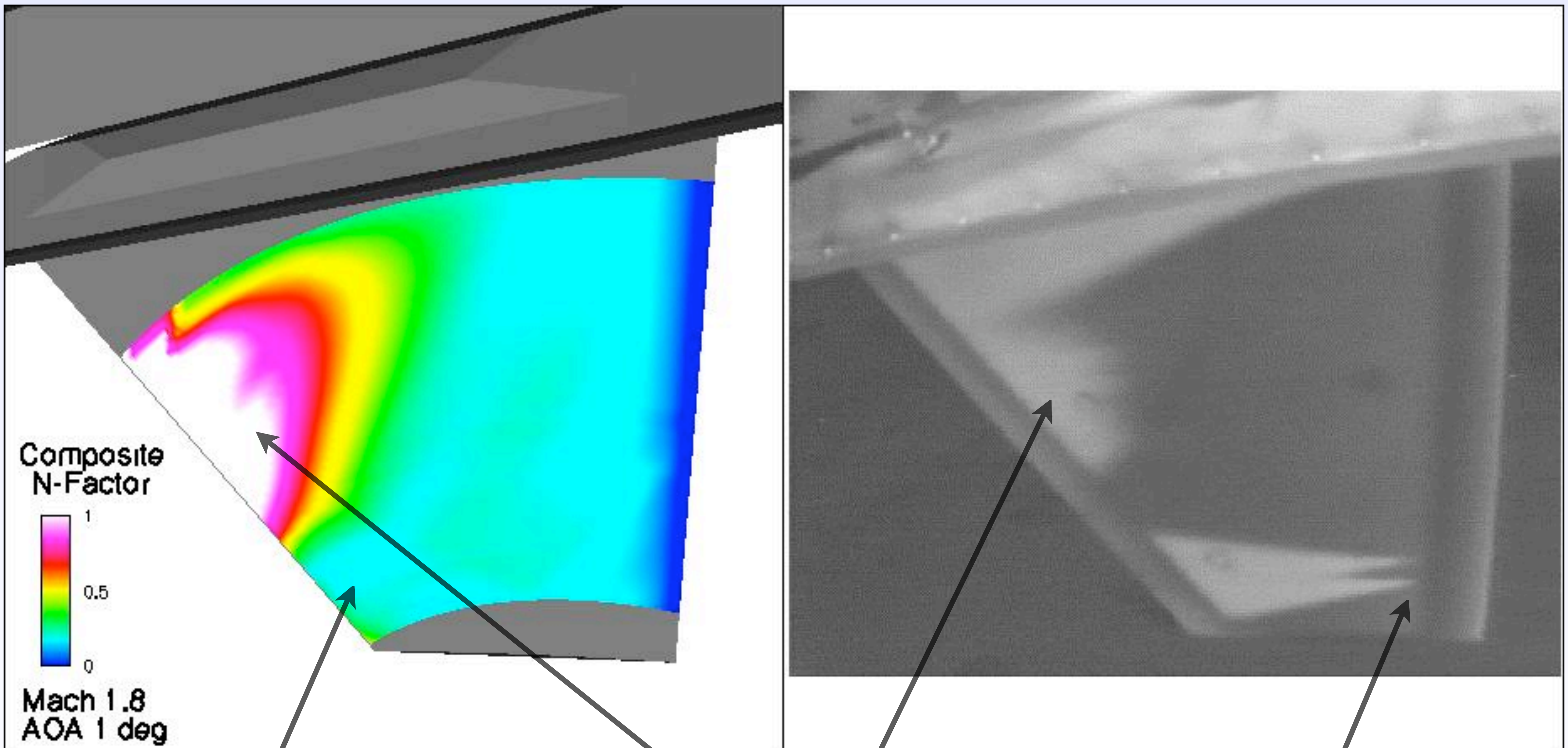
Does it Really Work?

Mach 1.8



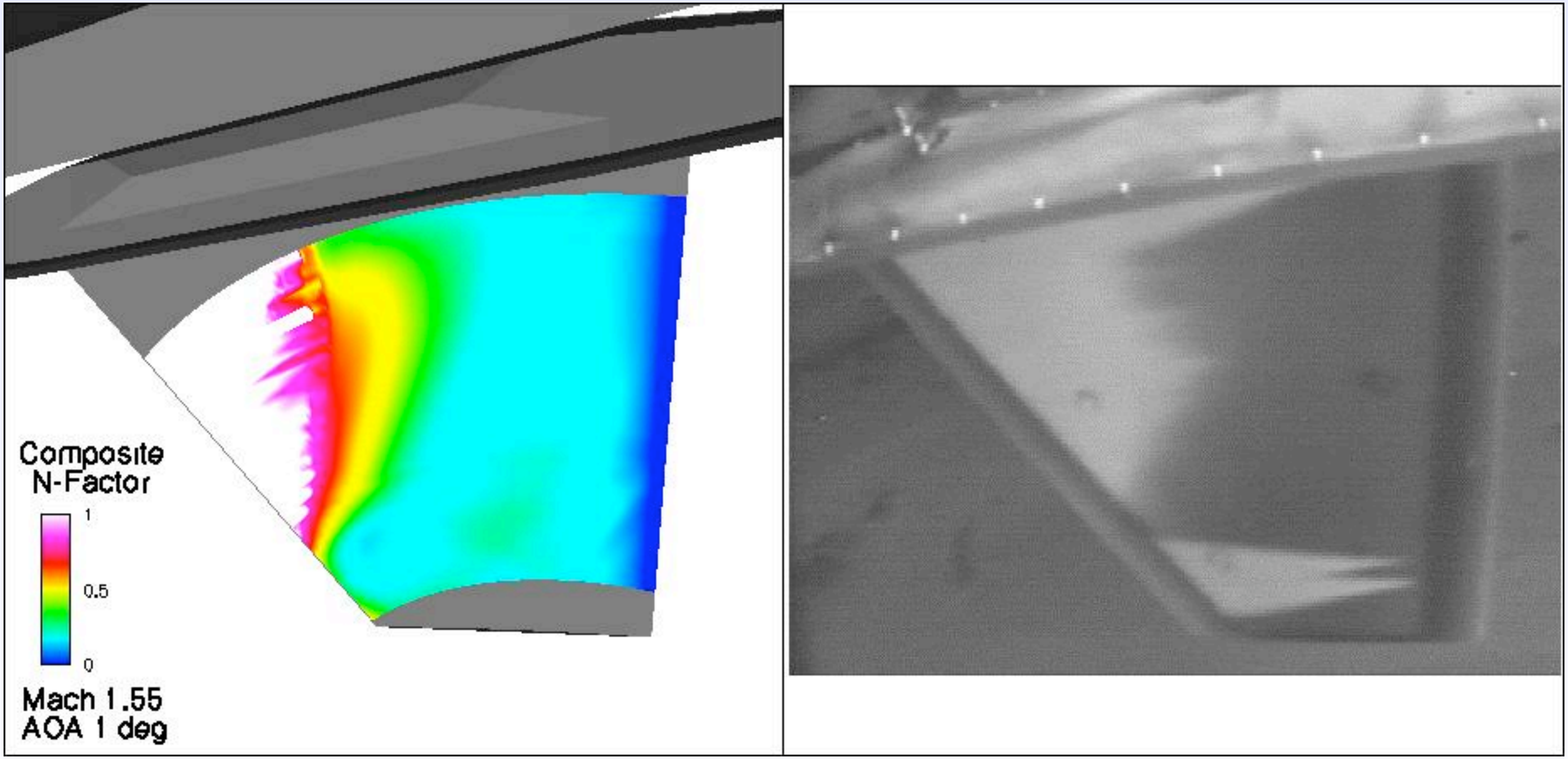
colors:
laminar flow

white:
turbulent flow

deliberate trips

Does it Really Work?

Mach 1.55



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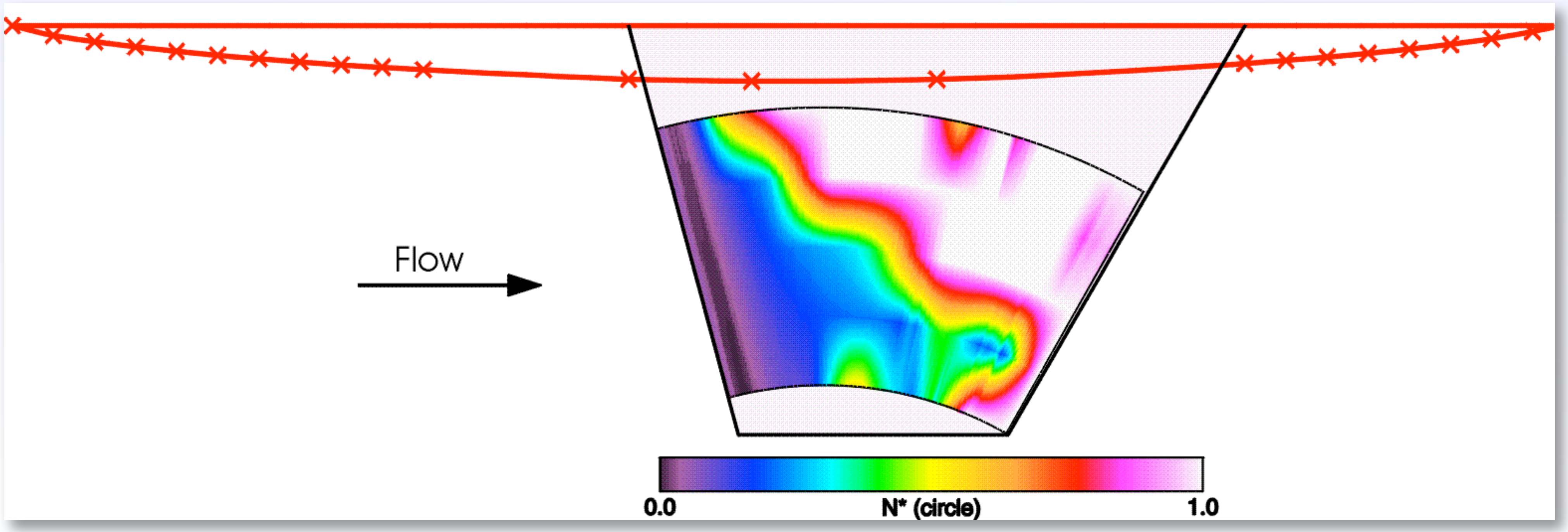
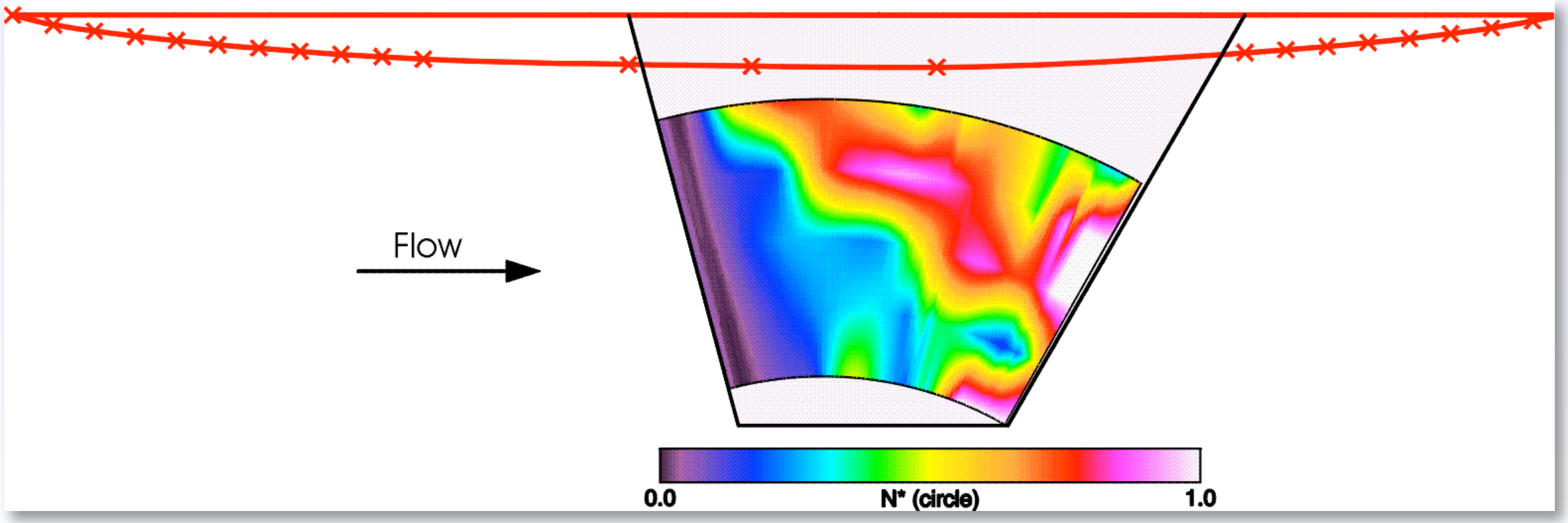
Early Design with Transition

- Proposed flight test article
  - fuselage half-body added to previous test article
  - Designed for Mach 1.8 at 40,000 feet
- Addition of half-body spoils laminar flow
  - Mach wave from wing leading-edge intersection
  - perhaps shaping can recover laminar flow?



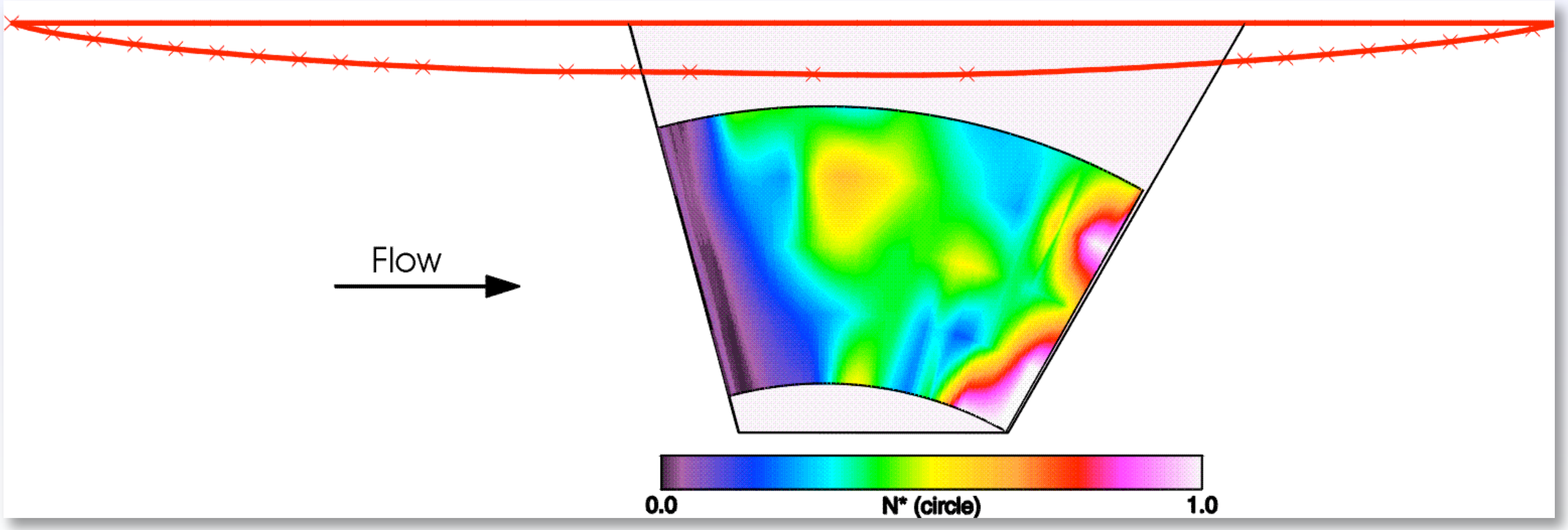
Early Design with Transition

- ✦ Shape optimization for laminar flow
  - quadratic response surface + trust region
  - 3 design variables initially
- ✦ Laminar flow increased
  - nearly to trailing edge
  - "hot spots" very close to transition



Early Design with Transition

- Final design iteration
  - increased to five design points on fuselage
  - transition margins increased



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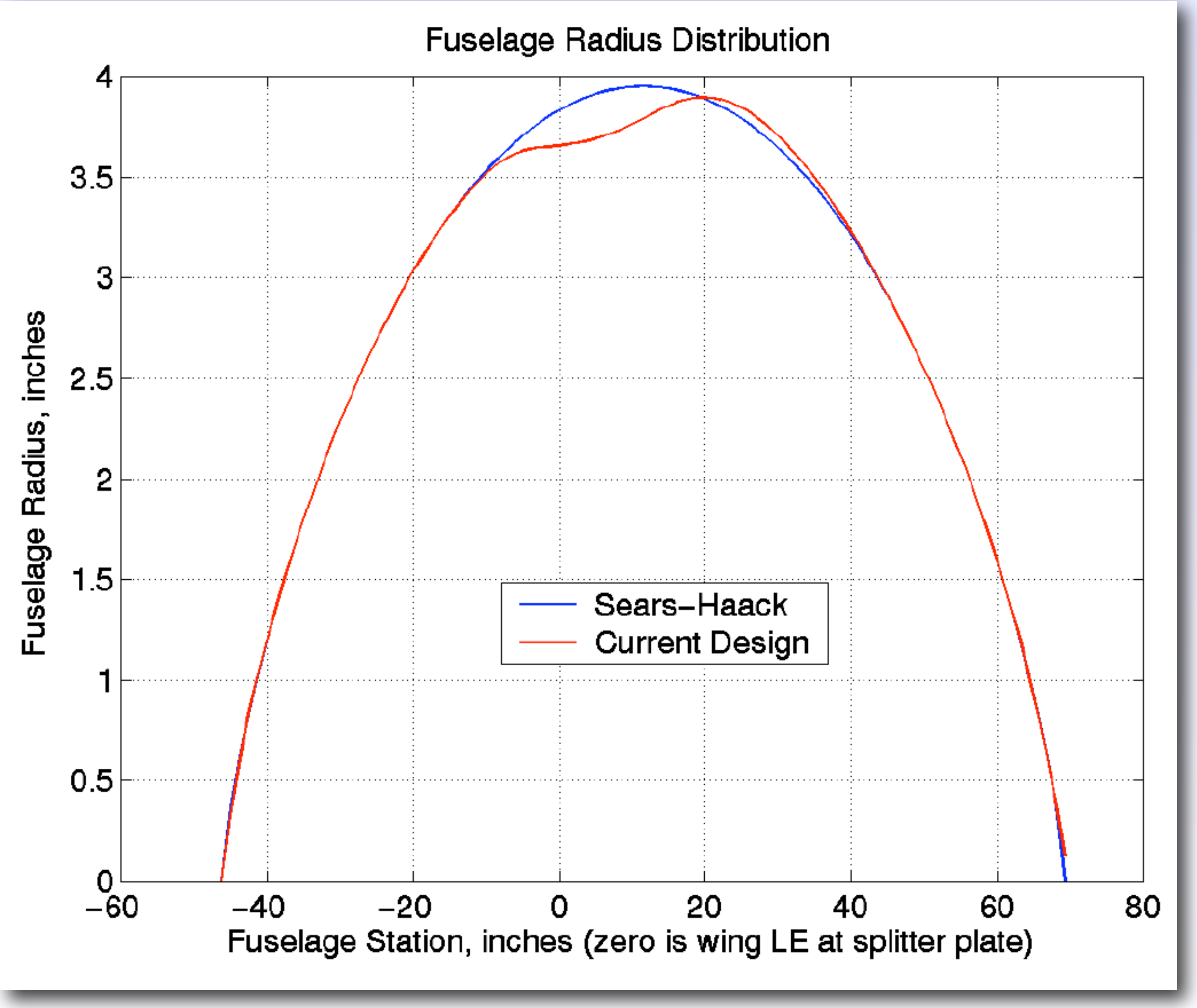
Early Design with Transition

- Fuselage reshaping is subtle
- Implies that design for laminar flow can be somewhat independent of area ruling



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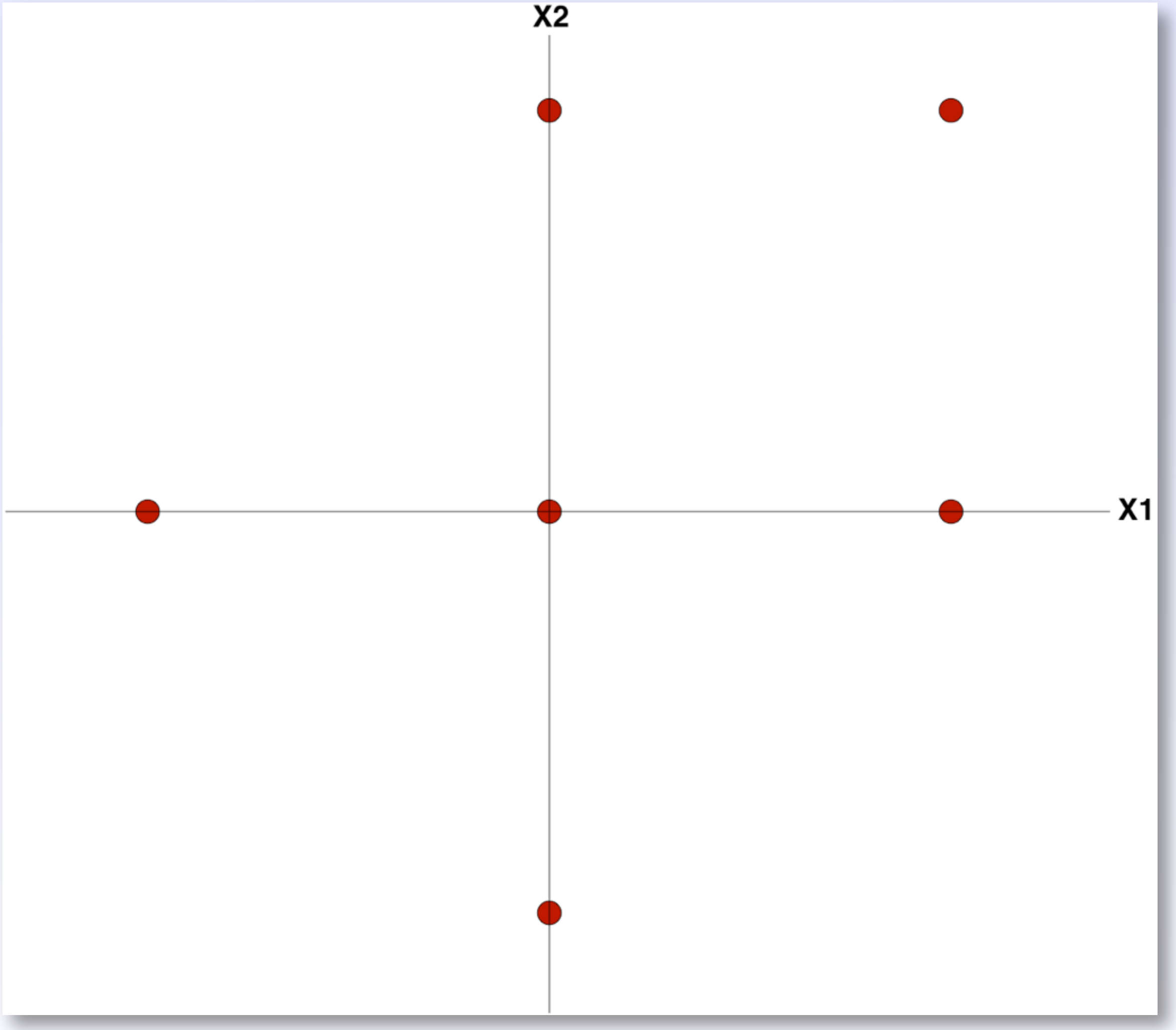
Details of Optimization

- Quadratic response surface with trust region algorithm
- Simplex-based point stencil
  - symmetric in design space
  - can sometimes reflect simplex to move trust region, re-using some old points
- 7 iterations
  - took advantage of reflection to save function evaluations
  - trust region updates by hand



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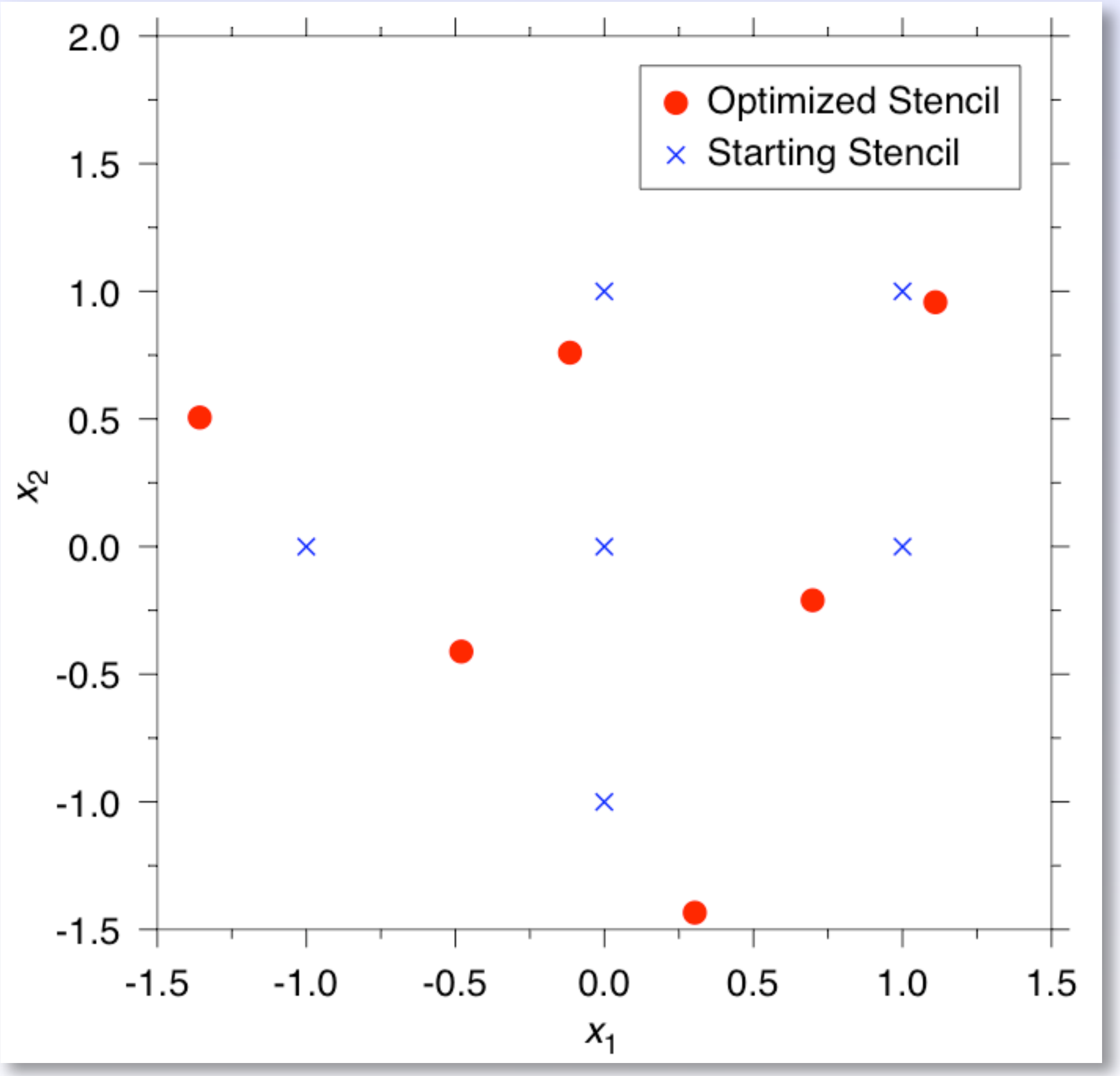

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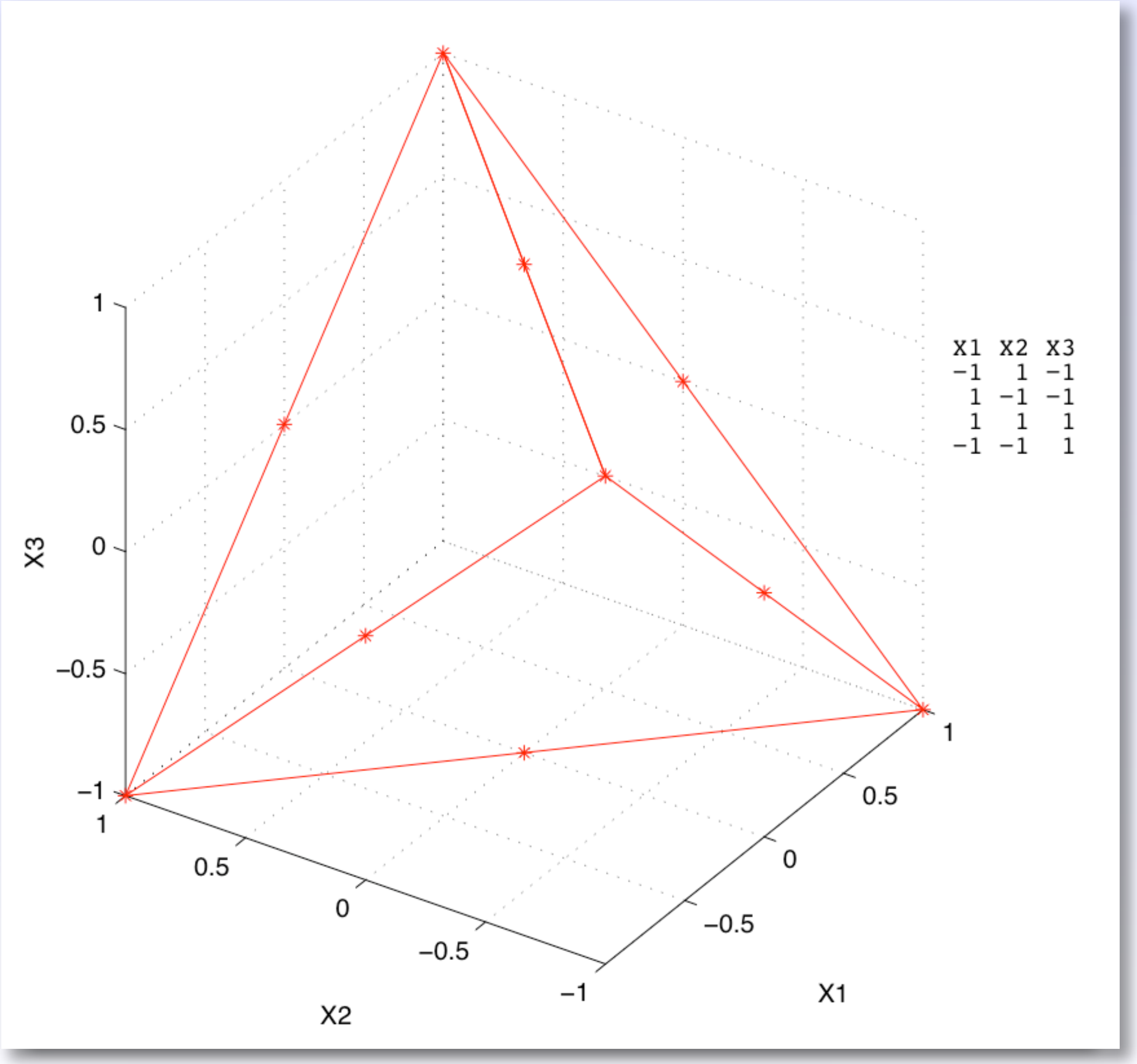

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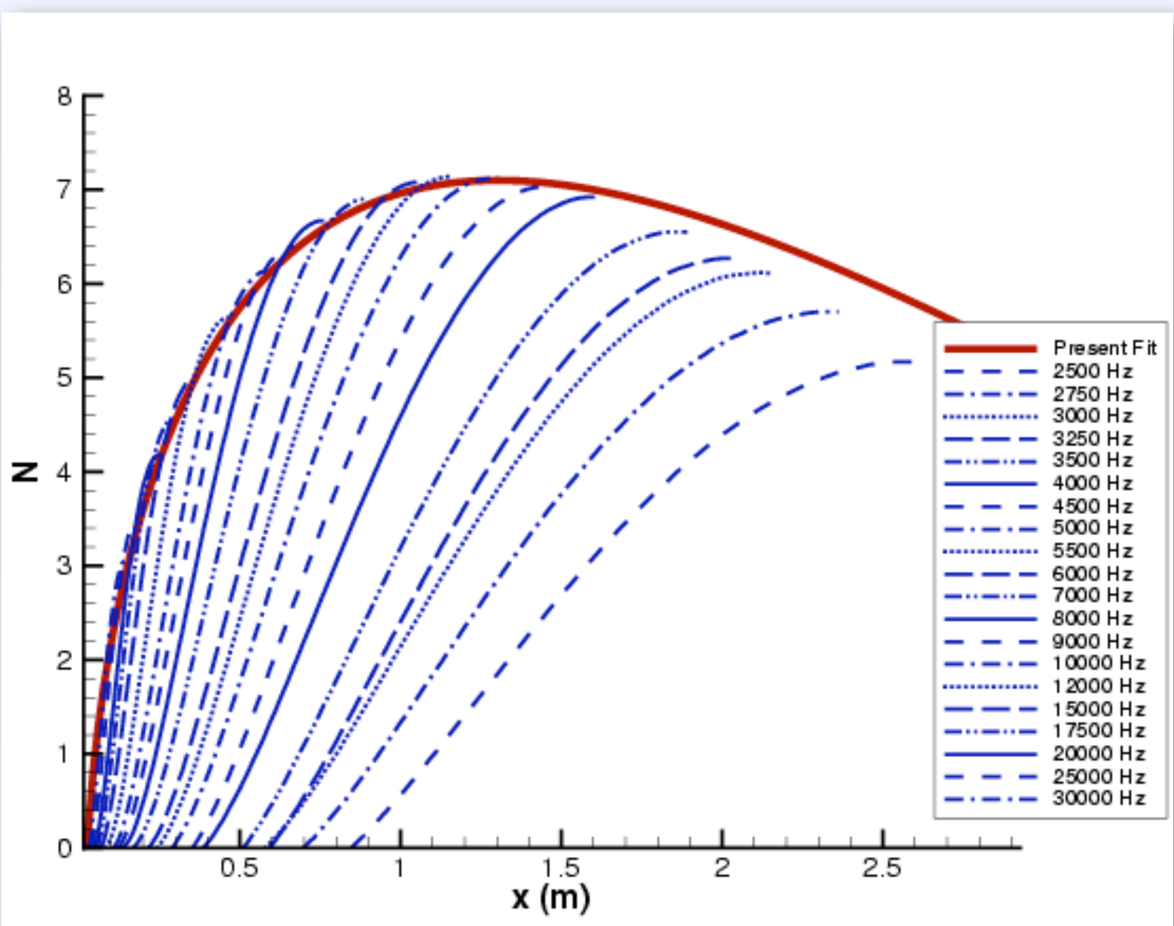
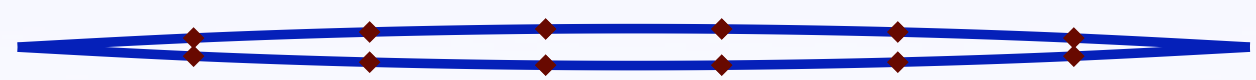
Airfoil Design for Laminar Flow

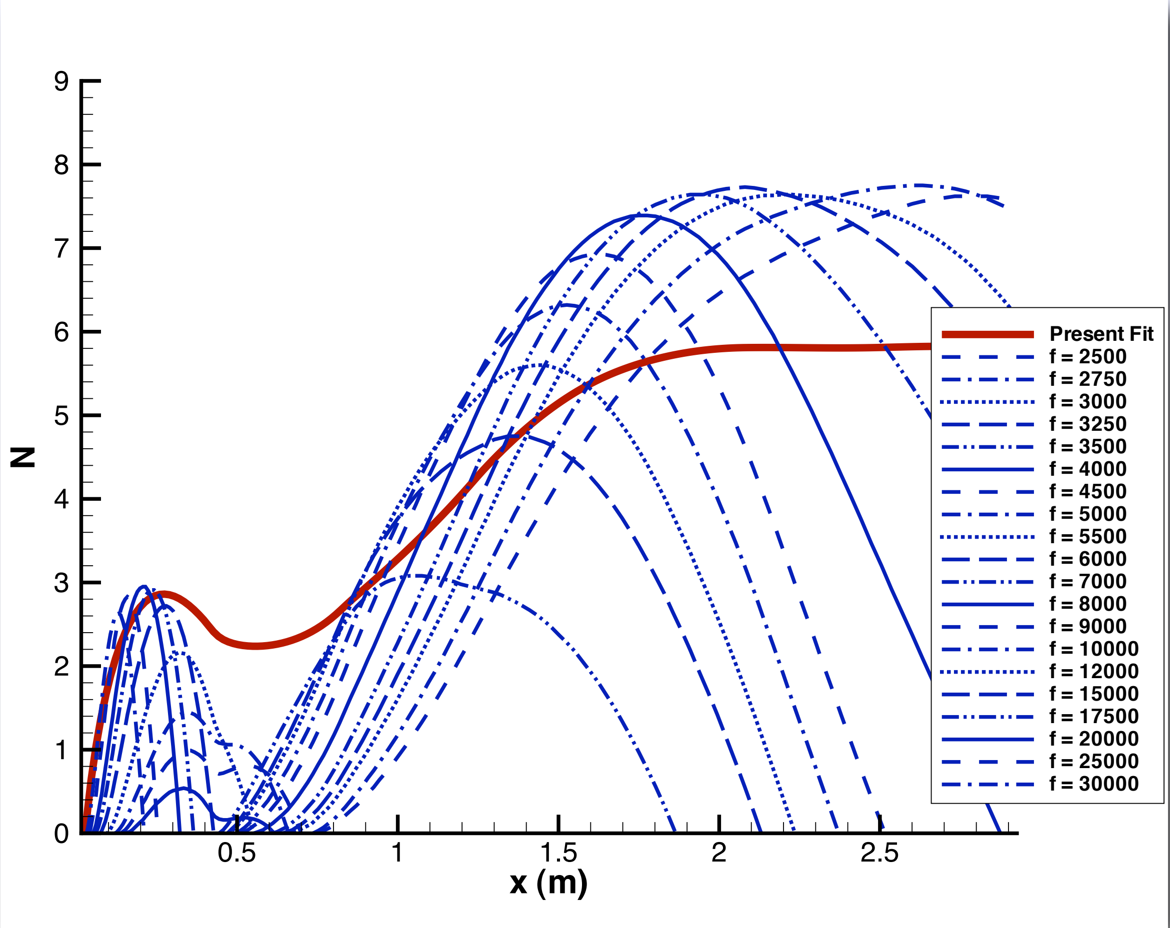
- Minimize N-factor on 2D airfoil at Mach 1.8
- 6 shape variables
- Thickness constrained to not more than 3% t/c
- Starting shape: parabolic biconvex



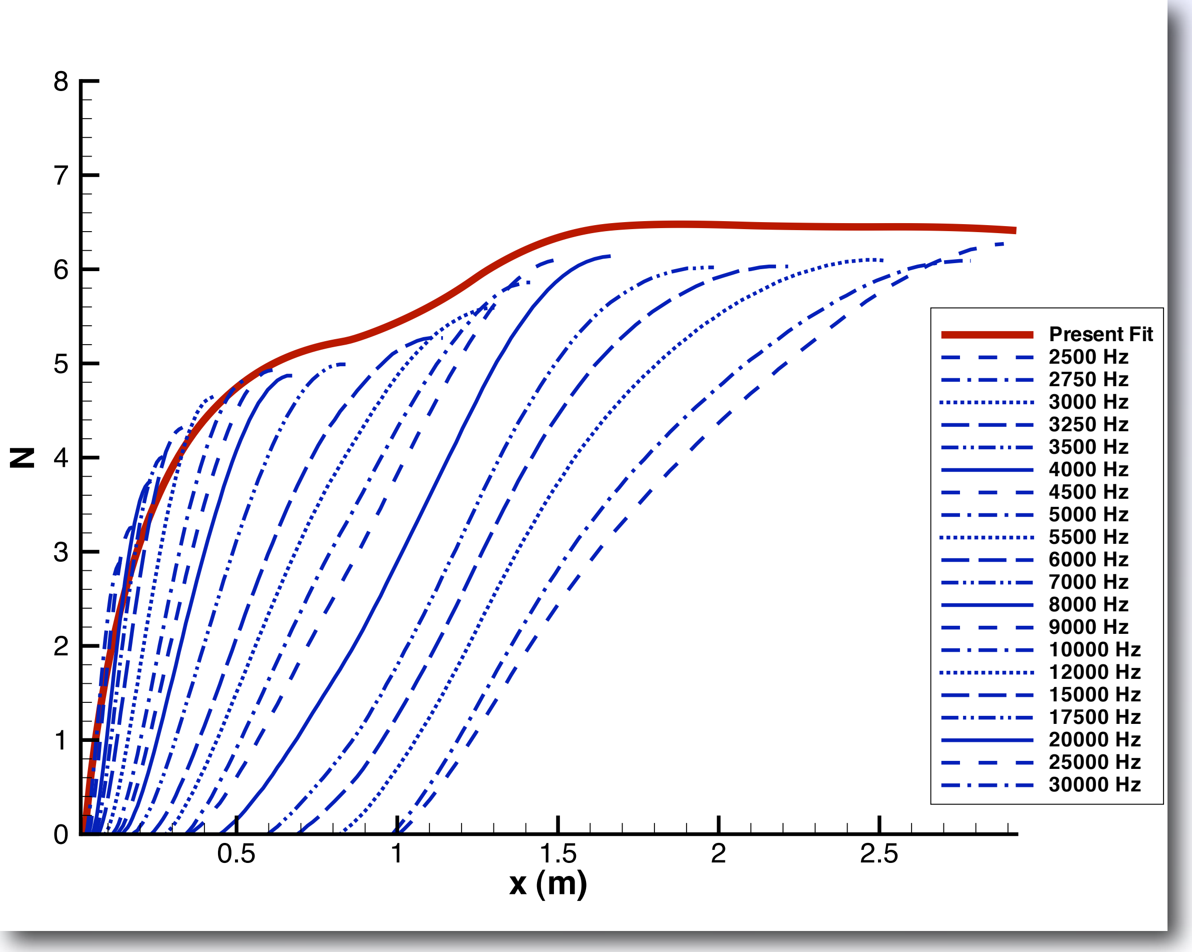


Airfoil Design for Laminar Flow

Initial optimization broke parametric fit

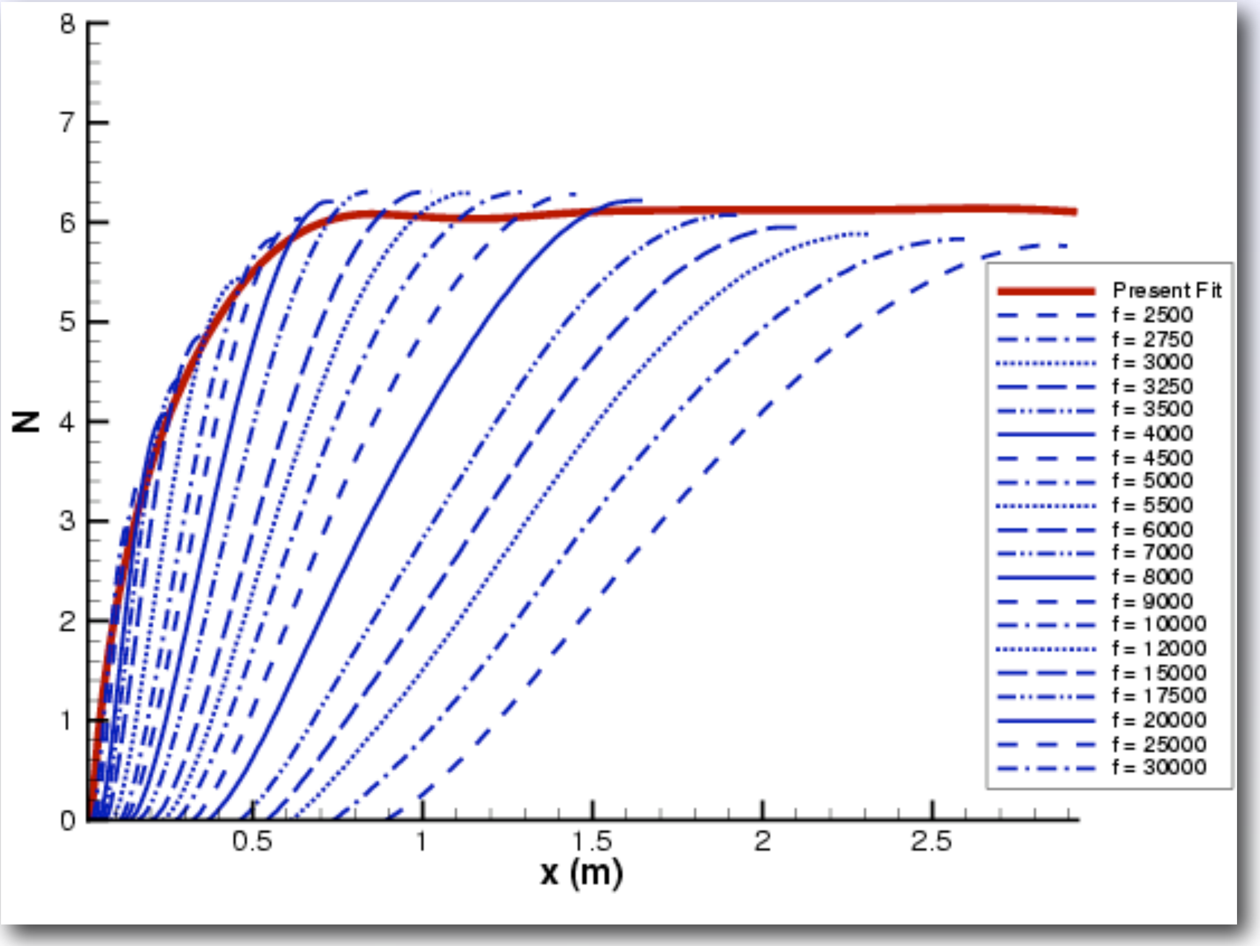


Quick fix: constraint on pressure gradient

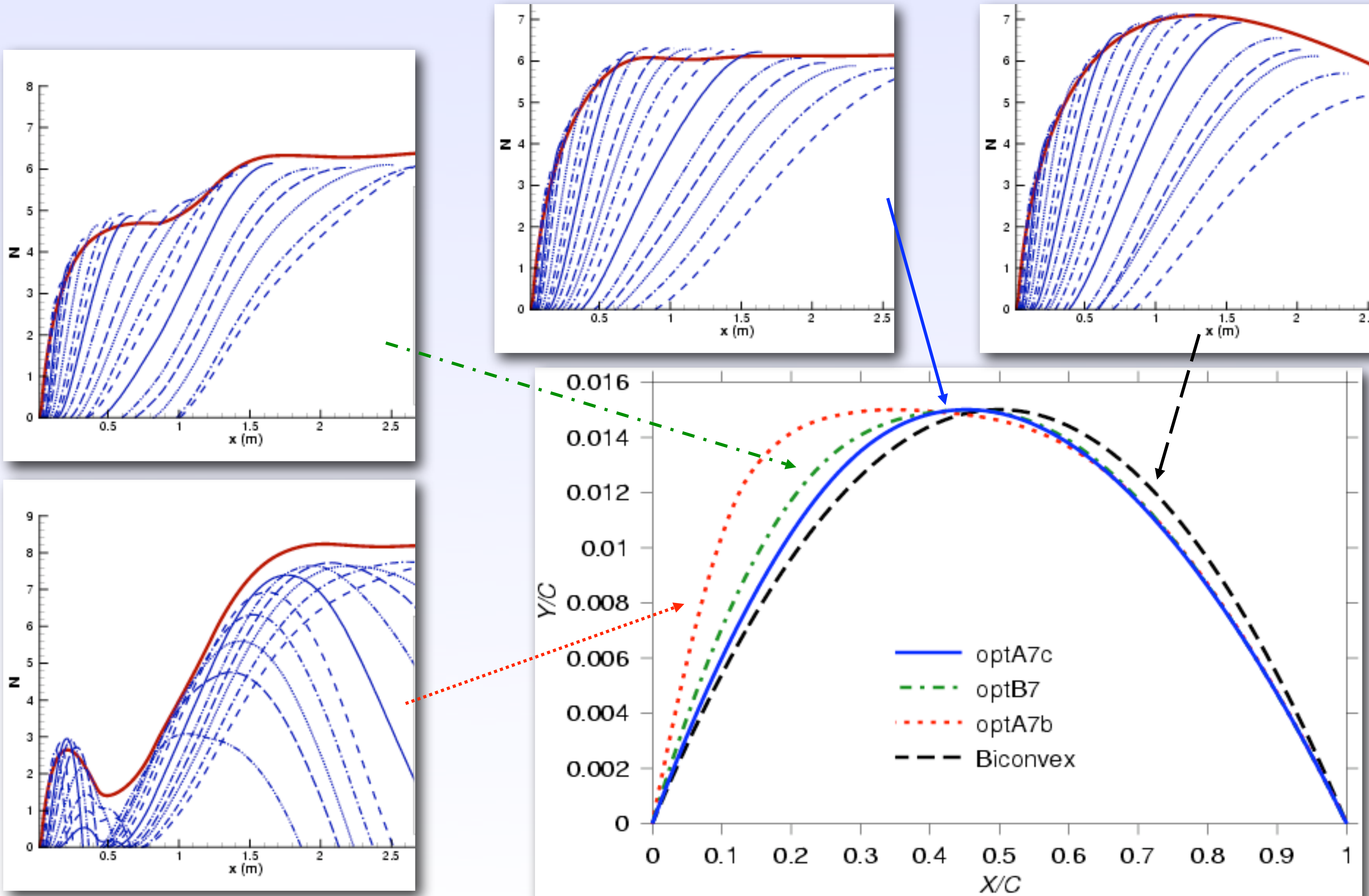


Airfoil Design for Laminar Flow

- Original N-factor fits too approximate
- Final design
  - flat N-factor aft of 20% chord
  - high-fidelity instability analysis in reasonable agreement
  - section maximum thickness slightly forward



Airfoil Design for Laminar Flow



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Details of Optimization

- ✦ Gradient-based sequential-quadratic optimization
- ✦ Complex-step derived gradients
- ✦ Maximum N-factor splined with Akima algorithm
- ✦ Issues when multiple maxima in N-factor arise
  - maximum location jumps between different peaks
  - optimizer sees inaccurate gradients near optimum
  - tried reformulated objective using norms of discrete N-factors
    - smooth objective near optimum
    - does not improve convergence rate
    - regions of airfoil with control over maxima still moves around

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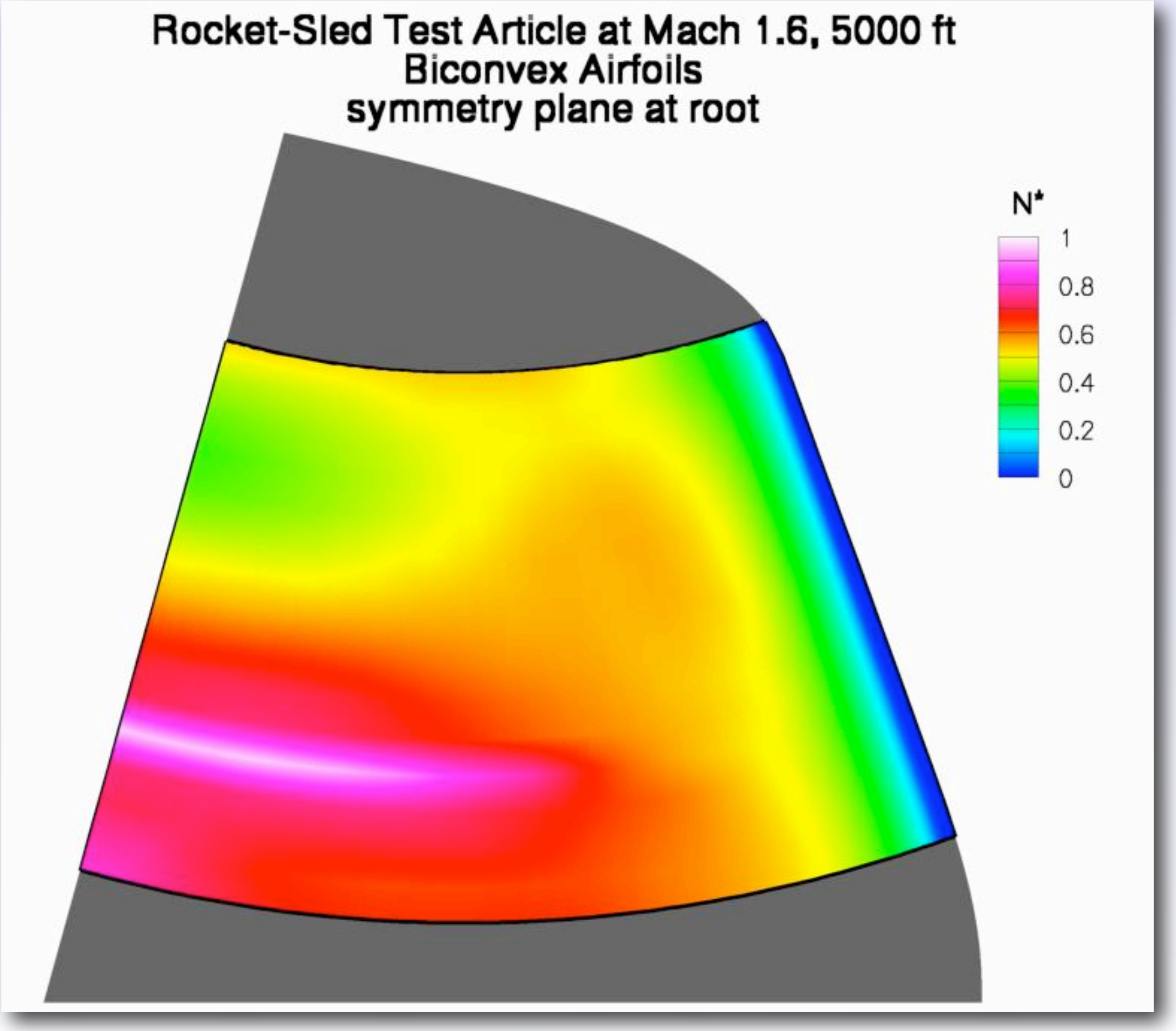
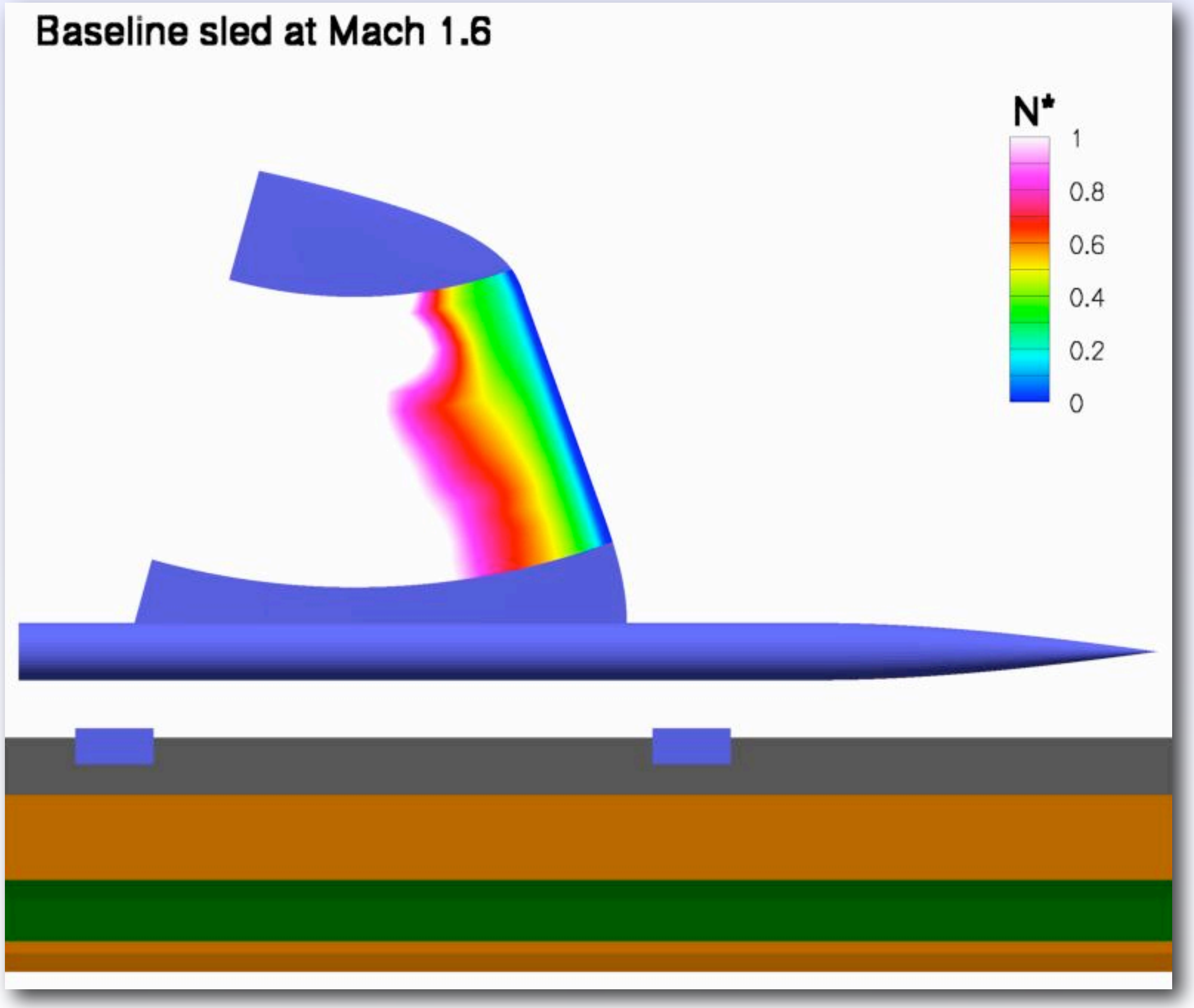
Rocket-Sled Test

- Rocket-propelled sled accelerated to Mach 1.5 - 1.6
  - Test blade representative of Aerion wing planform and airfoils
  - 30 million + Reynolds number
- Main issues
  - Structural vibration from sled runners and pusher rockets
  - Very high Reynolds/foot ~ 5x flight scale
    - Laminar stability requires higher surface quality (more polished)
    - IR requires high emissivity coating (less polished)
  - Heating from rocket plume destabilizes laminar flow
- Testing to determine feasibility is on-going

Rocket-Sled Test

Complex geometry necessary for aerodynamic analysis and design of test article





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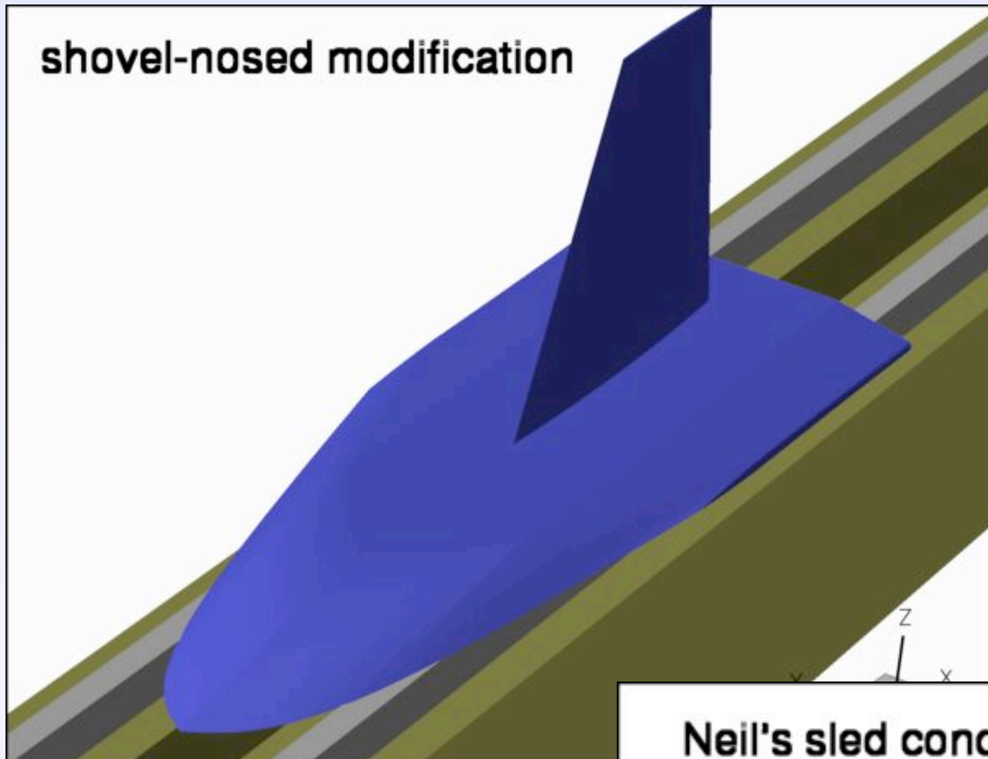
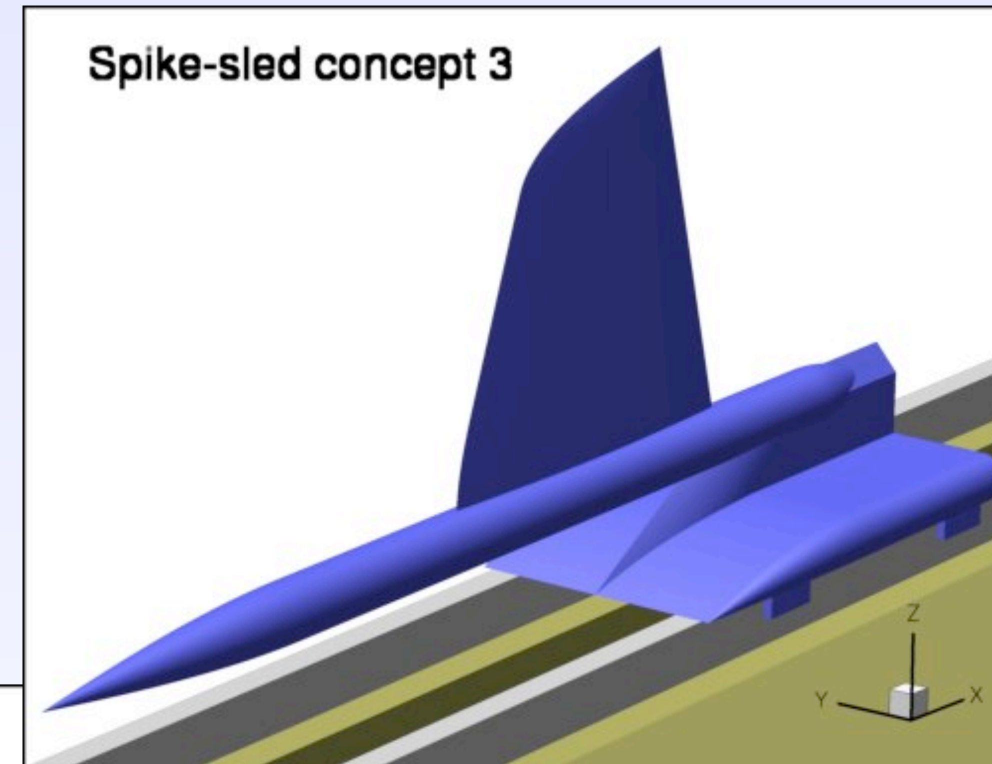
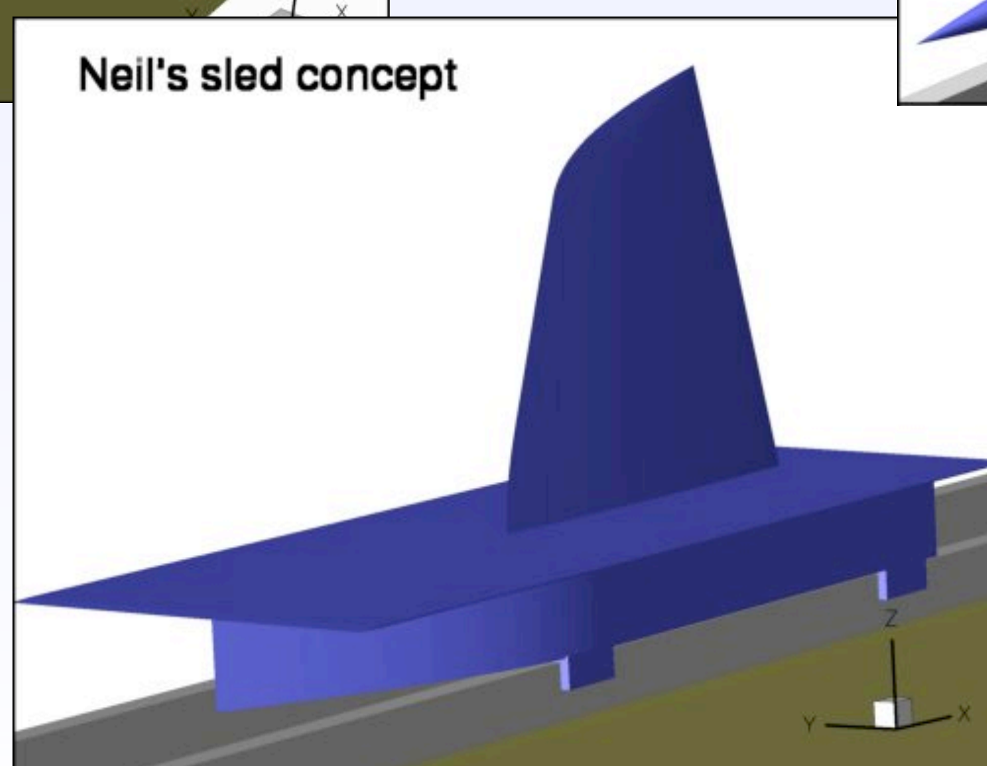


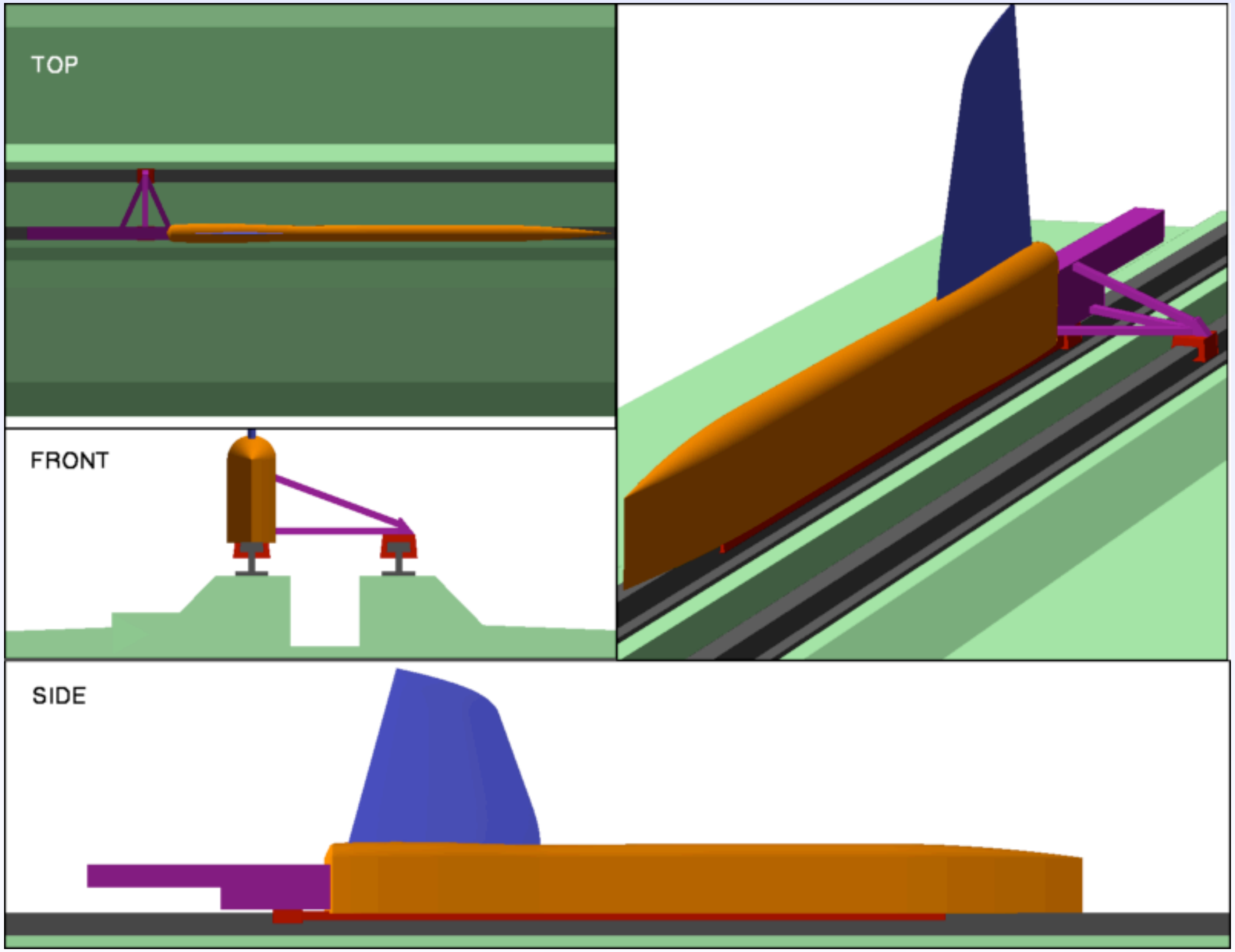




CFD-ready geometries analyzed with Cart3D

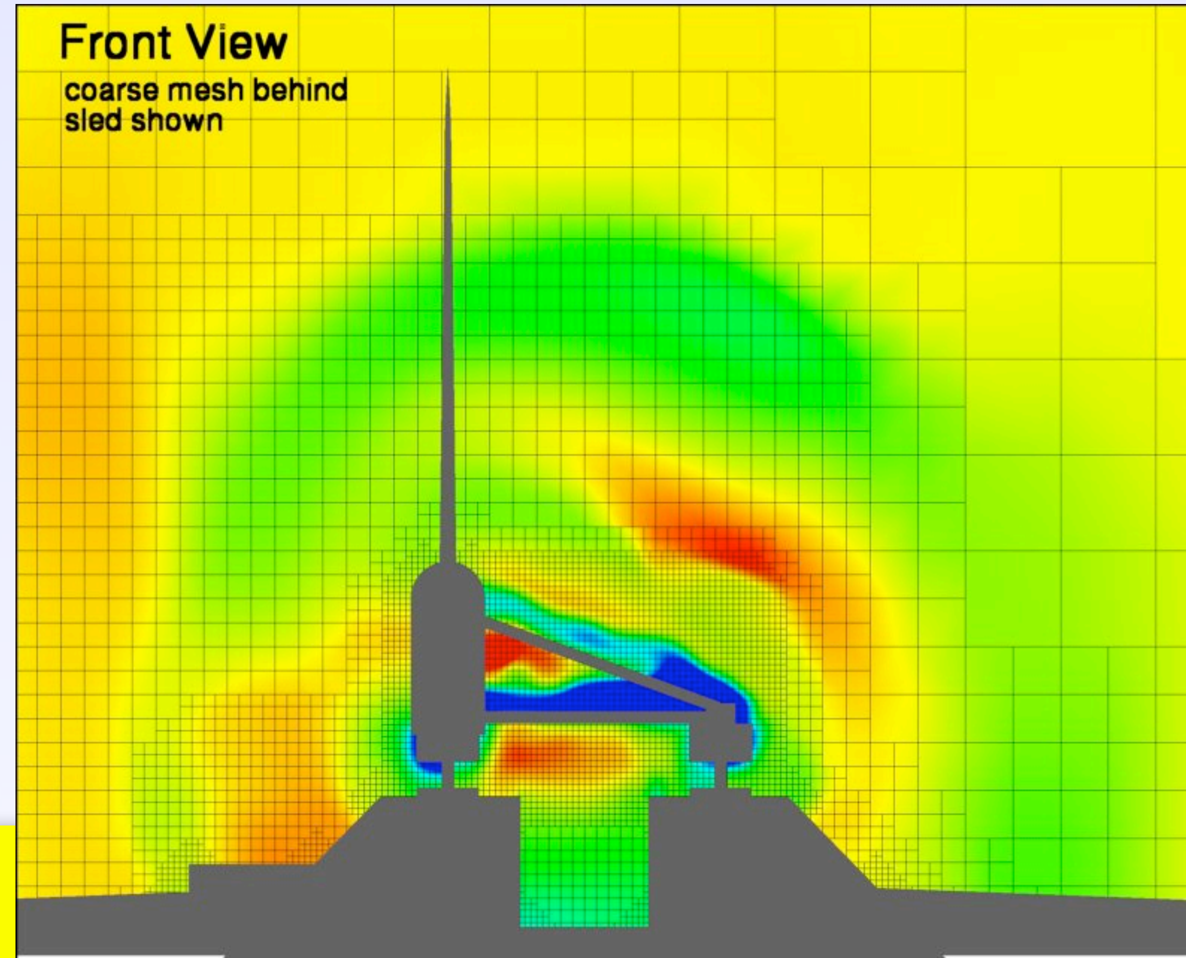
Rocket-Sled Test

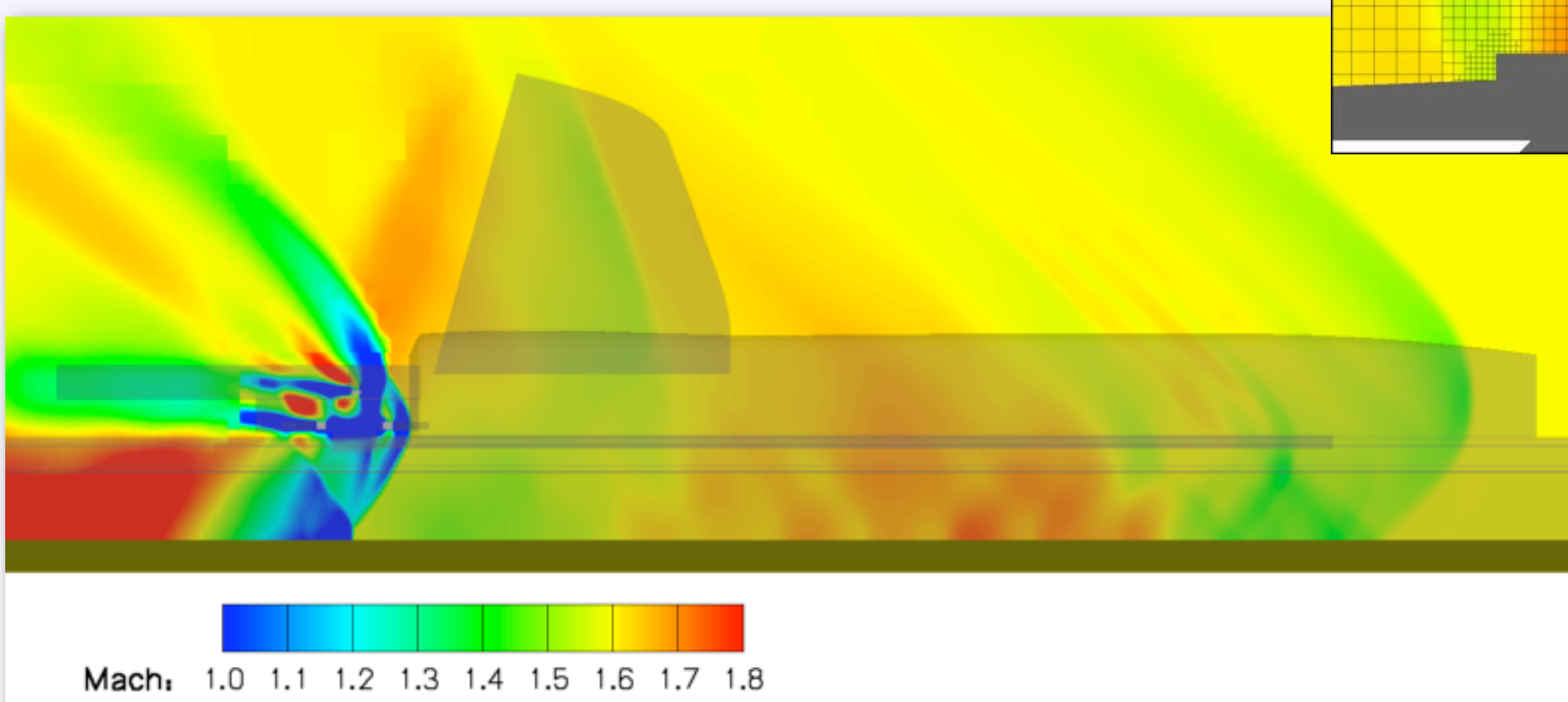
- Settled on monorail sled design
- Minimizes flow disturbances on test surface
- Allows more flexibility for avoiding choking and excessive forces due to flow in channel between rails
- Good spread of shoes to react forces and moments



Rocket-Sled Test

- Typical Euler solutions on full geometry
  - test wing
  - sled fairing and outrigger
  - rails
  - track bed





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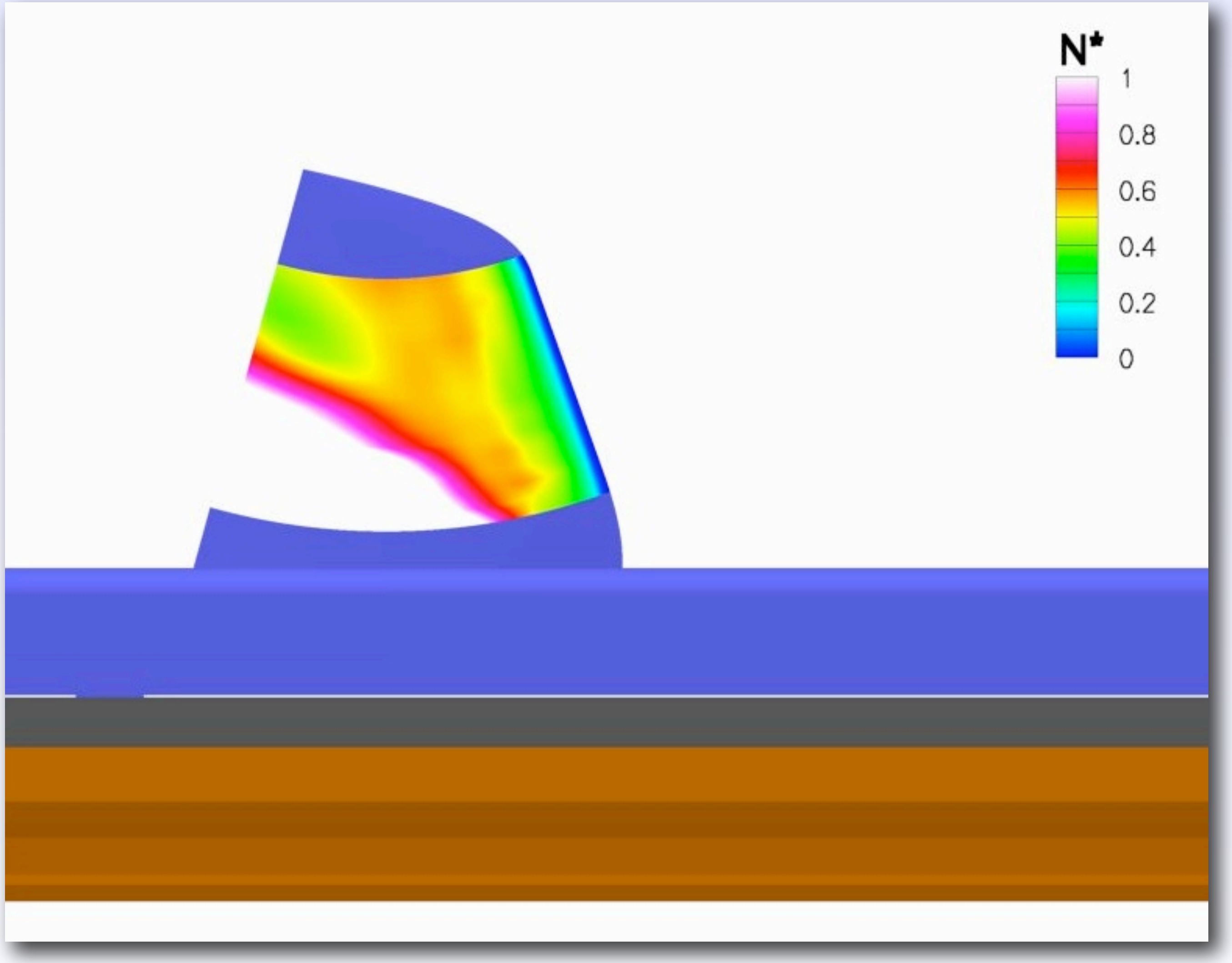
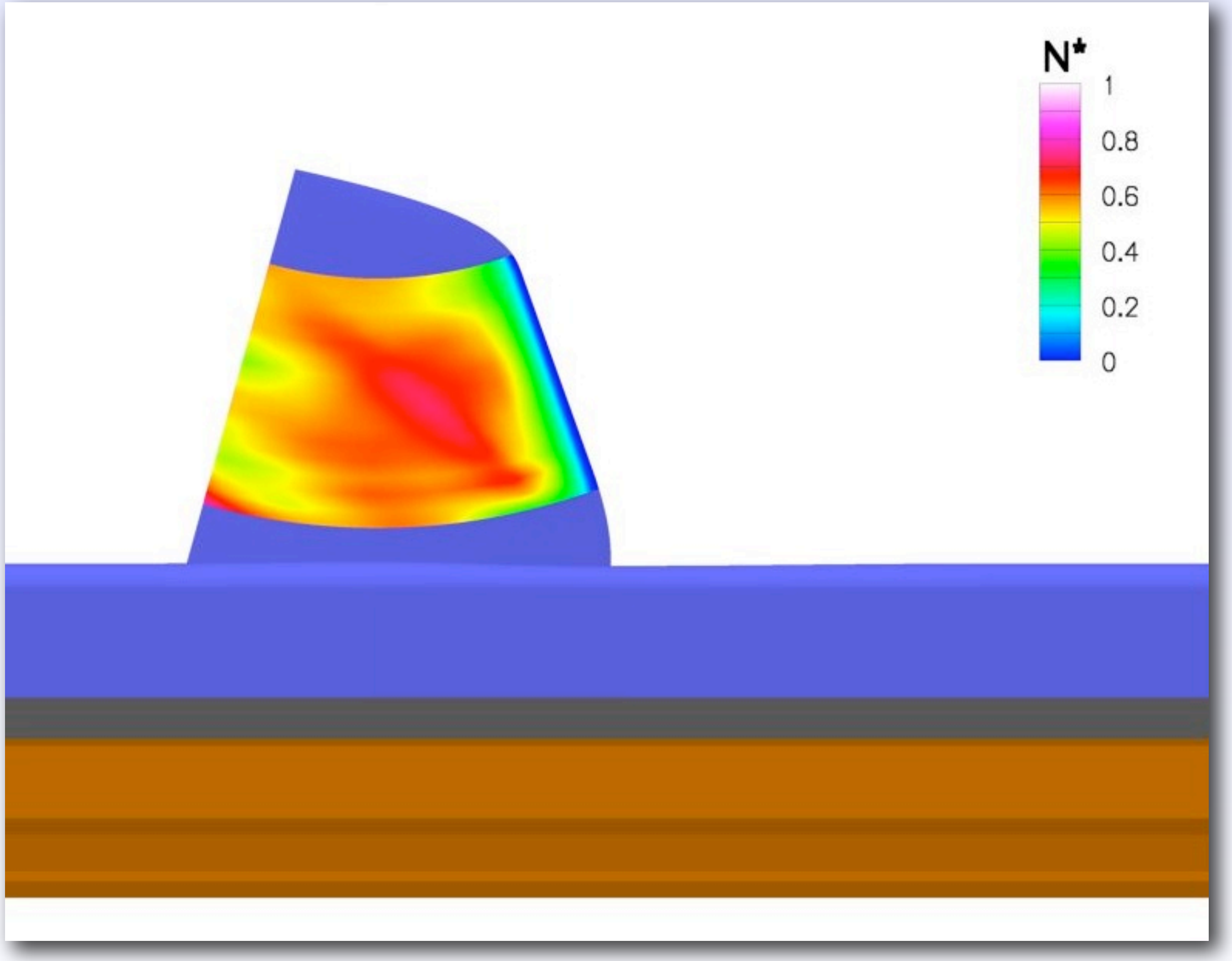
Rocket-Sled Test

- ✦ Baseline sled design still not ideal for laminar flow
- ✦ Increase in boundary-layer crossflow compared symmetry plane
  - similar to half-wing
  - nose shock and other pressure disturbances bounce around



Rocket-Sled Test

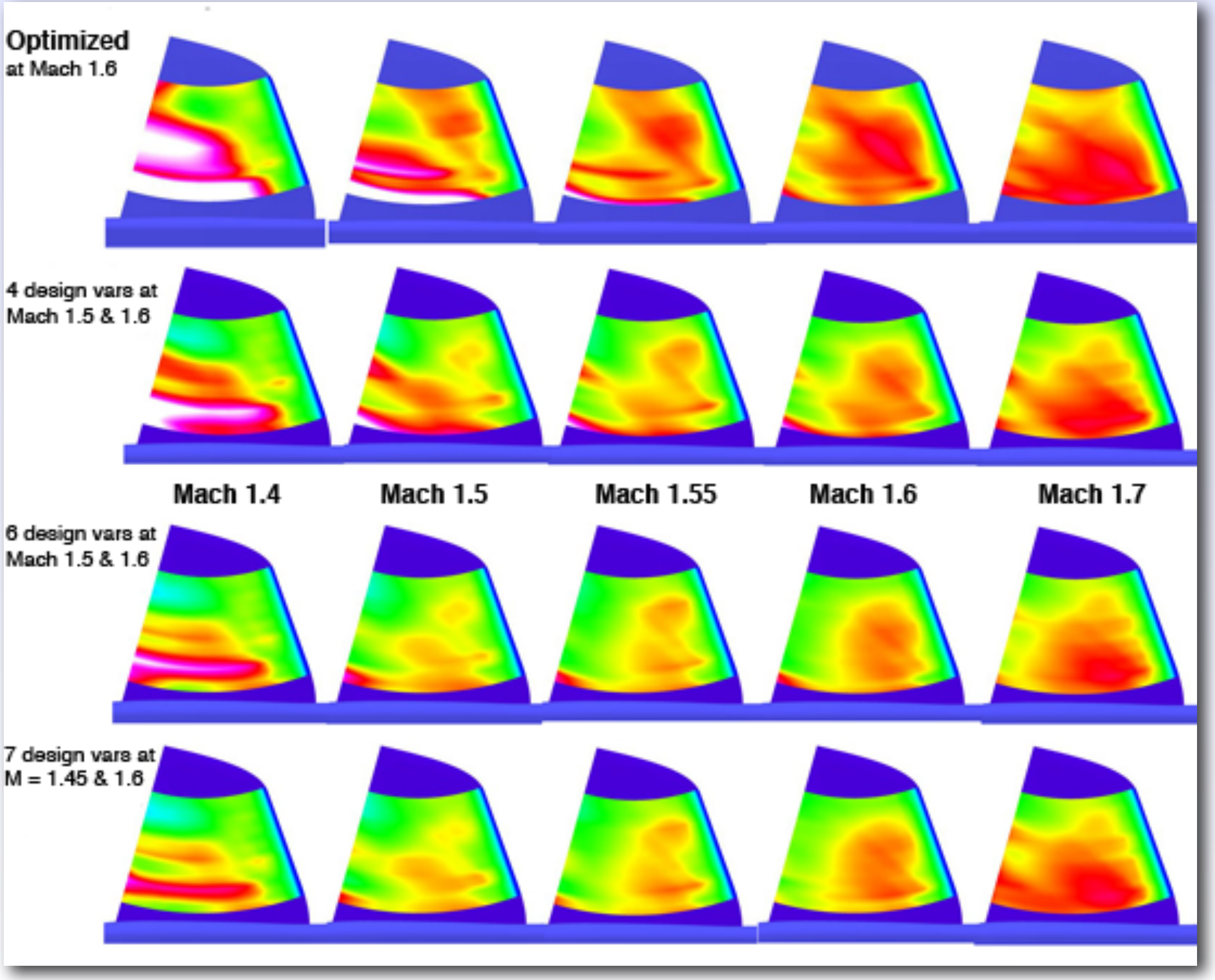
- ✦ Sled fairing modified to lower maximum N-factor
  - Cart3D coupled with transition design code
  - nonlinear simplex optimization
- ✦ Airfoil modifications also effective



Rocket-Sled Test

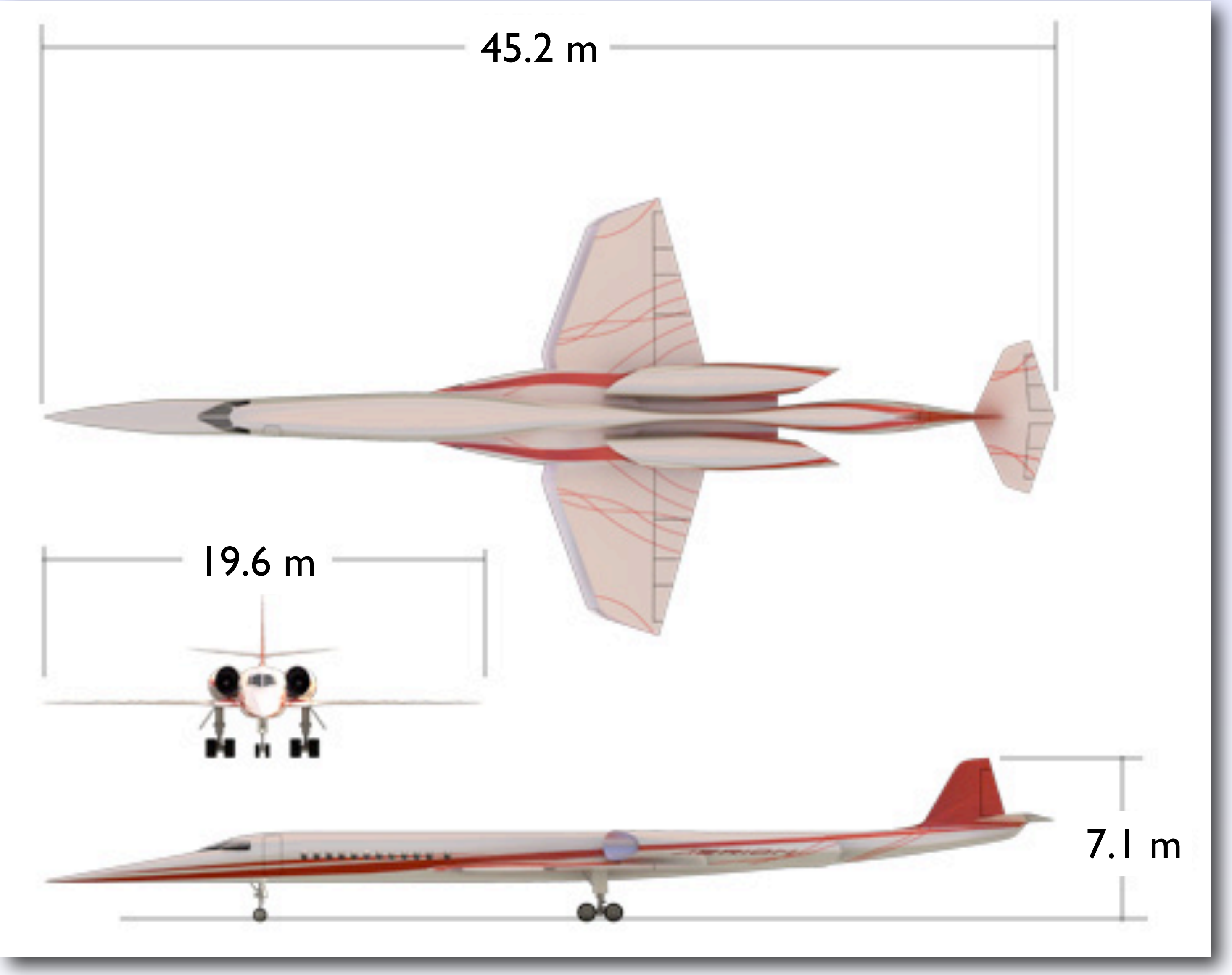
Dual-point optimizations

- ✦ Objective is linear combination of laminar extent at two Mach numbers
- ✦ Widens useful Mach number range
- ✦ Allows more design variables



Full Aircraft Aerodynamic Optimization

- Two-part optimization
  - inviscid full-configuration drag minimization
  - viscous wing/body drag minimization
- Due to supersonic cones of influence



Geometry Generation

- CAD-based
  - labor-intensive, time-consuming
  - geometric instead of aircraft design parameters
    - control points
    - trimming surfaces
  - not practical for trade studies, optimization
- Perturbation method
  - modifications to a baseline geometry model
  - powerful when making small local changes
  - impractical when making gross changes
- Parametric geometry

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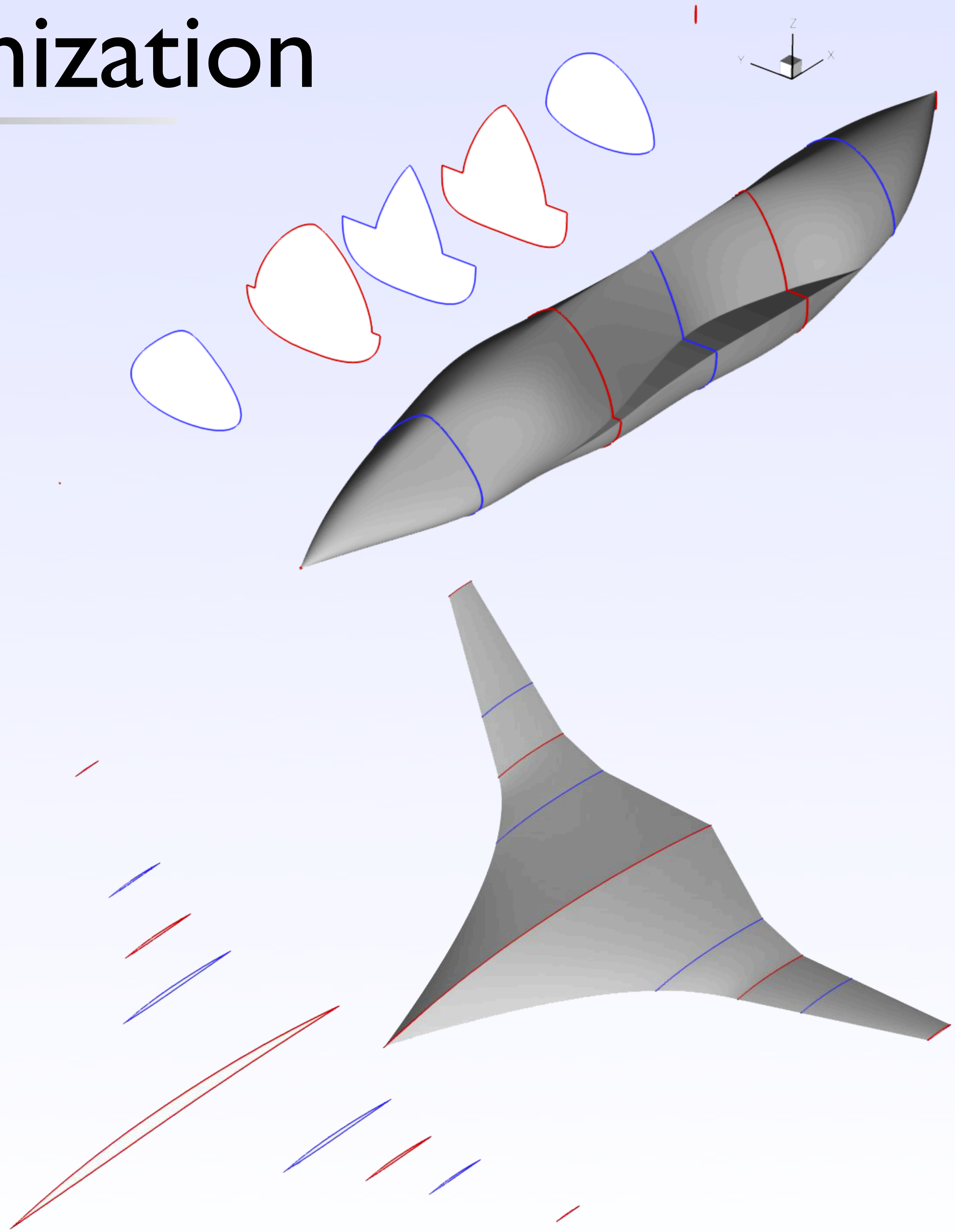
Geometry Generation for Optimization

- ✦ Rapid Aerospace Geometry Engine (RAGE)
- ✦ Axially splined bodies
  - fuselages
  - nacelles
- ✦ Lofted stack of airfoils
  - wings
  - tails
  - pylons



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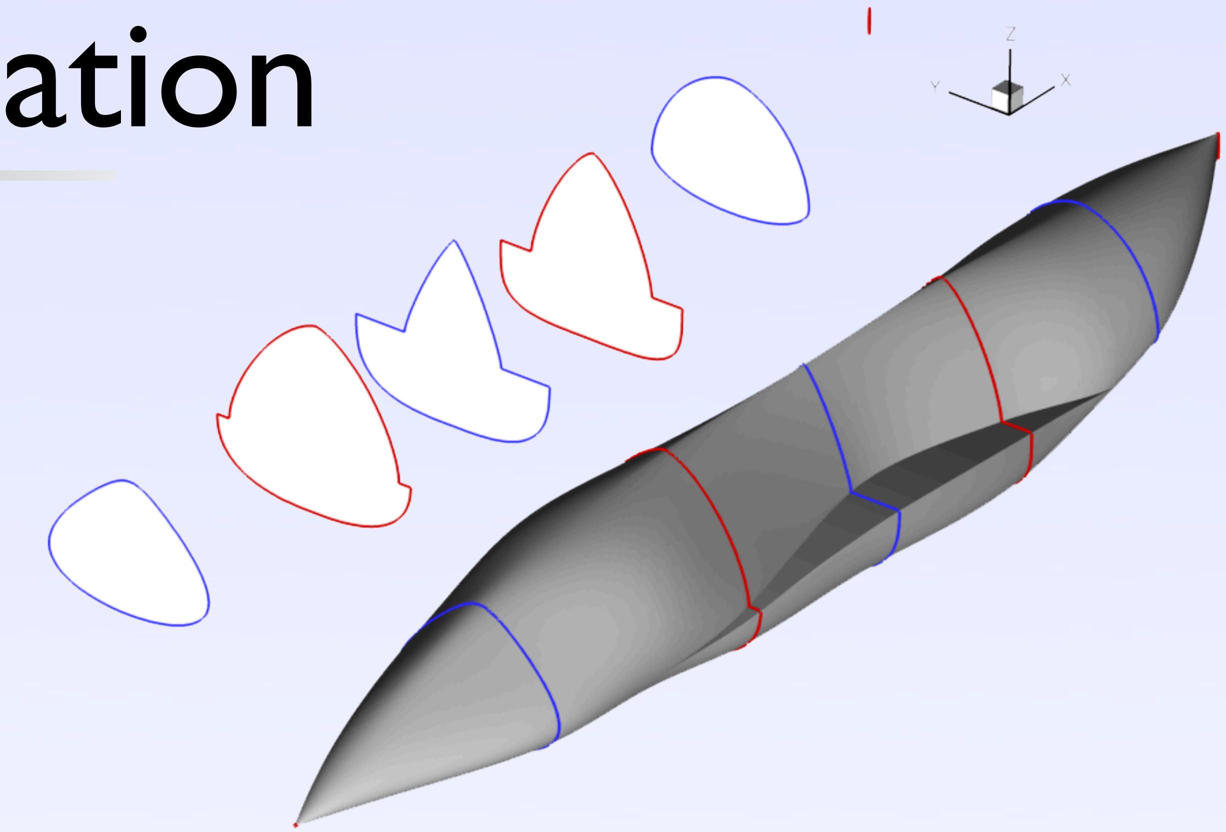

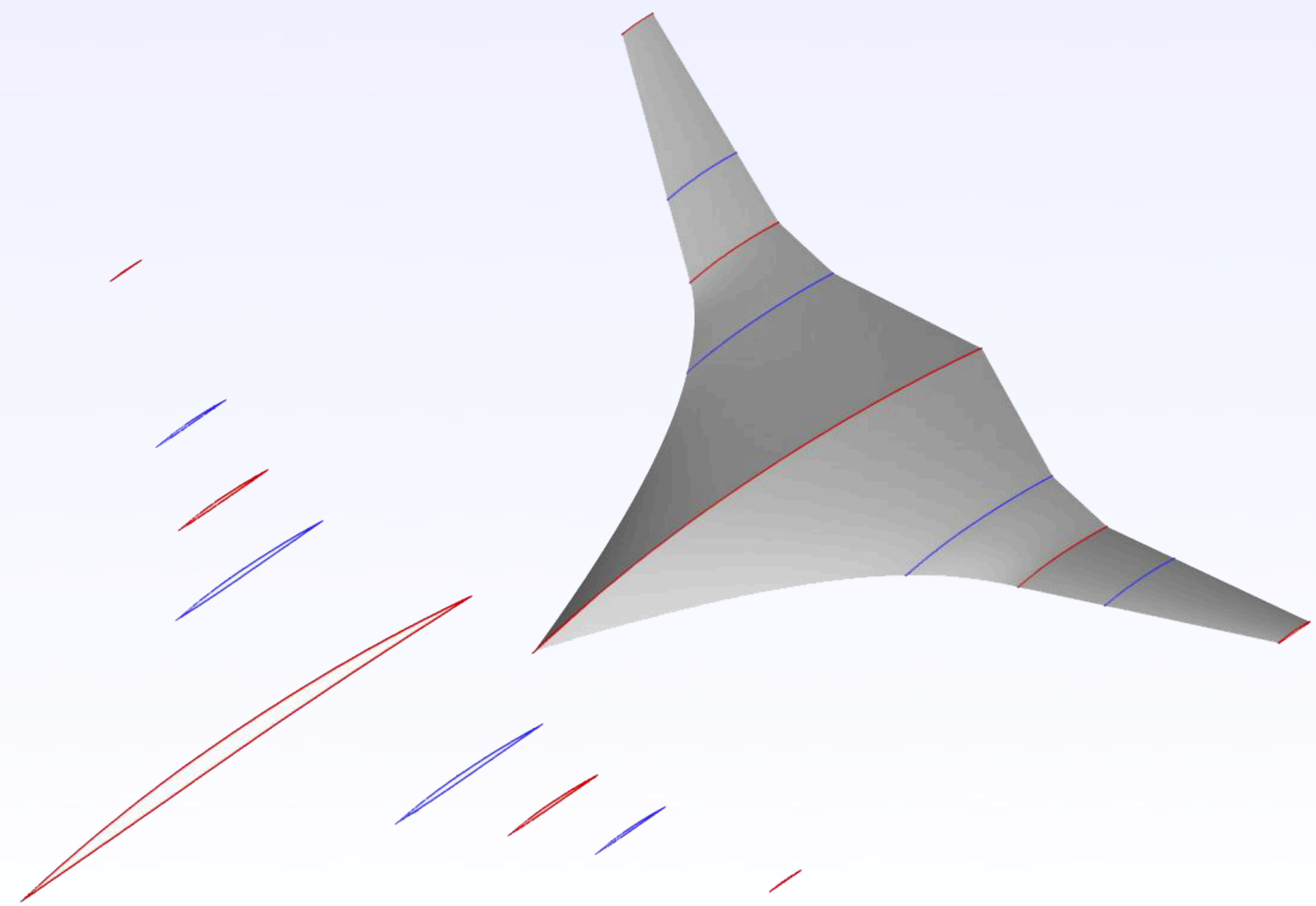

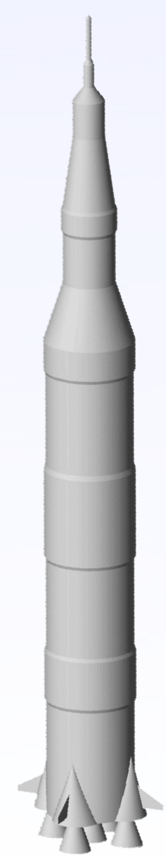

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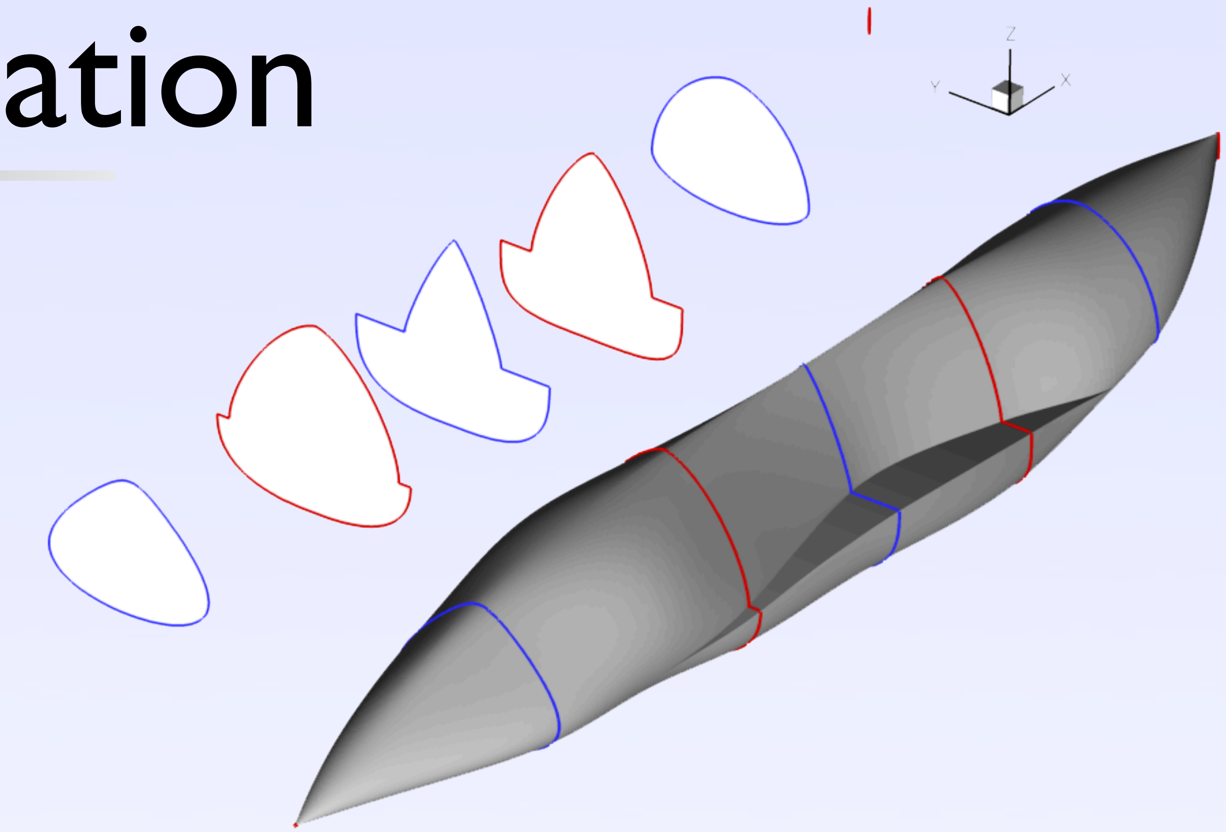

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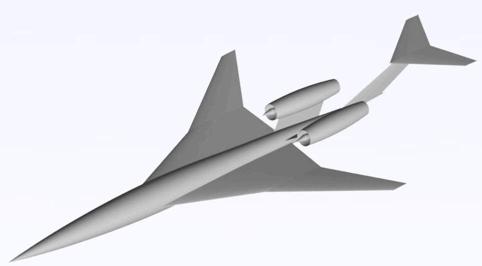

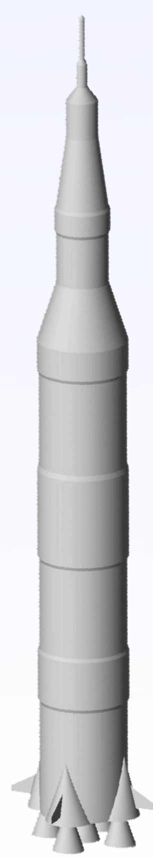

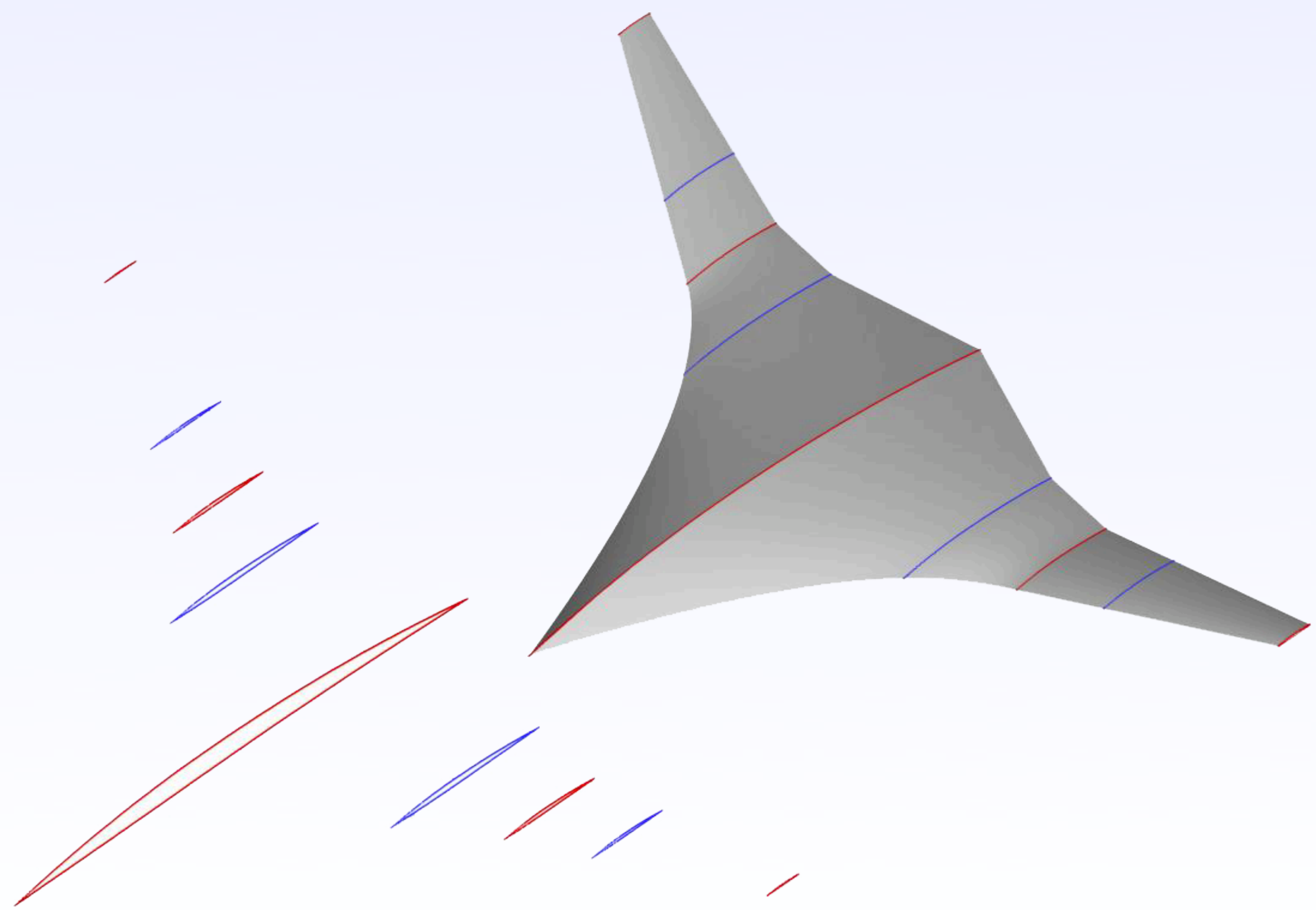

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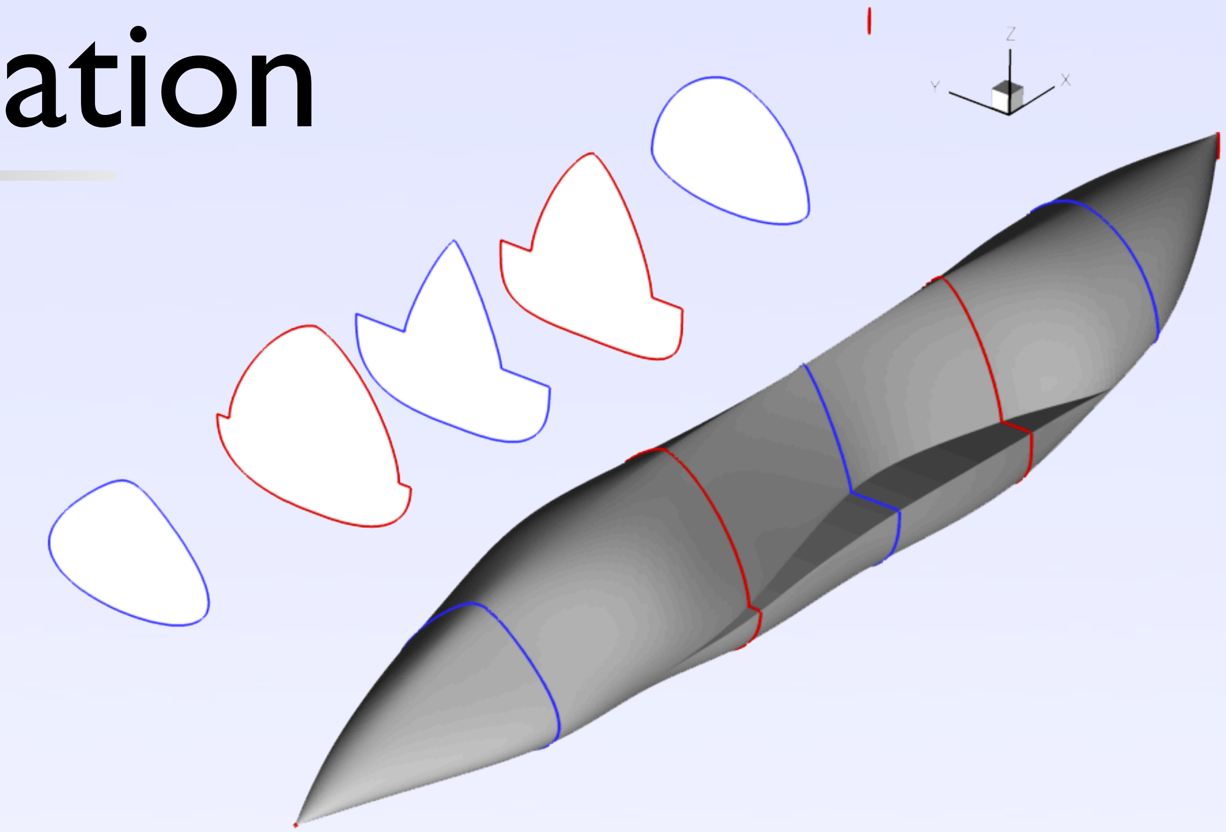

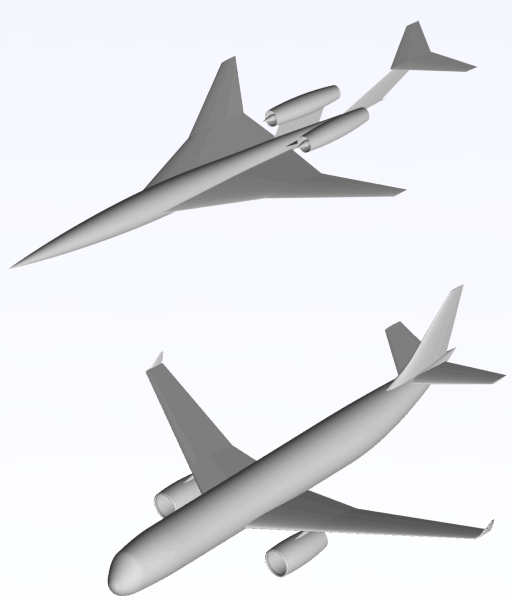

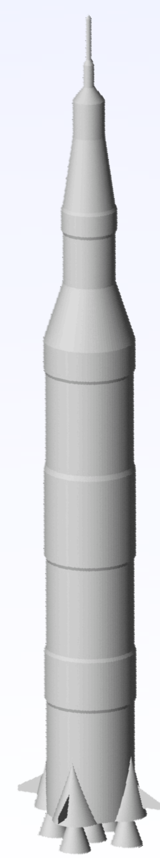

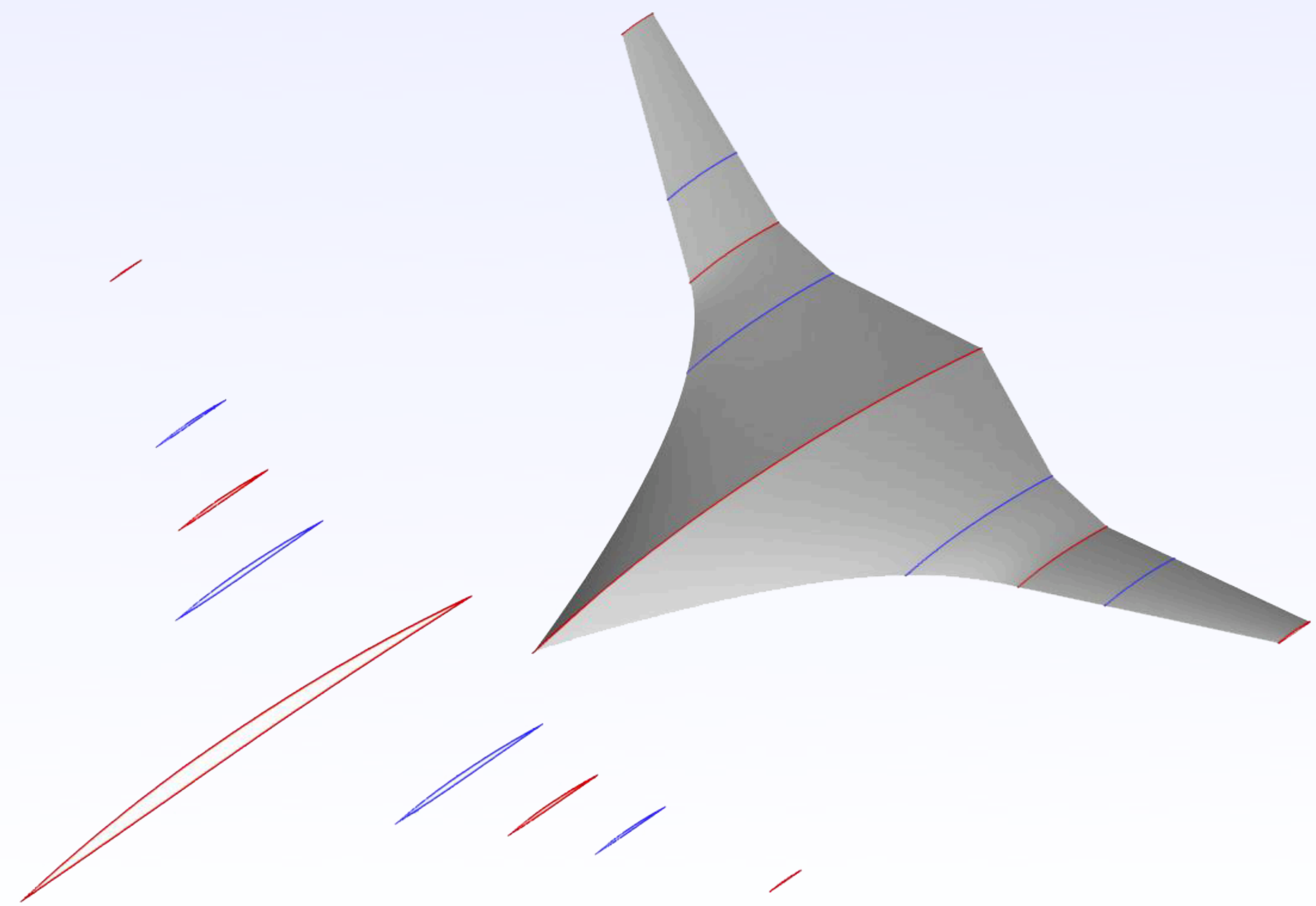

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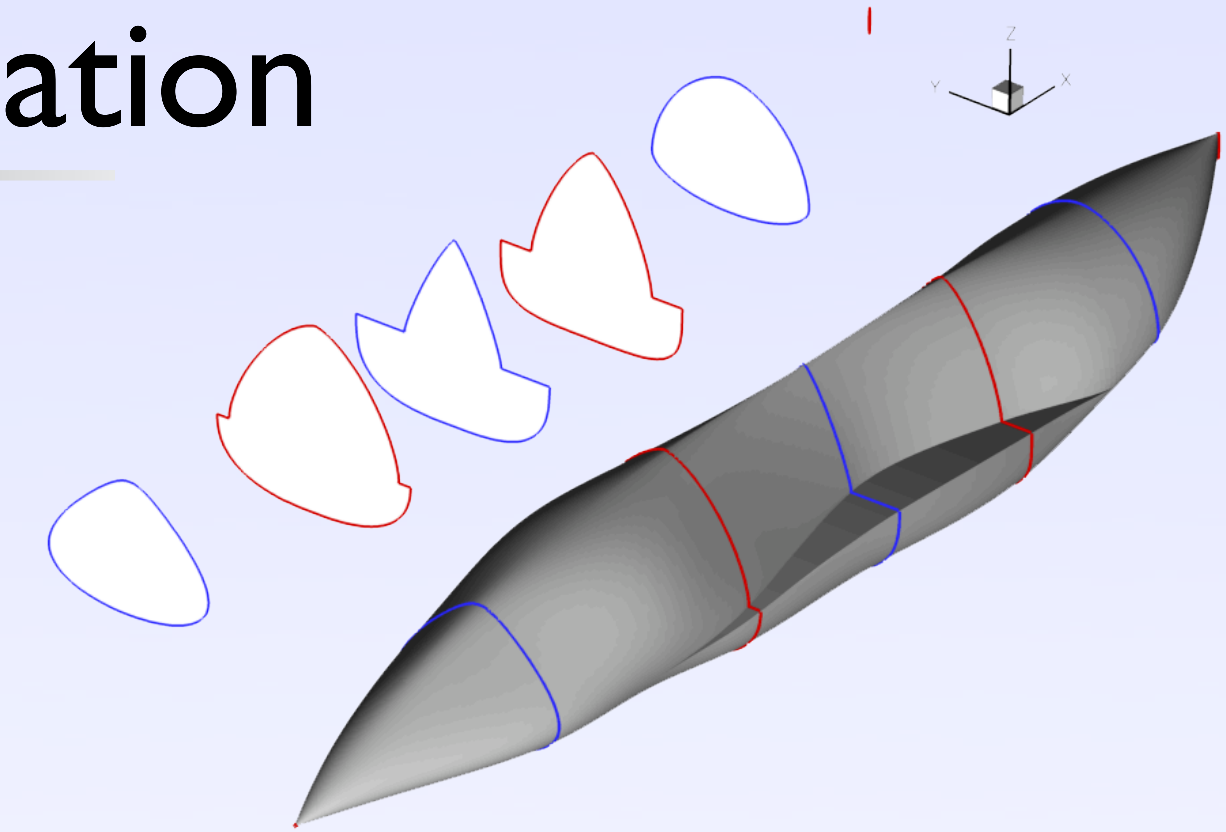

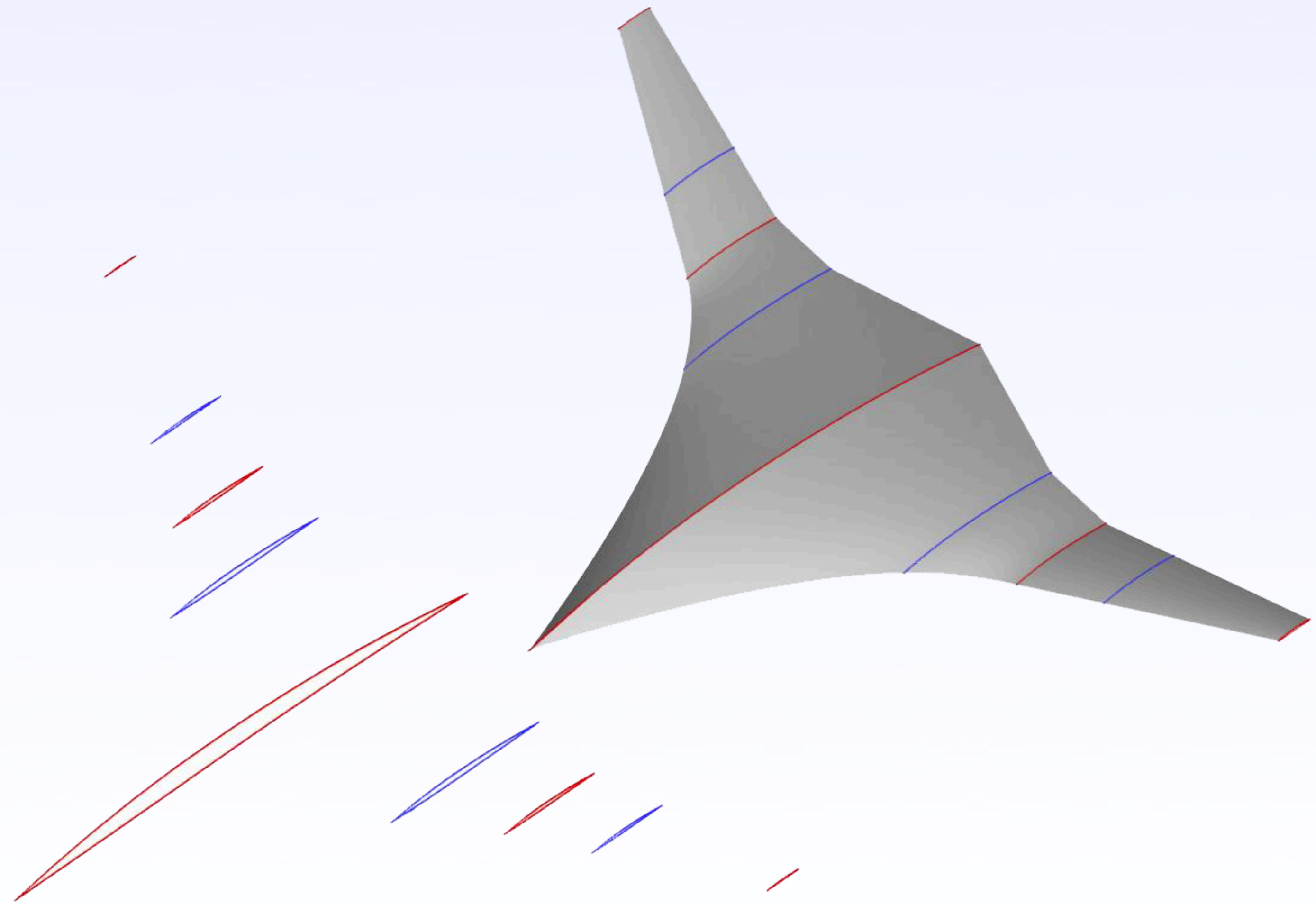

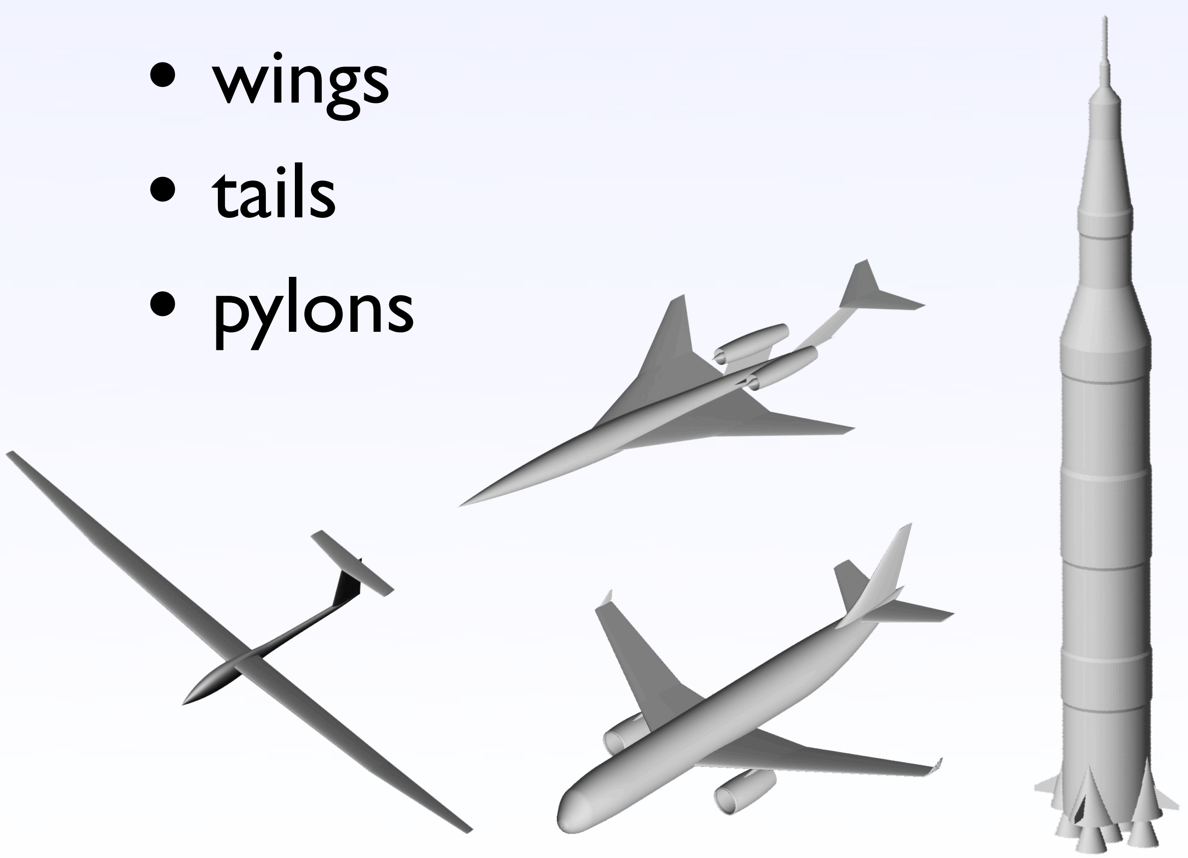

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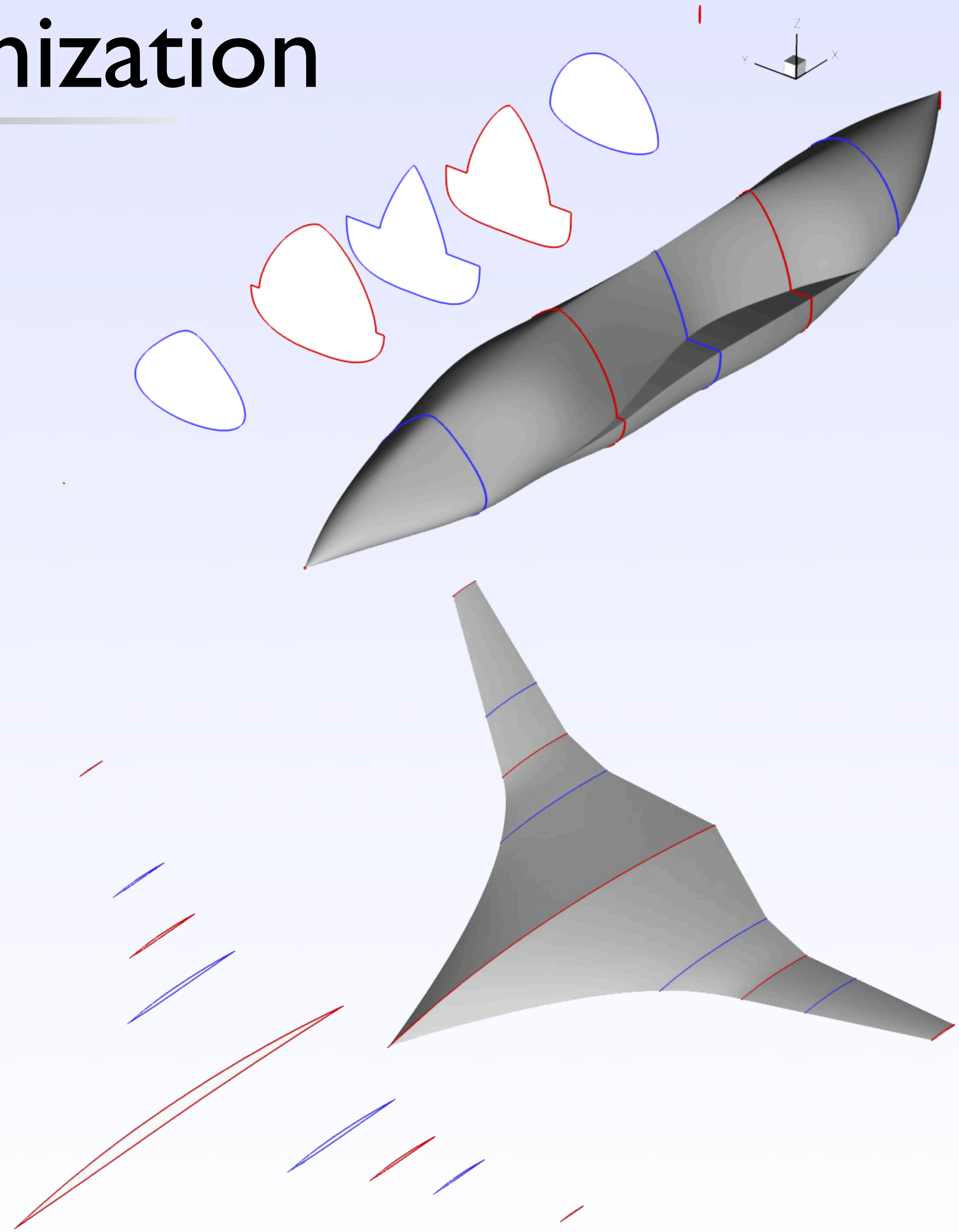
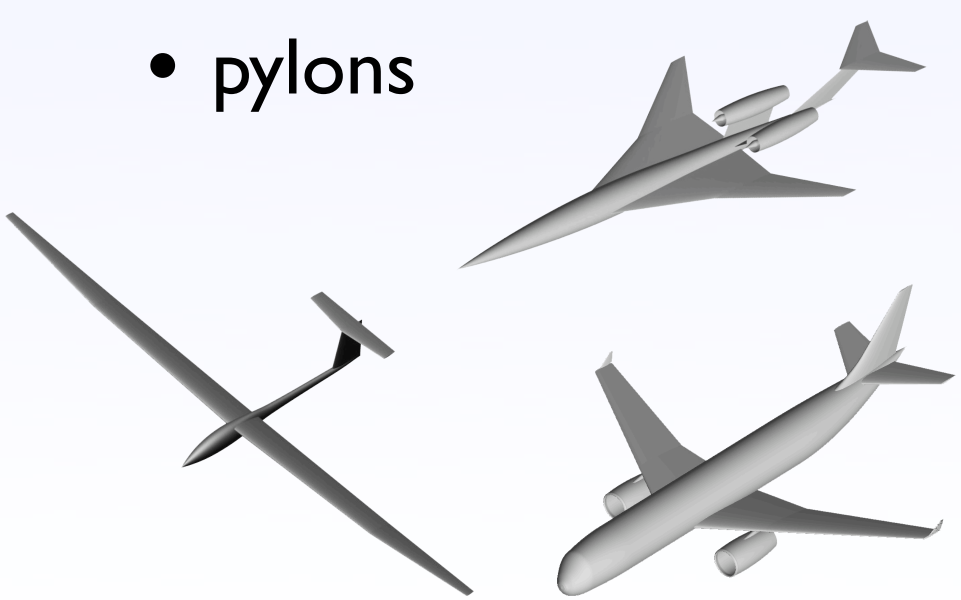
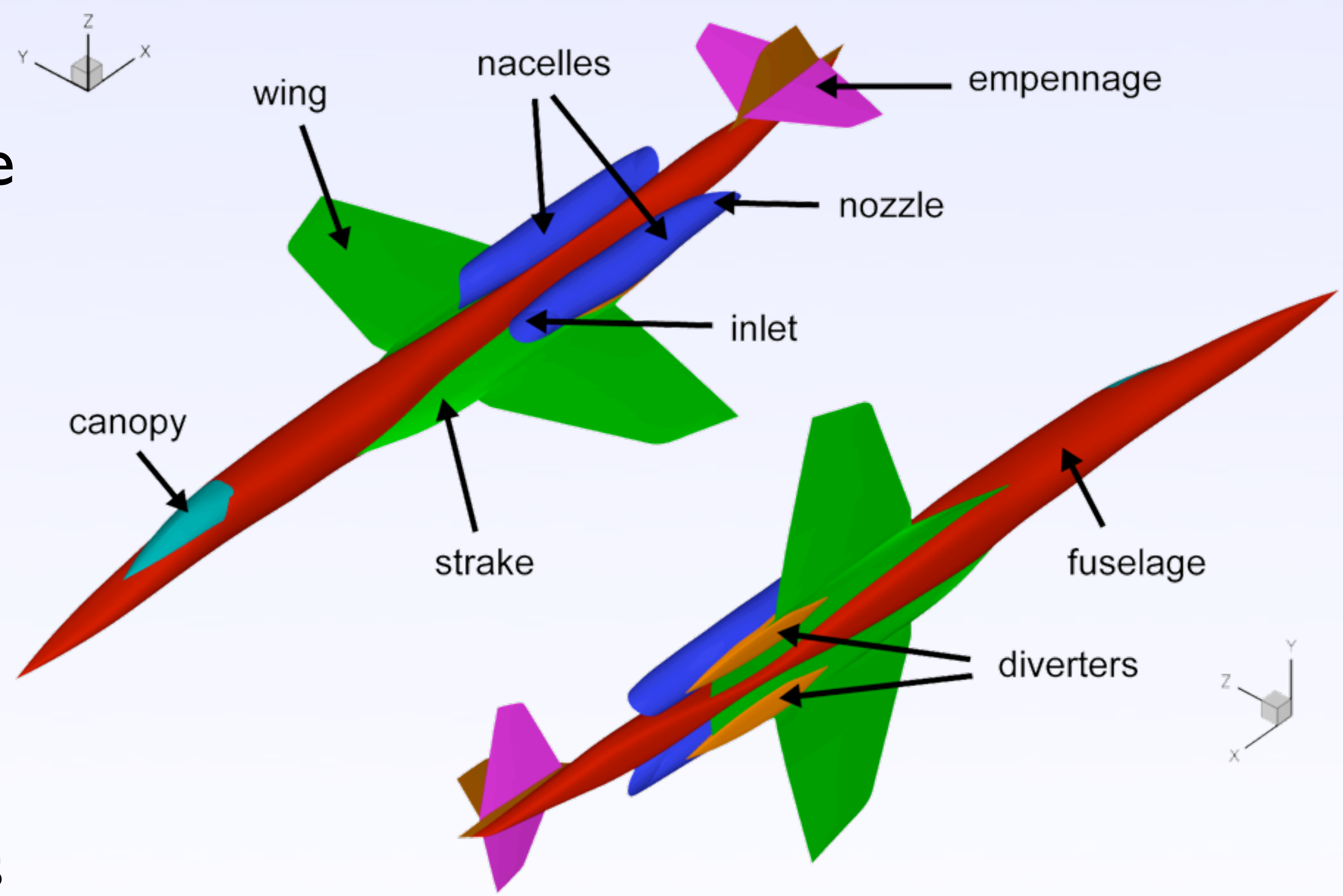




Full Aircraft Aerodynamic Optimization

Inviscid Drag Minimization of Full Configuration

- ✦ Geometry
  - wing, strake, fuselage, canopy, inlet, nozzle, diverter, empennage
  - fix portions of fuselage, strake and wing to maintain laminar flow
- ✦ Optimization
  - nonlinear simplex
  - geometric constraints
  - inlet and nozzle flow constraints
  - lift constrained



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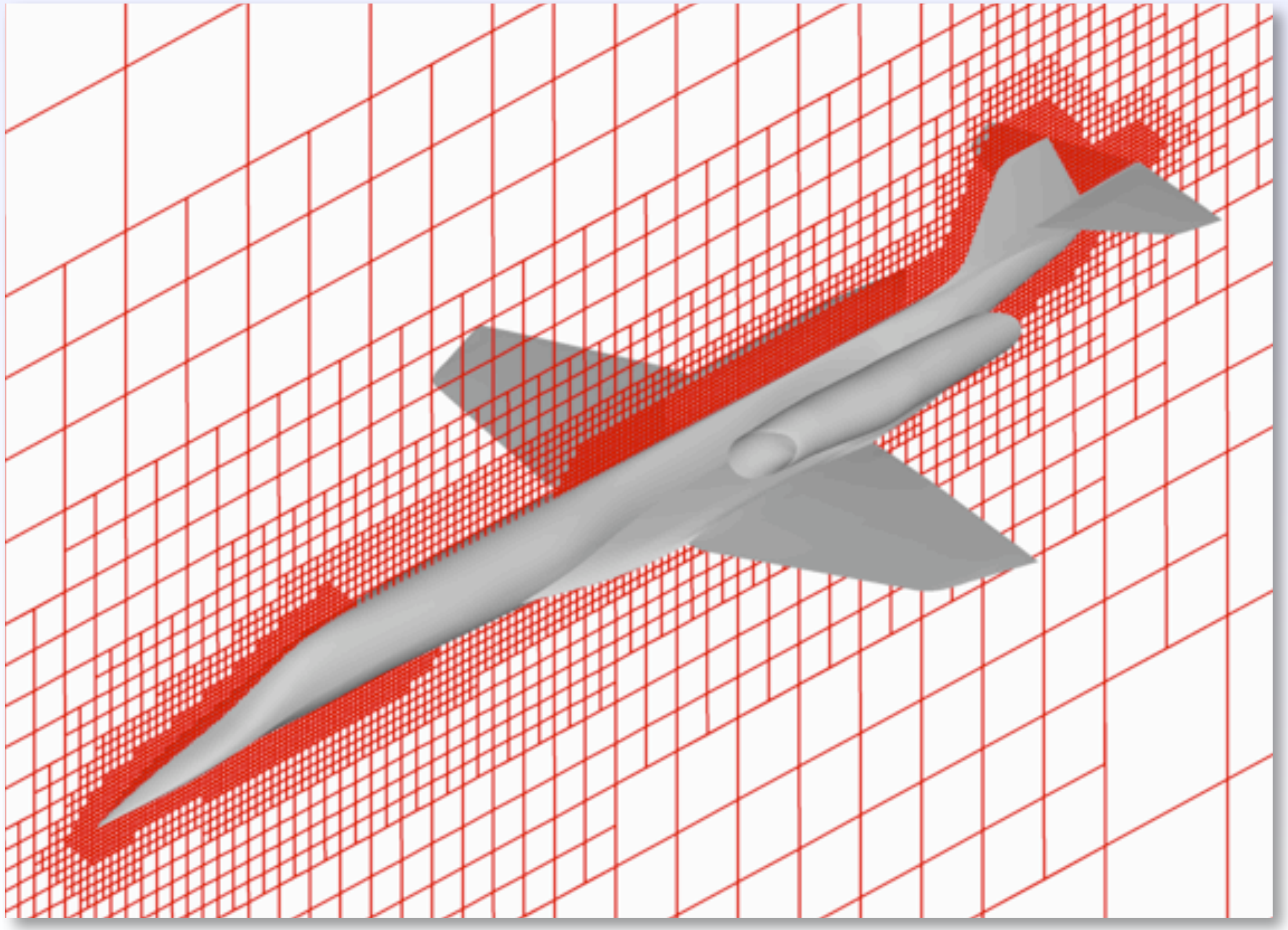
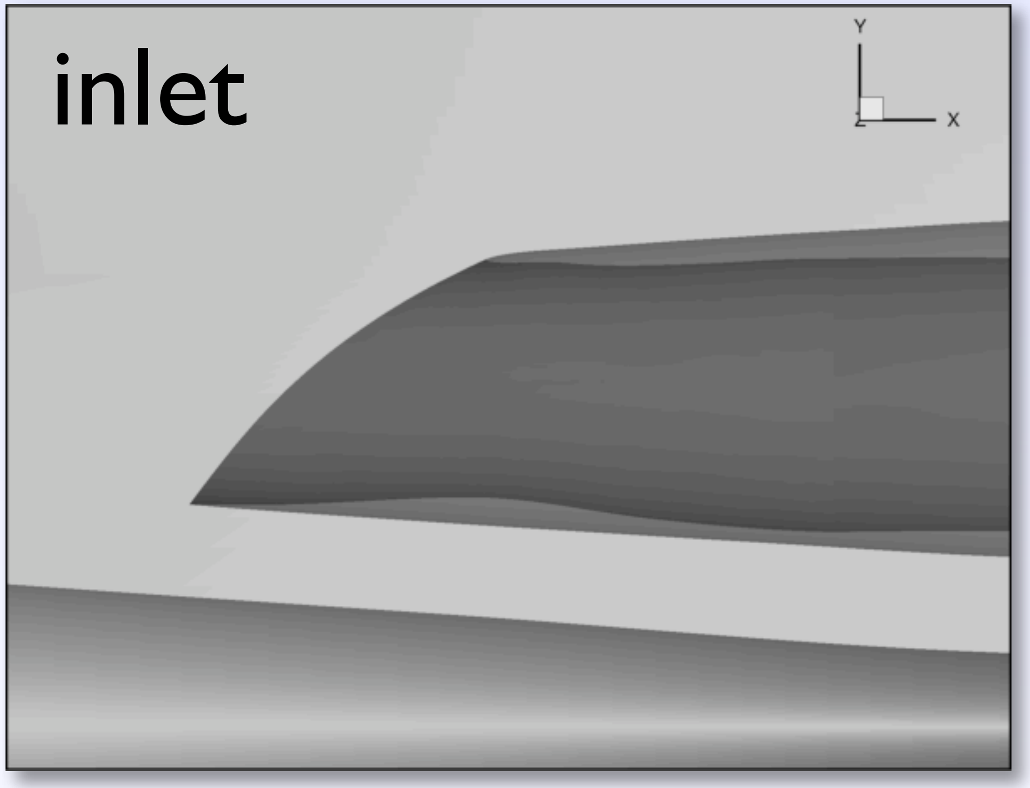
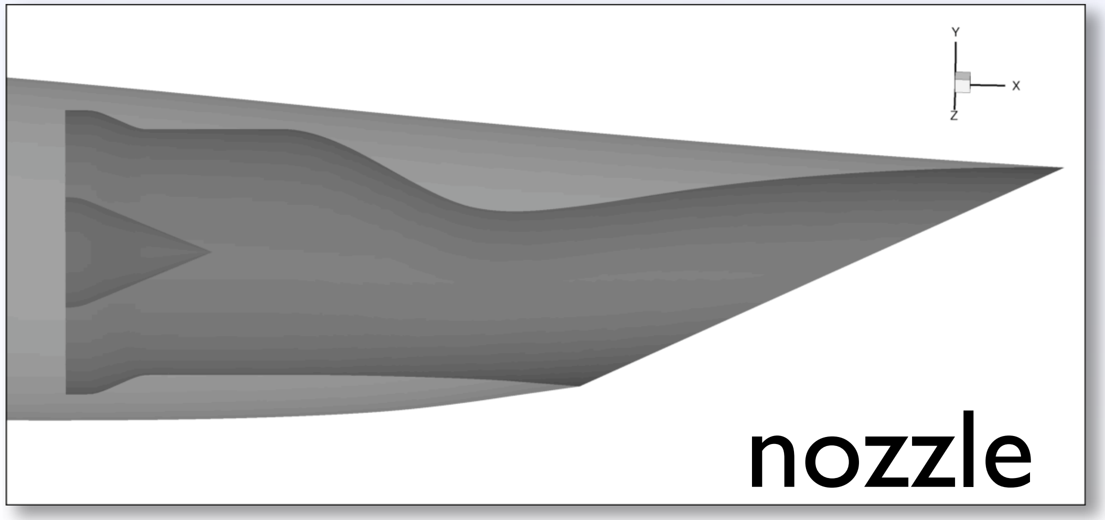
Inviscid Optimization

- Cart3D inviscid Euler solver
- Minimize drag and maximize thrust
- Off-design constraints







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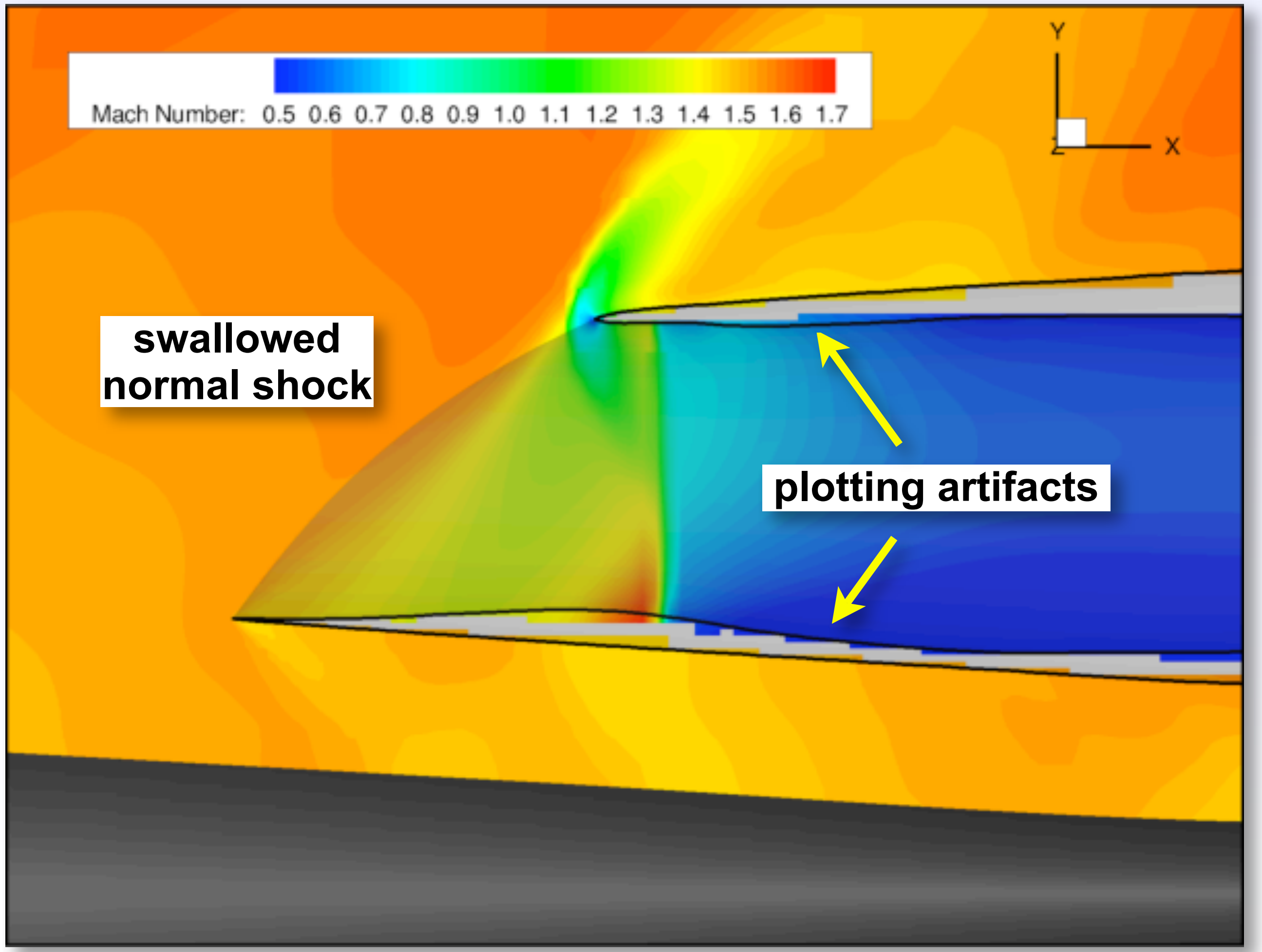
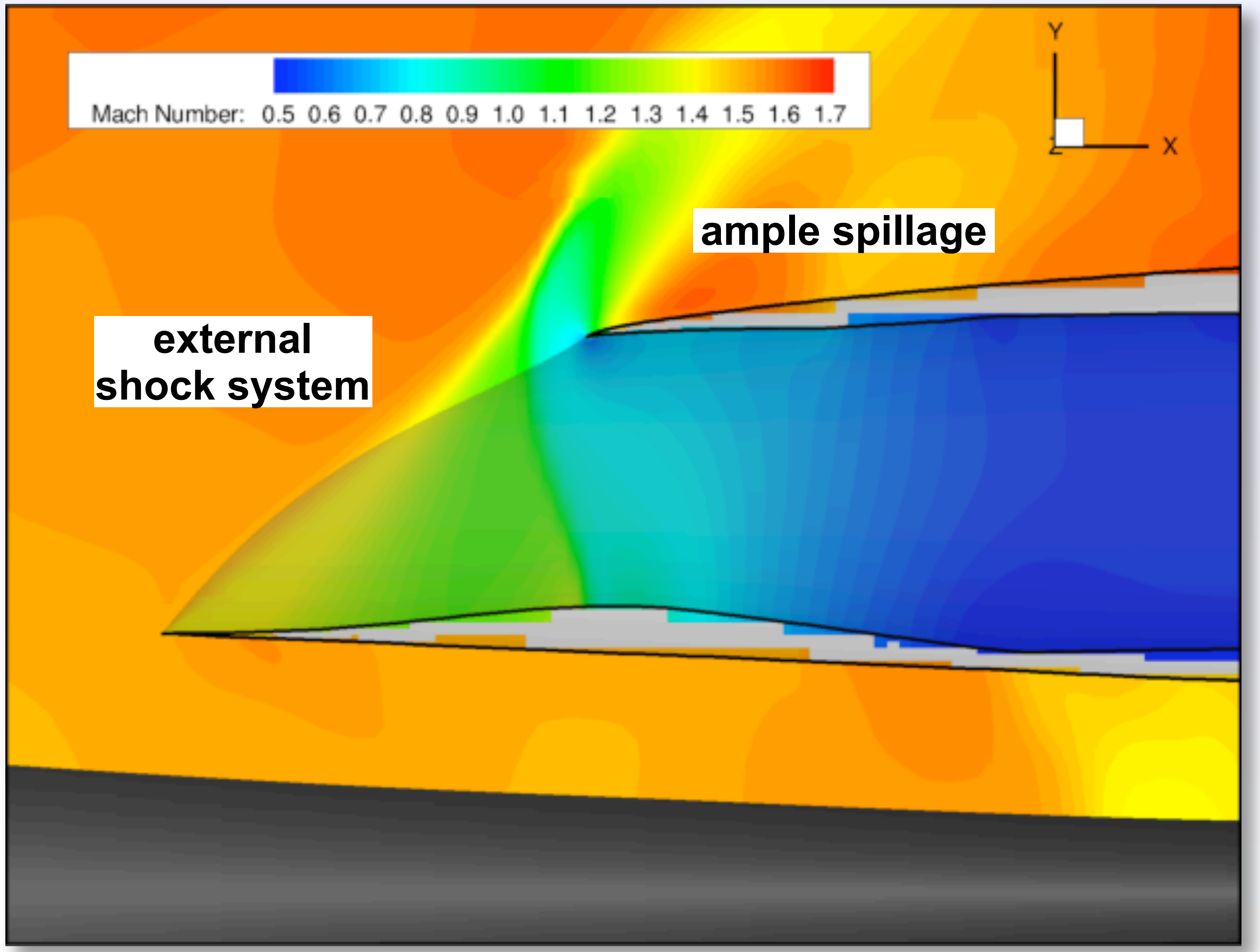
Inlet Optimization at Mach 1.5

- 4.6% increase in pressure recovery
- 4.8% increase in aircraft drag
- Stable inlet throughout mission profile
- 5.8% decrease in objective function

Initial geometry by "stream tracing"



Optimized Geometry



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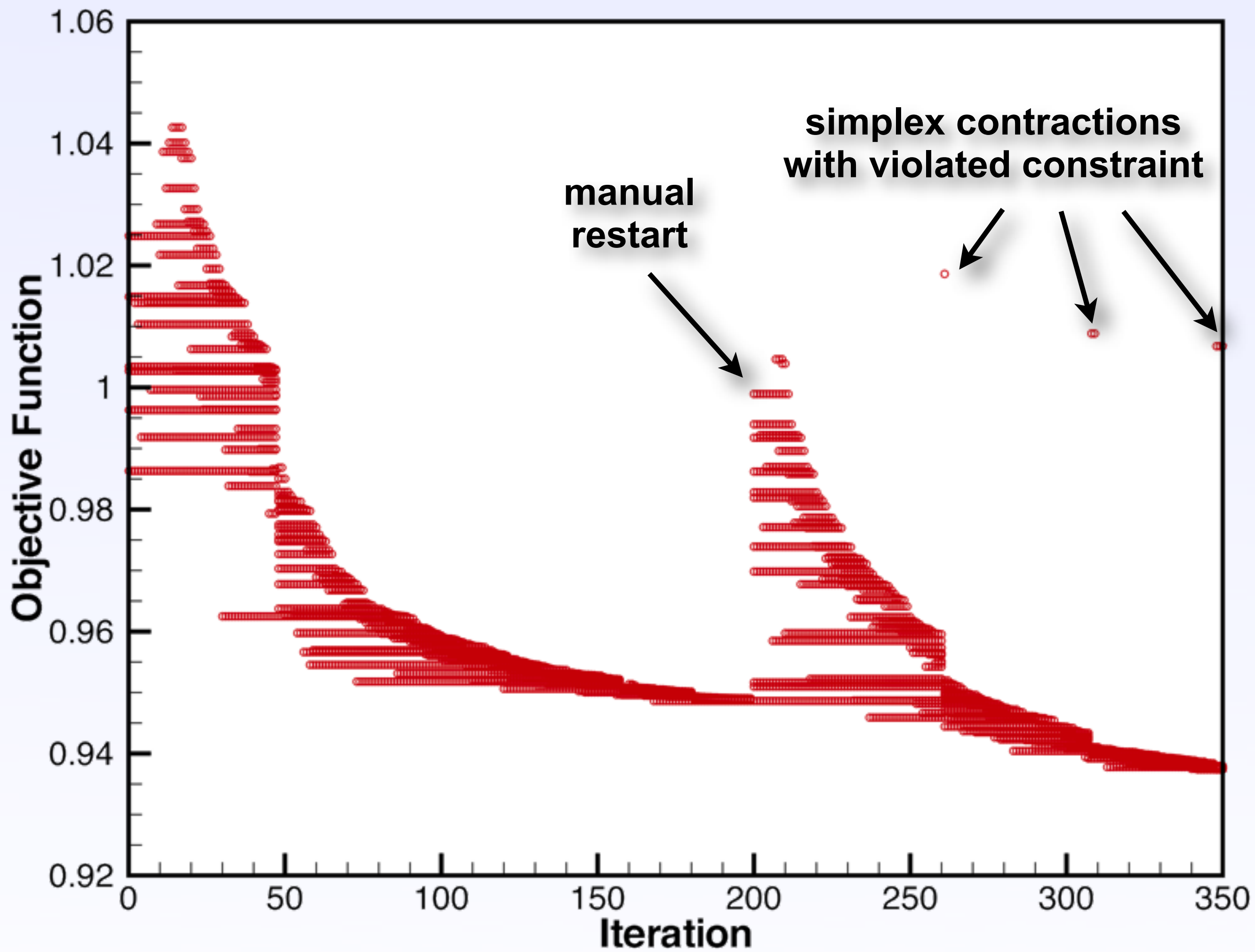
Inlet Optimization Details

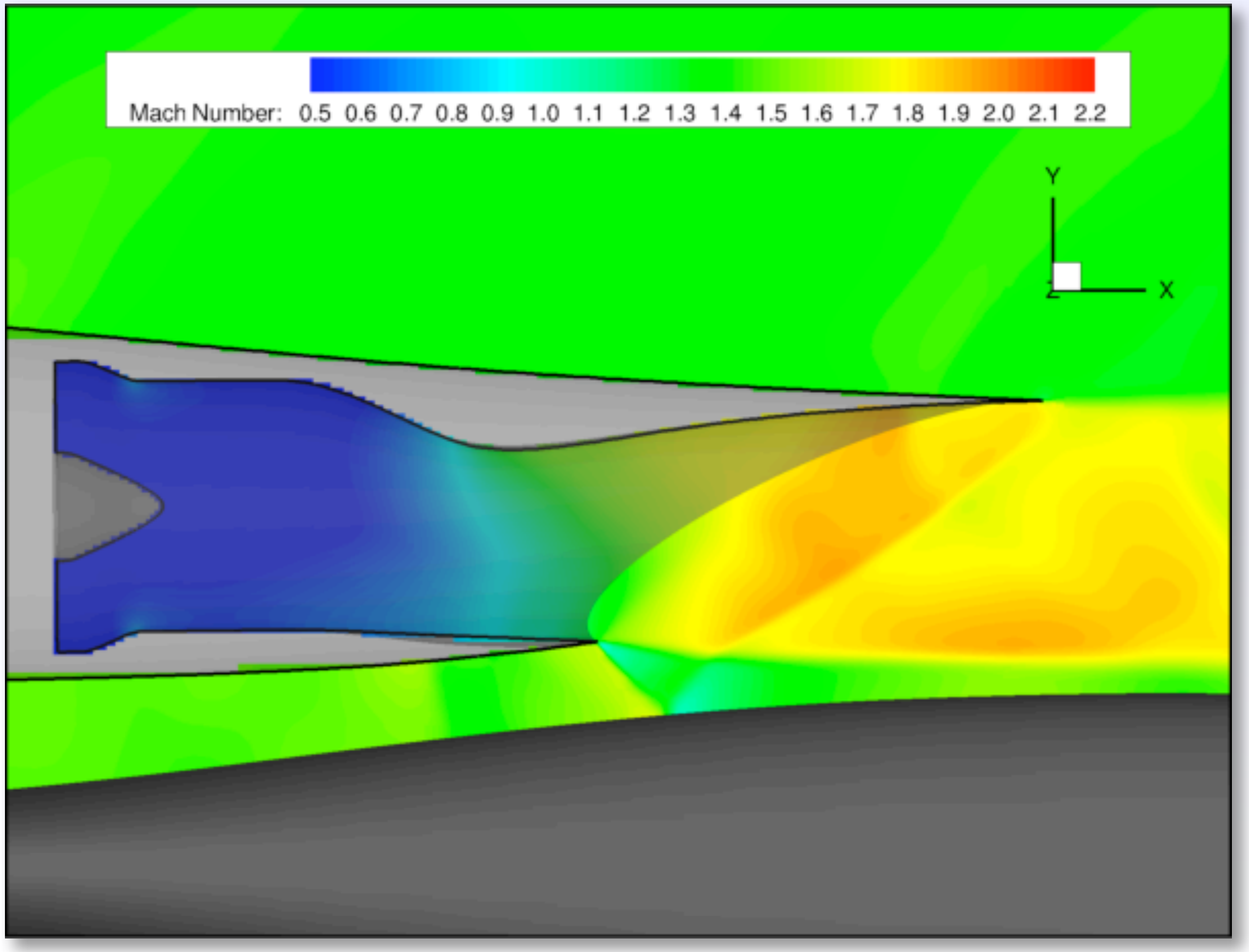
- Minimize weighted sum of aircraft drag and pressure recovery at Mach 1.5
- Constrain inlet lip Mach number to force ample spillage region at Mach 1.5 and Mach 1.6
- Constrain lift coefficient
- Vary all geometric parameters plus angle of attack
  - 100 distinct design variables
  - 15-20 at a time

constrained Nelder-Mead nonlinear simplex method



Nozzle Optimization

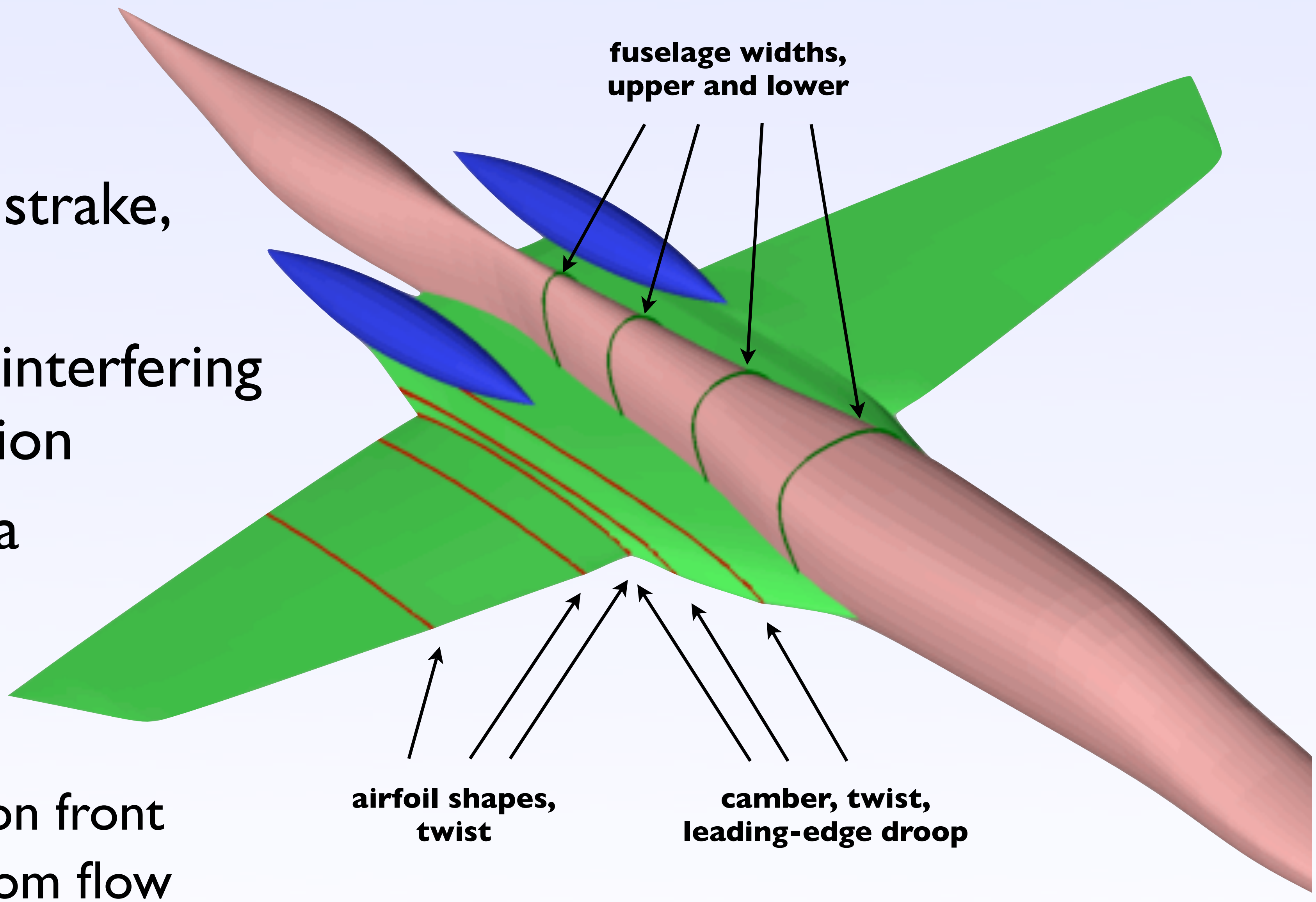
- Similar optimization techniques as inlet design
- 10% thrust improvement
- Less than 1% increase in airframe wave drag
- Currently also using takeoff condition constraint



Full Aircraft Aerodynamic Optimization

Optimization for Laminar Extent

- ✦ Geometry
  - simplified nacelles, wing, strake, fuselage
  - fix aft portions to avoid interfering with propulsion integration
  - approximate canopy area
- ✦ Optimization
  - genetic algorithm
    - erratic jumps in transition front
    - occasional bad points from flow solver
  - geometric and lift constraints



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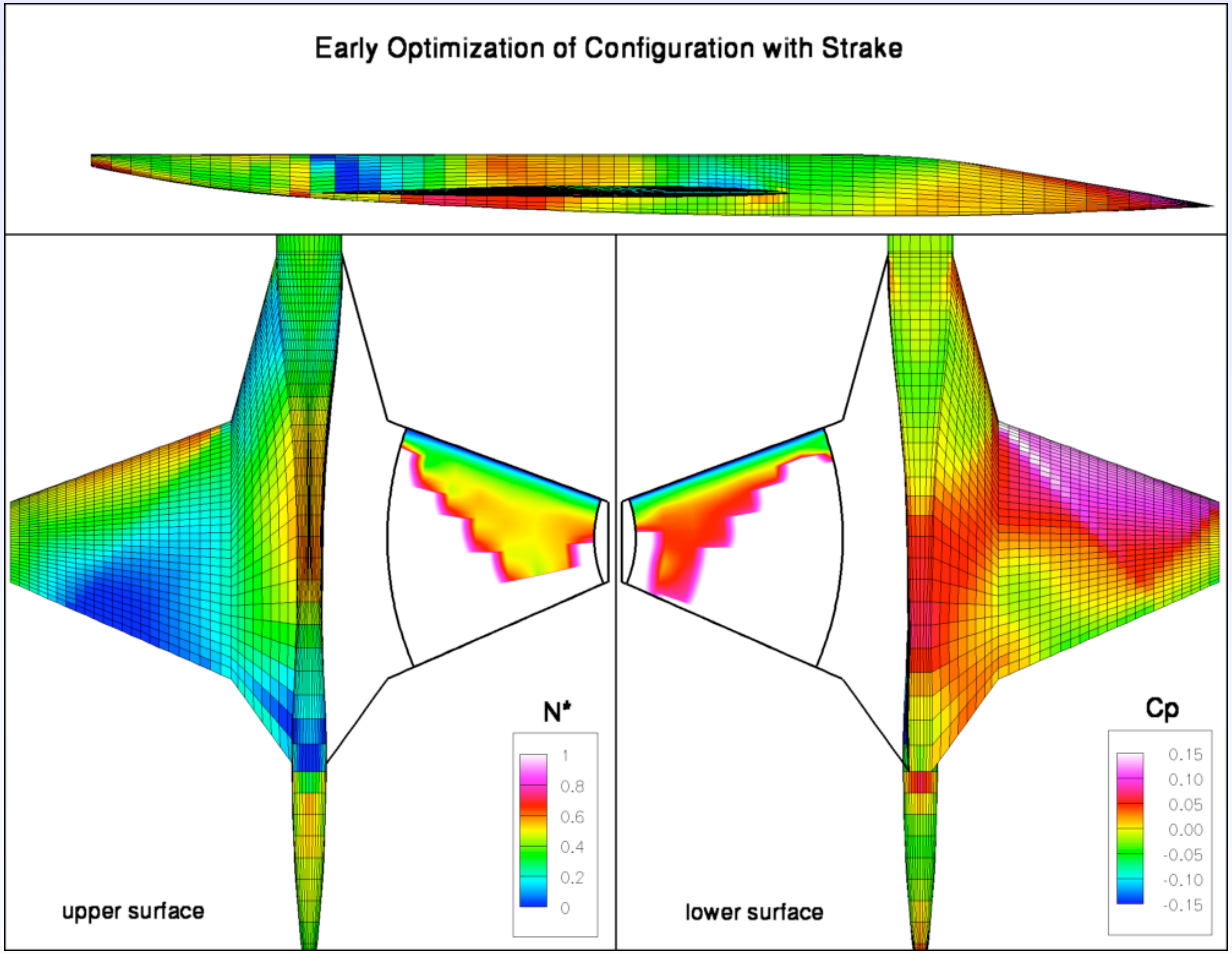
Viscous Optimization: Early Difficulties

- White areas indicate turbulent flow
- Difficulties in obtaining adequate laminar flow due to addition of strake



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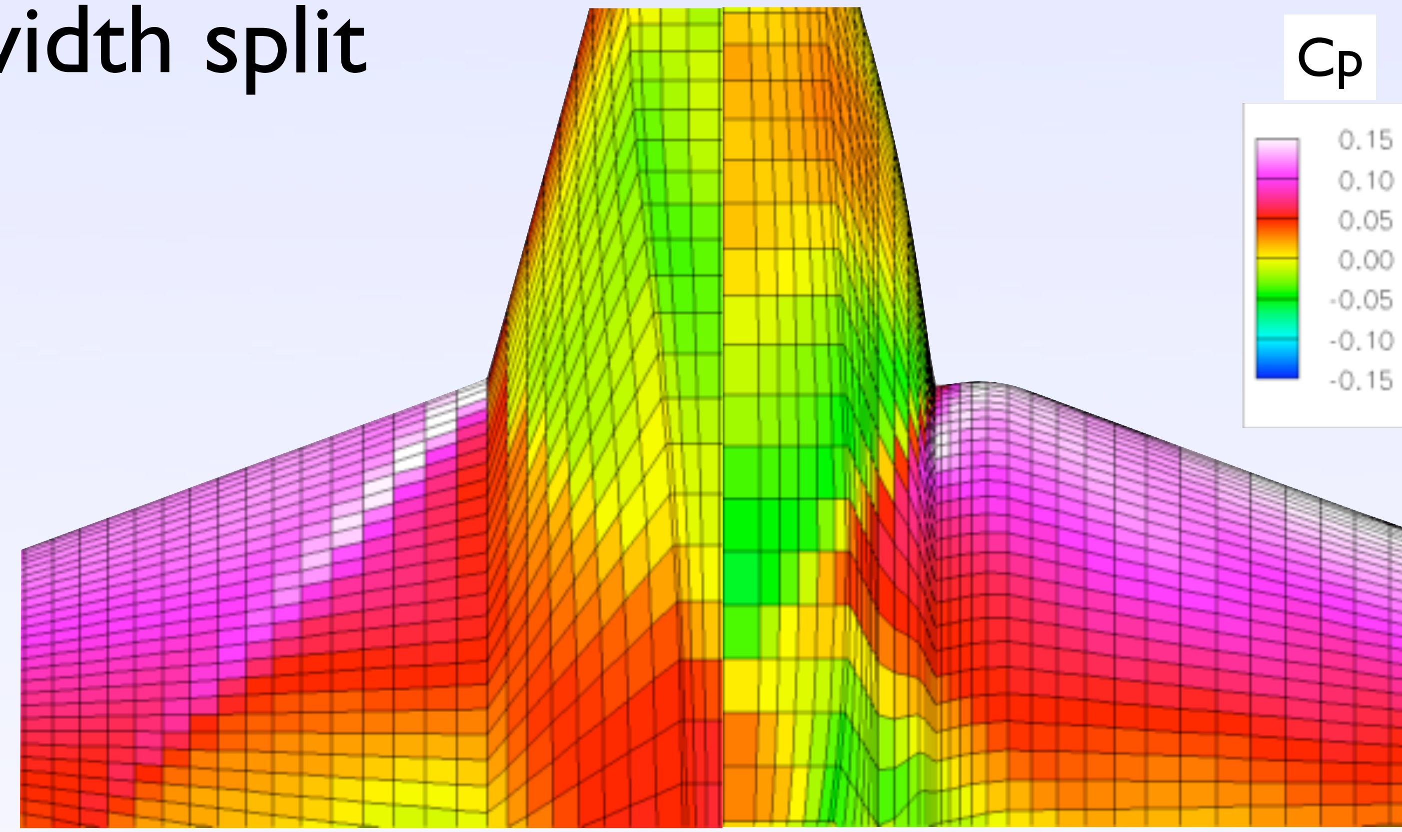
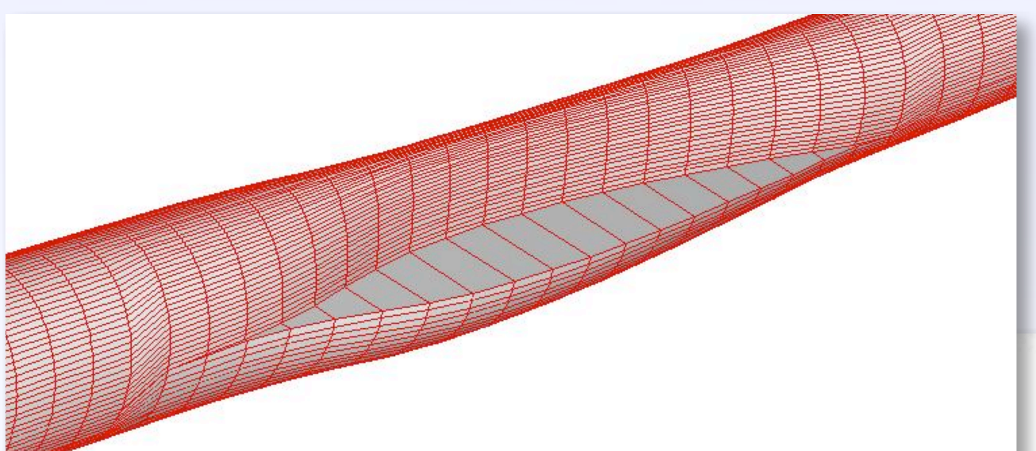
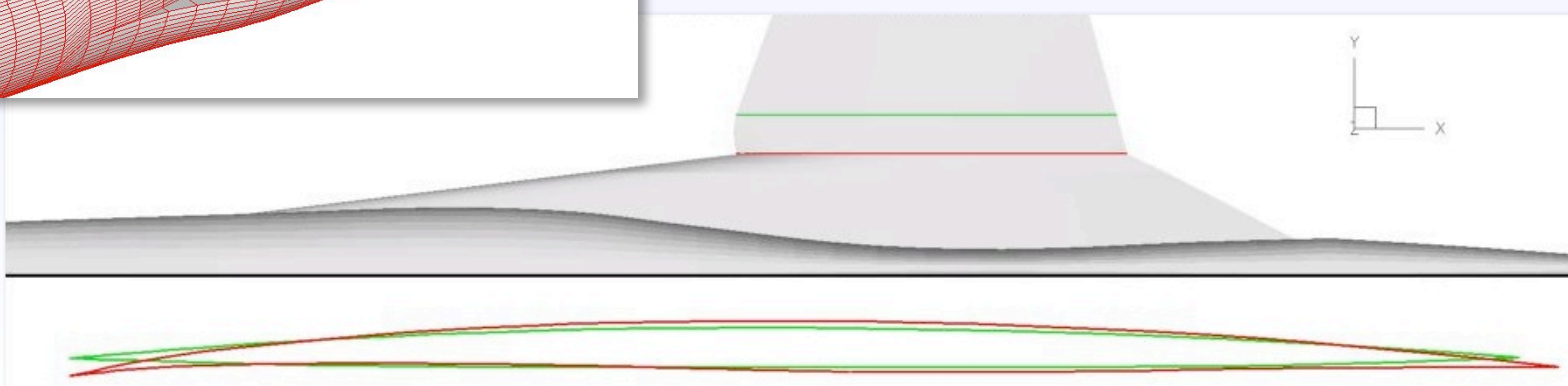
Viscous Optimization: Key Elements

- ✦ Upper/lower fuselage width split
- ✦ Airfoil nose droop
- ✦ The notch

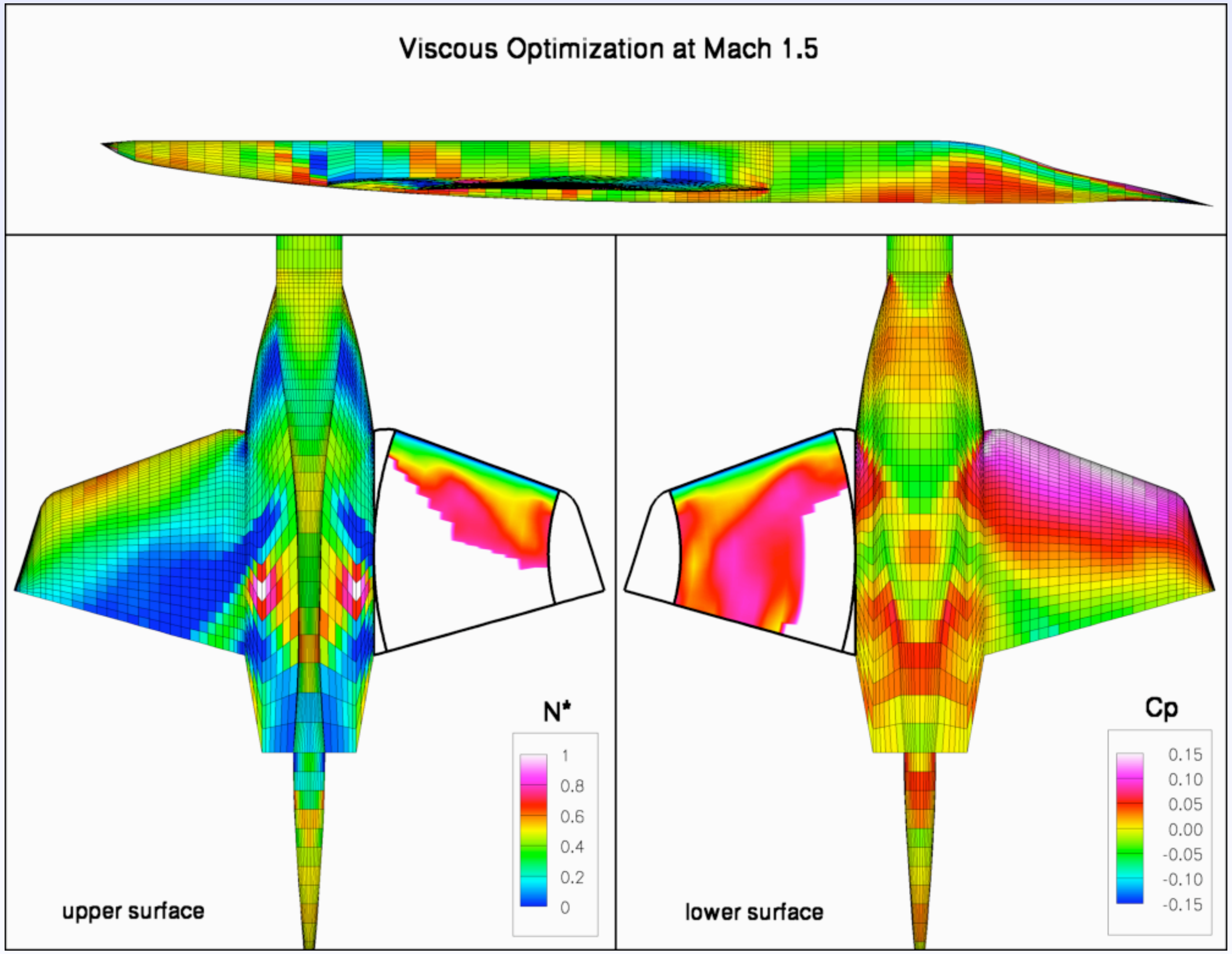






Viscous Optimization: Typical Result

- Less than 100% laminar fraction due to wave drag trade
- Optimization "encouraged" to favor lower surface due to nacelle and spoiler placement



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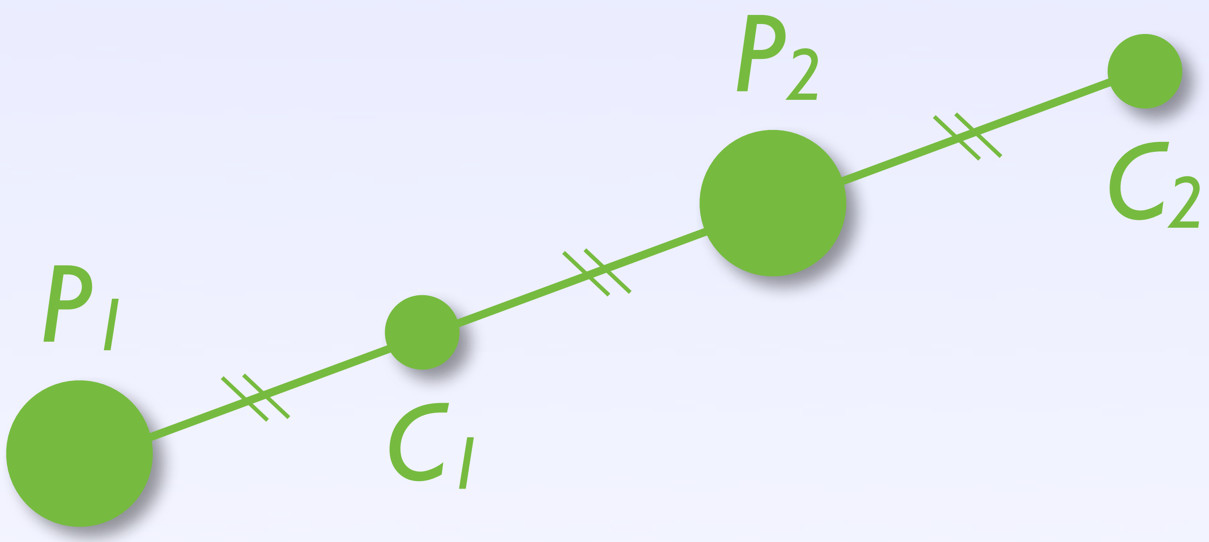
Details of Optimization

- Genetic Algorithm
  - real-valued crossover, mutation
  - least-squares Lagrange multiplier estimate for constraint penalty
  - Highly parallelizable
- 10 to 25 variables
- 400 to 2000 population members
- A502 panel method used insead of Euler solver



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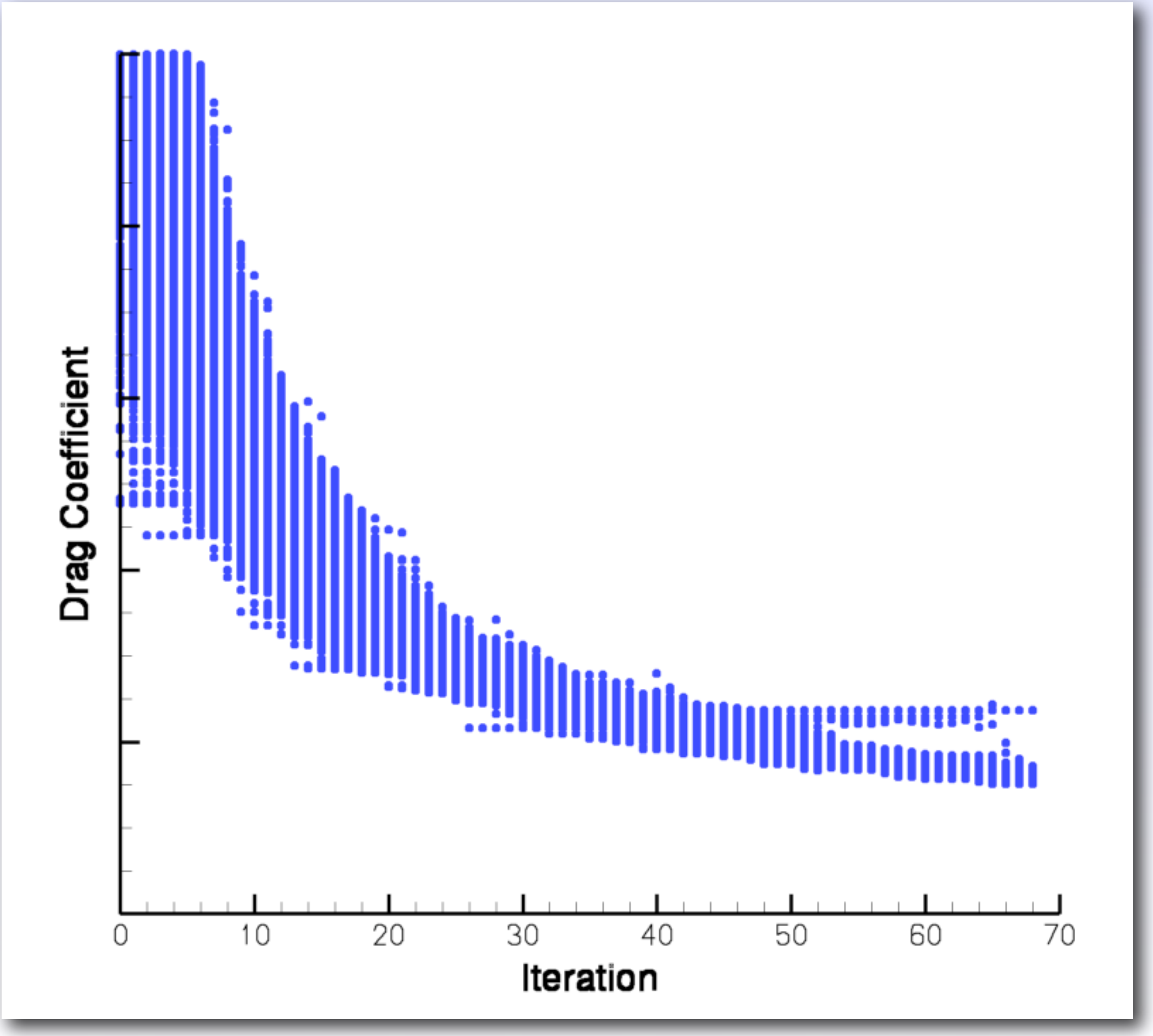
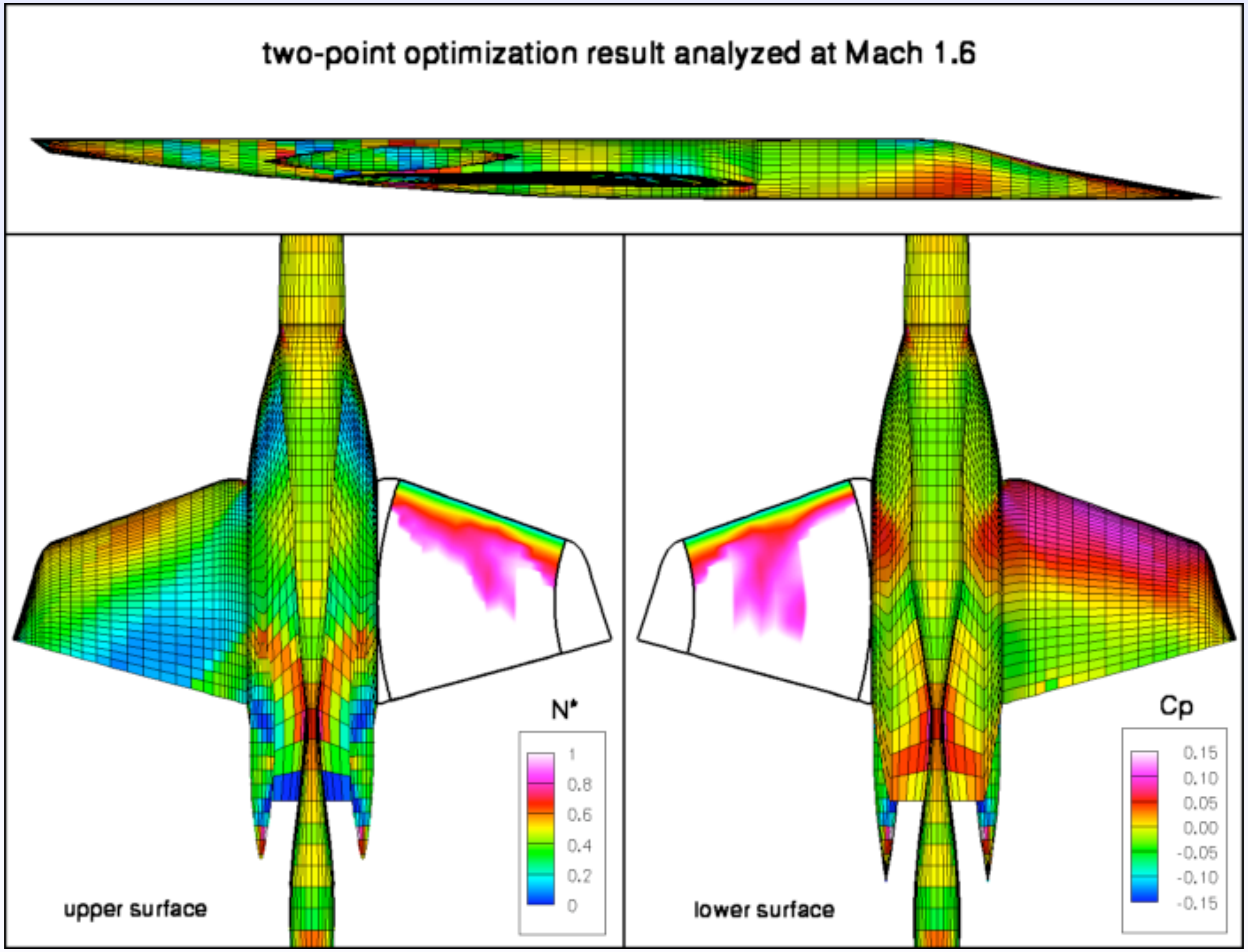
Details of Optimization

- Example convergence history
  - 24 design variables
  - population: 2304
  - 16 cpu-weeks



Sensitivity to Mach

- Long-range cruise at Mach 1.4
- High-speed cruise at Mach 1.6
- Laminar extent poor at Mach 1.6



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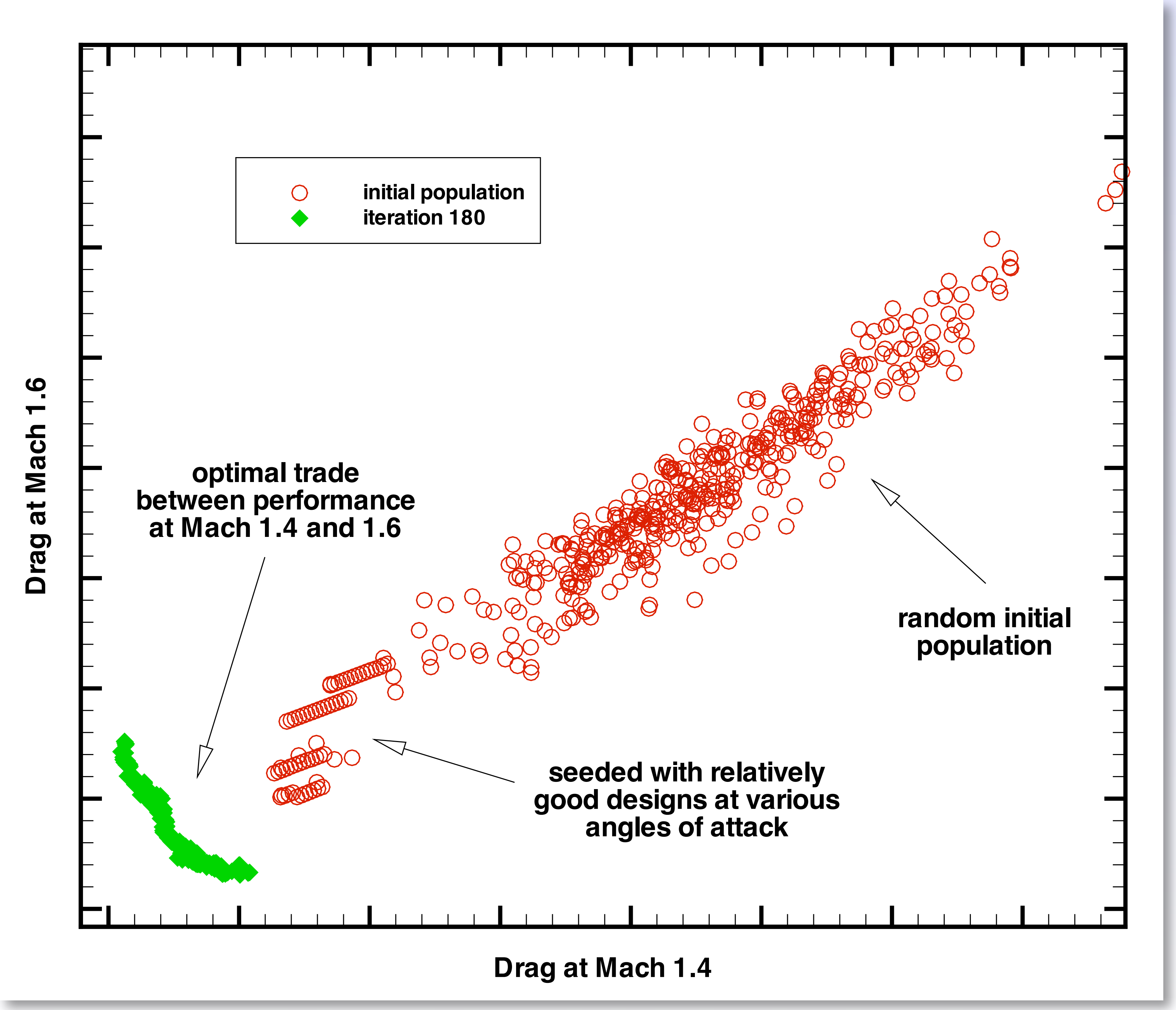
Multi-Objective Optimization

- Optimized at both Mach 1.4 and 1.6 simultaneously
- Pareto-optimal set
- Population-based optimization (GA)
  - ranking and niching per book by Deb



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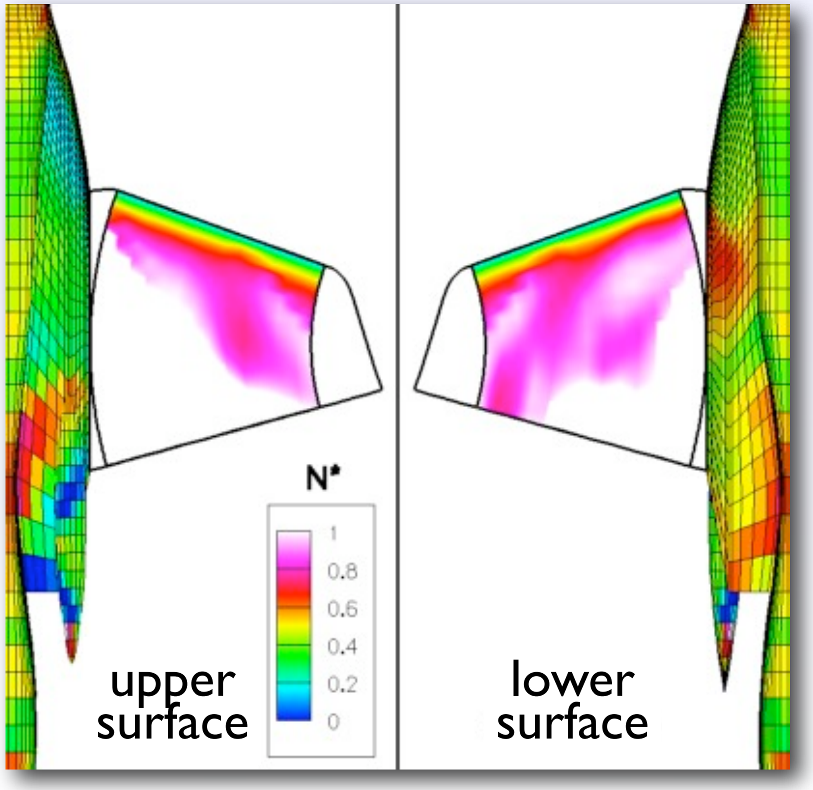
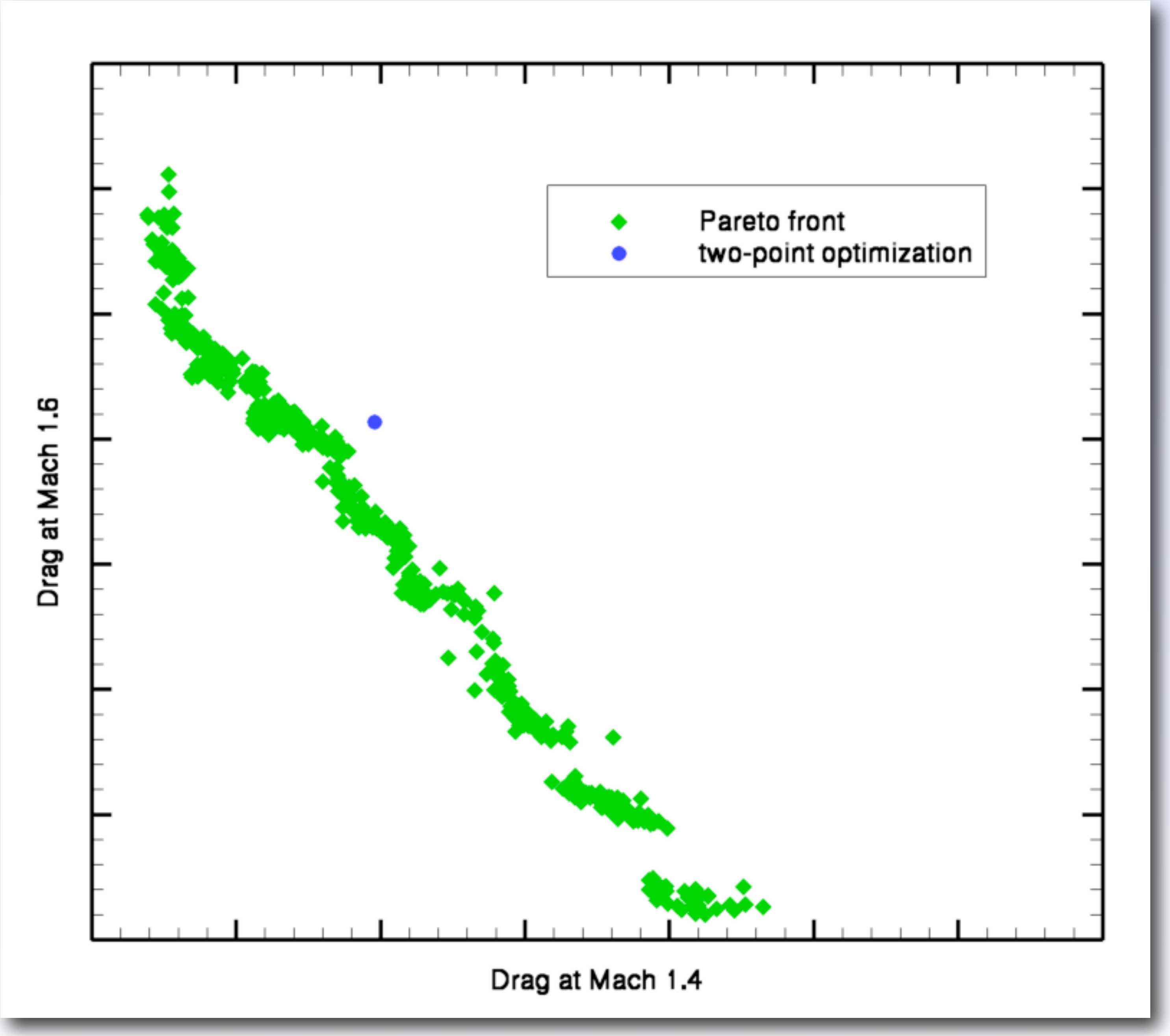
Multi-Objective Optimization

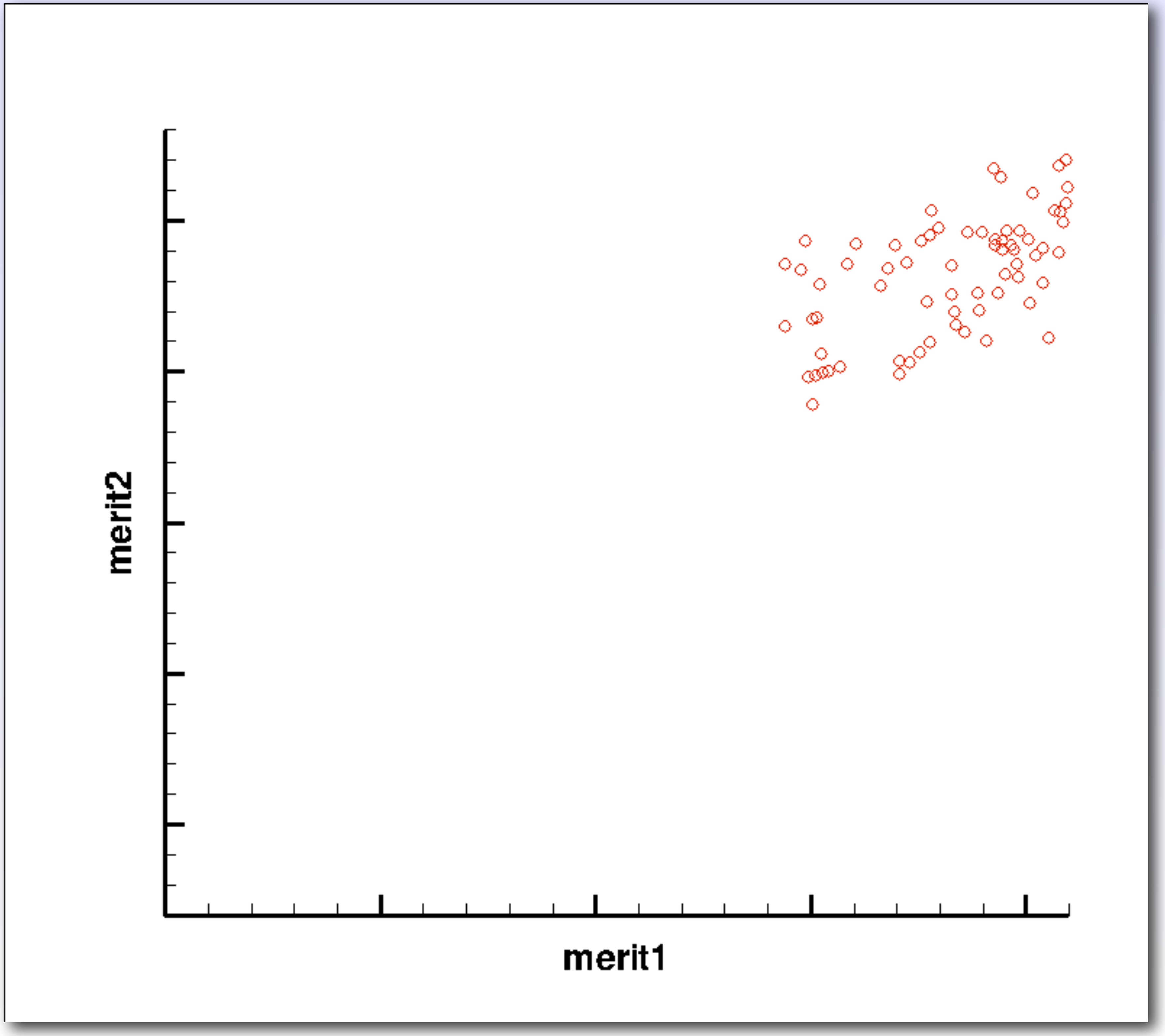
- Shows tradeoff between drag at two cruise speeds
- Found better Mach 1.6 result than single-point optimization





Multi-Objective Optimization

Multi-Objective Optimization



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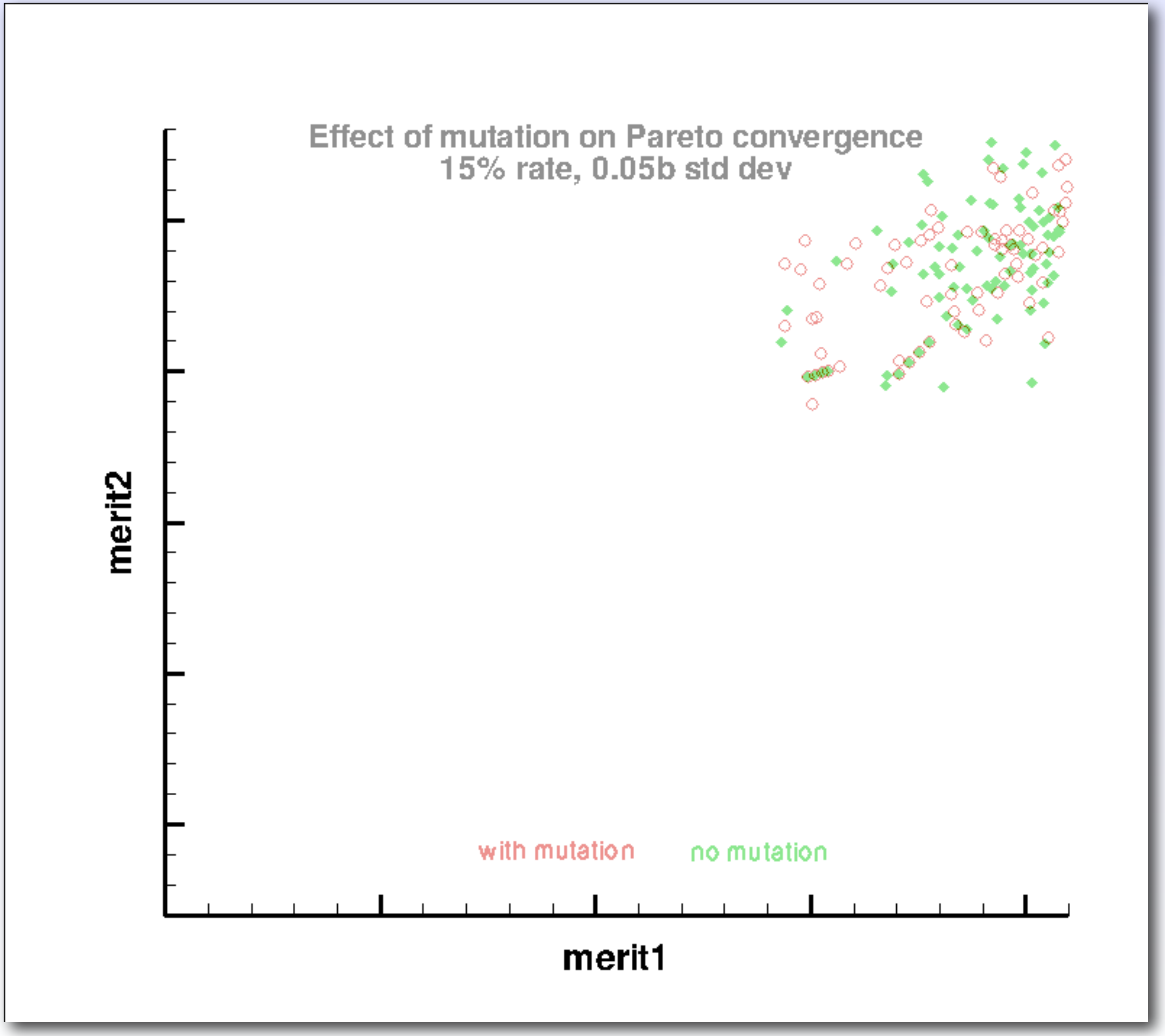
Multi-Objective Optimization

Multi-Objective Optimization



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Conclusions

- ✦ Optimization is key to Aerion natural laminar flow design
  - achieving laminar extent with minimal wave drag penalty
  - propulsion integration with 3D intakes and nozzles
- ✦ Simple optimization algorithms can be quite useful
- ✦ Robustness more important than fast convergence
- ✦ Some improvement more important than a provable optimum
  - "An optimal airplane is one that is out on the ramp ready to fly a mission." *C. L. Johnson*

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Conclusion