Ablation Modeling Capabilities and Development Efforts at Sandia National Laboratories

7th Ablation Workshop

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Dave Kuntz, Micah Howard, Justin Smith, Ross Wagnild, Don Potter, and Roy Hogan
Aerosciences Department/Sandia National Laboratories

Ben Blackwell
Blackwell Consulting/Sandia National Laboratories

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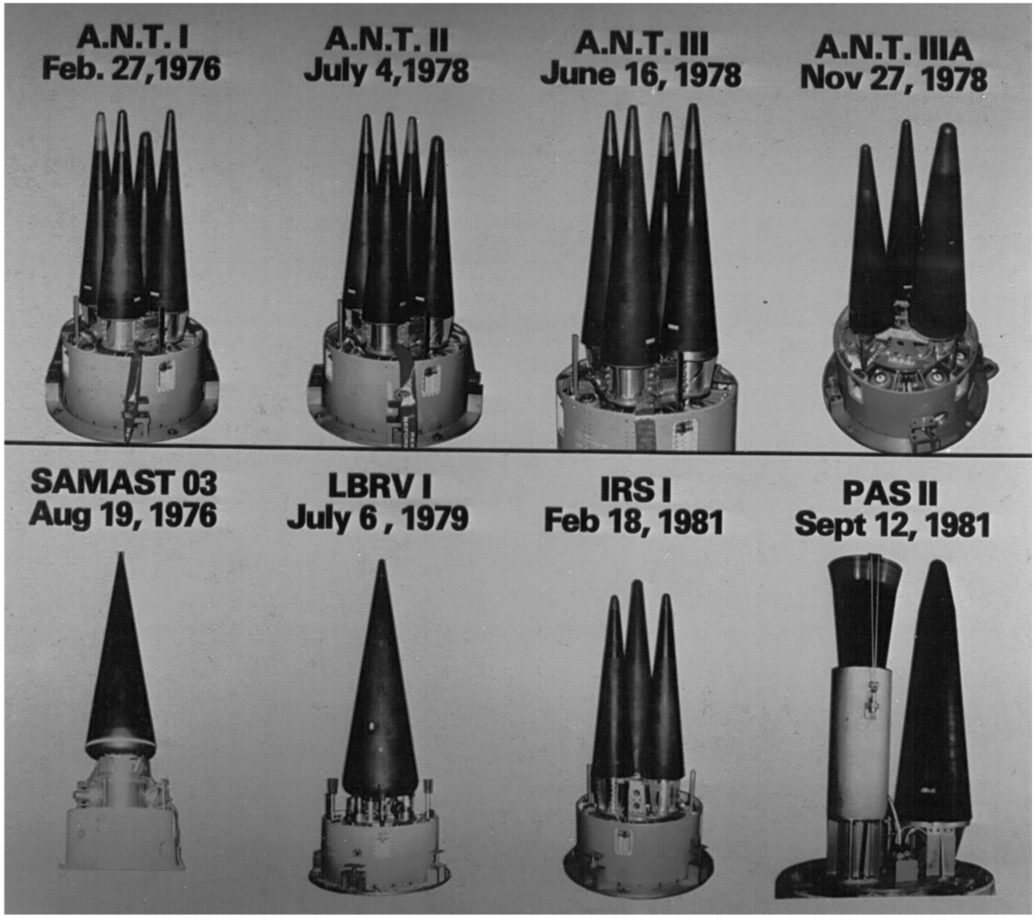
Sandia's Historical Roots in Hypersonic Reentry Systems

U.S. RV Performance
- Ballistic vehicle dynamic behavior
- Component environments and performance

Materials Development
- Heatshields
- All carbon-carbon vehicles
- Antenna windows
- Nosetips

Hypersonic Vehicle Recovery
- Pioneered the soft recovery of hypersonic vehicles for post-flight inspection



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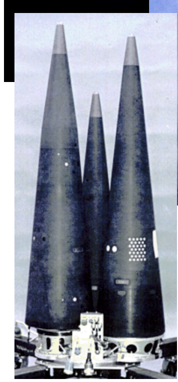
Aerothermal
Flight Vehicle Support

Minuteman Launch
from VAFB

- More than 100 Instrumented RV/RB's flown (1968-present)
- 7 Carbon-Carbon vehicles
- 6 RV's soft recovered
- 10 RV's on 9 AO's [USAF;MM III & PK]
- 9 RB's on 4 DASO's [USN]
- Most vehicles, One-of-a-kind, unique R & D tests
- High risk, excellent track record [>96% of flight test objectives satisfied]

MaST Recovery
Vehicle



MaST
Payload

SAMAST/MINT
All Carbon-Carbon
Vehicle

GRANITE

NASA SHARP-B01
Vehicle

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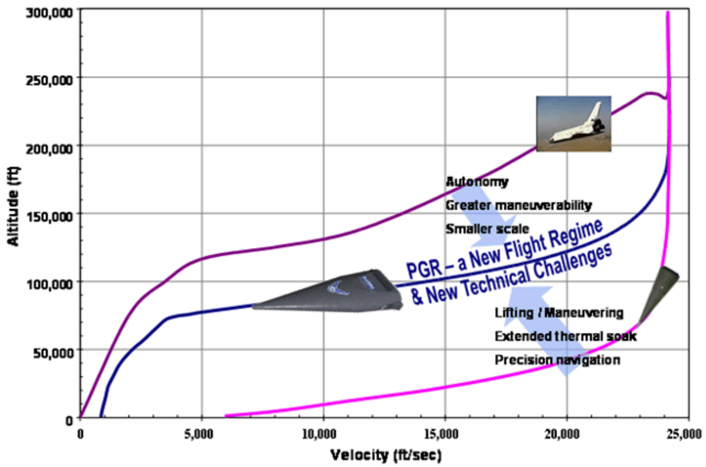
Emerging Needs
Boost-Glide Vehicles

- **Boost-Glide Vehicles cruise for long periods of time in the atmosphere and typically have complex geometries.**

- **Analysis techniques developed for short-duration flights of axisymmetric vehicles are no longer adequate for modeling these vehicles.**



- **New Material Thermal Response codes are necessary to model these next-generation flight vehicles, including significant shape change and complex internal structures.**

Sandia Current Capabilities
Aeroheating Environment

- **Aeroheating tools are necessary to determine boundary conditions for Material Thermal Response codes.**
- **Current tools vary in sophistication and complexity:**
  - **Correlation-based codes**
  - **Inviscid-Boundary Layer codes**
  - **Full Navier-Stokes codes**

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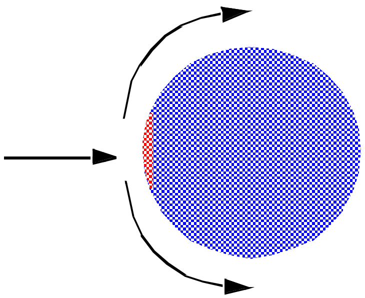
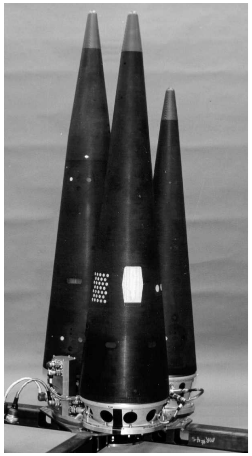
Sandia Current Capabilities
Aeroheating Environment

- Correlation-Based Codes:
  - HANDI
    - Analytical/empirical relationships applied to specialized heating & engineering design problems

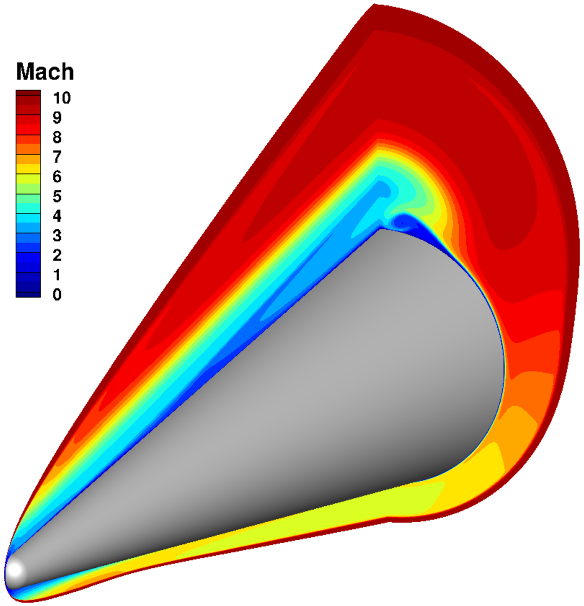


- Inviscid-Boundary Layer Codes:
  - 2IT/SANDIAC/HIBLARG
    - 2IT – Solves for the inviscid flow on the spherical portion of the nosetip
    - SANDIAC – Solves the Euler equations for the inviscid flow over the afterbody
    - HIBLARG – Solves the integral boundary layer equations over the complete body
    - Used for sphere/multi-conic geometries and relatively simple 3-D shapes



Sandia Current Capabilities
Aeroheating Environment

- **Full Navier-Stokes Codes**
  - **DPLR**
    - **Full three-dimensional Structured Navier-Stokes code**
    - **Maintained at NASA Ames**
    - **Used at Sandia primarily as a flowfield and heating code, but has not yet been used for material thermal response calculations**
  - **US3D**
    - **Full three-dimensional Unstructured Navier-Stokes code**
    - **Developed at the University of Minnesota**
    - **Used at Sandia as a flowfield, heating, and material thermal response boundary condition code**



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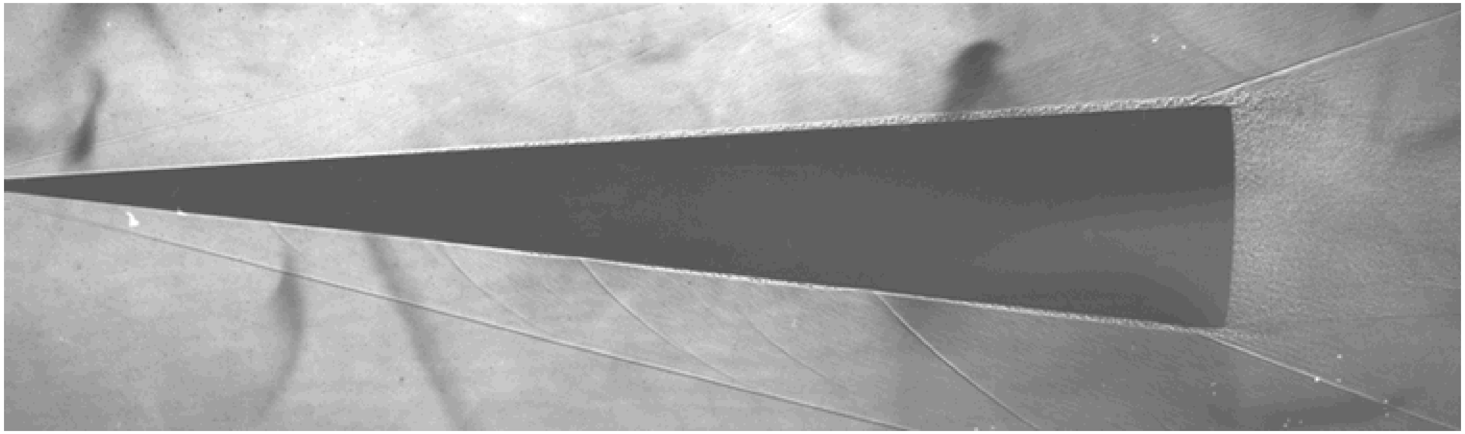
Sandia Current Capabilities
Boundary Layer Transition Prediction

- **A Boundary Layer Transition (BLT) prediction capability is necessary to determine the Aeroheating Environment.**
- **BLT correlations have been used for decades and are currently incorporated within existing Aeroheating Environment codes.**
- **Two three-year internally-funded R&D projects have been completed to investigate the applicability of Stability Theory to realistic hypersonic flight vehicles.**



Ballistic Range Schlieren Photograph of a Sharp Cone Undergoing Boundary Layer Transition, from Dan Reda, NASA Ames

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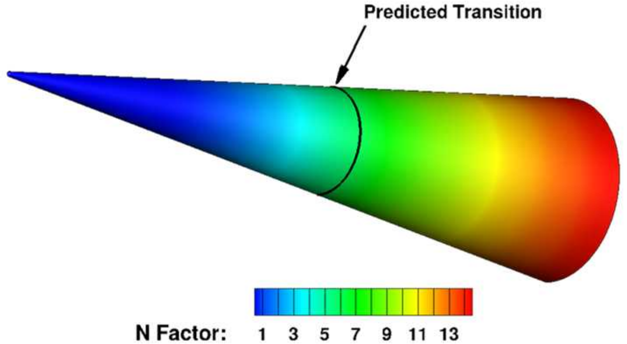
Sandia Current Capabilities
Boundary Layer Transition Prediction

- Modal Linear Stability Analysis
  - Based on linear stability theory and the parabolized stability equations
    - Assumes locally parallel and slowly varying flow in the streamwise direction
  - Transition analysis based on the N Factor
    - $N(\omega) = -\int_{S_0}^{S} \sigma(s,\omega)\,ds$



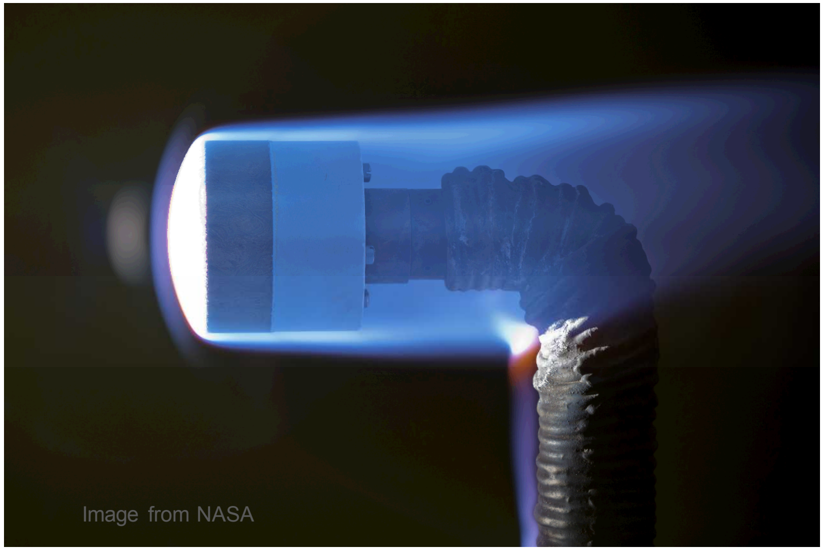
- Codes
  - STABL
    - Developed at the University of Minnesota
    - 2D and Axi-symmetric
  - STABL3D
    - Developed at the University of Minnesota
    - Parabolized stability equations not yet implemented
    - Applies to 2D manifolds derived from 3D flowfields

Sandia Current Capabilities
Material Thermal Response Codes

- **Several Material Thermal Response Codes are currently in use at Sandia**

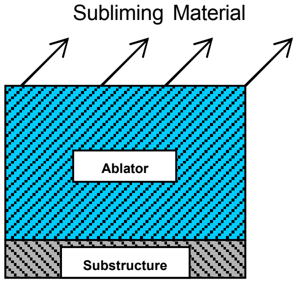
- **The code used for a particular analysis depends upon:**
  - **Vehicle geometry**
  - **Vehicle complexity**
  - **Vehicle materials**
  - **Desired thermal response**

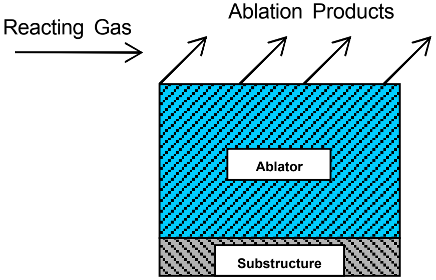
- **Code types include:**
  - **1-Dimensional**
  - **Dedicated Nosetip**
  - **3-Dimensional**

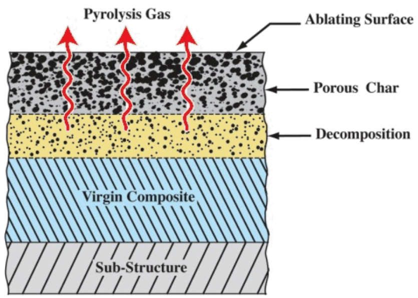


Sandia Current Capabilities
Material Thermal Response Codes

- **1-Dimensional Codes**
  - **CMA (Charring Material Ablation)**
    - **Originally developed by Aerotherm**
    - **Heavily integrated into multiple automated analysis codes in use at Sandia**
  - **Chaleur**
    - **Relatively new code developed at Sandia by Ben Blackwell and Micah Howard**
    - **Real-time equilibrium chemistry, B' table look-up capabilities, and approximate finite-rate carbon ablation chemistry model based on the work of Welsh and Chung available**
  - **ParChaleur**
    - **Fortran driver code for Chaleur**
    - **Uses heating data extracted from US3D solutions of complex geometries at each surface node**
    - **1-D Material Thermal Response solutions then performed at each surface node**

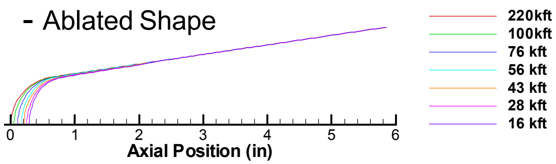


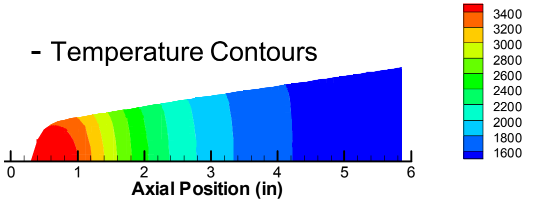




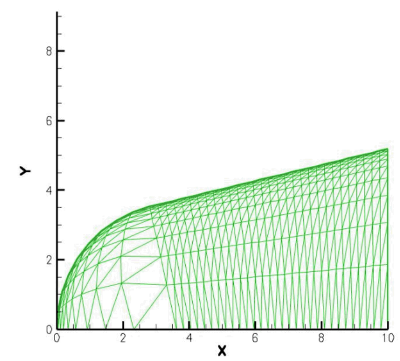
Sandia Current Capabilities
Material Thermal Response Codes

- Dedicated Nosetip Codes
  - ASCC (ABRES Shape Change Code):
    - Originally developed by Aerotherm
    - 2-D Axisymmetric Nosetip Code
    - Inviscid flowfield computed with an engineering-based approaches, heating computed with Momentum/Energy Integral Technique (MEIT)
    - Surface ablation model only (no decomposition)





  - SMITE (Simple Multi-dimensional In-depth Thermal Evaluation):
    - Relatively new code currently under development at Sandia
    - Two-dimensional code with unstructured internal grid generation
    - Axisymmetric sphere-cones & two-dimensional cross sections



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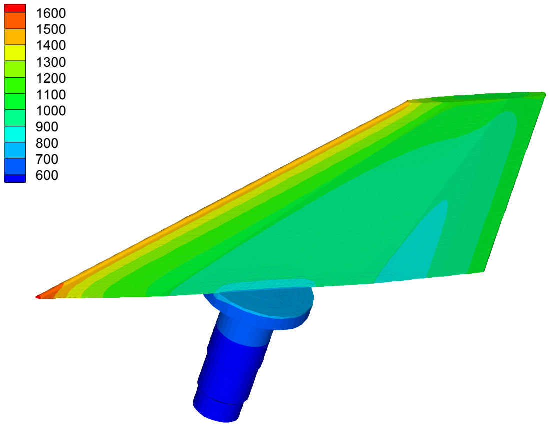
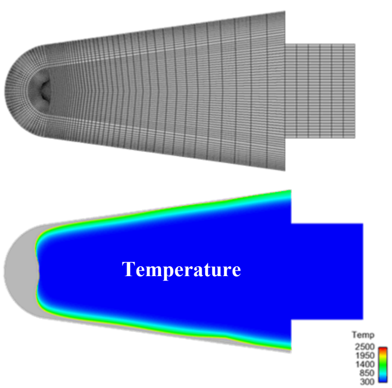
Sandia Current Capabilities
Material Thermal Response Codes

- **3-Dimensional Codes**
  - **COYOTE-ab**
    - **Developed at Sandia for complex thermal problems**
    - **Finite Element program for non-linear heat transfer problems**
    - **Moving mesh for ablation problems (non-decomposing ablators only)**
    - **Multiple boundary condition types available**



  - **SPARC (Sandia Parallel Aerosciences Research Code)**
    - **Research code for compressible CFD and ablation model & algorithm development**
    - **Cell-centered finite volume method for CFD problems**
    - **Galerkin finite element method for ablation/thermal problems**
    - **Continued development is underway**



Arc-Jet Simulations Using US3D and SPARC

- CFD Simulations of Arc-Jets
  - Using framework laid out by Prabhu et.al.*
  - Simulating arc-jet conditions for 2 NASA ARC arc-jets
    - AHF – 20-MW Aerodynamic Heating Facility
    - IHF – 60-MW Interaction Heating Facility
  - Flowfield simulated with the US3D CFD code
    - Modeling assumptions:
      - 6 specie gas model (N_2, O_2, NO, N, O, Ar)
      - Chemical and thermal non-equilibrium
      - Park's T-Tv model for thermal non-equilibrium
      - Uniform inflow conditions for the plenum for both AHF and IHF
      - Cold isothermal wall BC (293K)
    - Both AHF and IHF CFD grids are axisymmetric with ~ 60 – 70 k cells
    - Both CFD simulations converge in 8 – 10 k iterations

* Prabhu, D., et al., "CFD Analysis Framework for Arc-Heated Flowfields, I: Stagnation Testing in Arc-Jets at NASA ARC", *Proceedings of the 41st AIAA Thermophysics Conference*, 22-25 June 2009, San Antonio, Texas.

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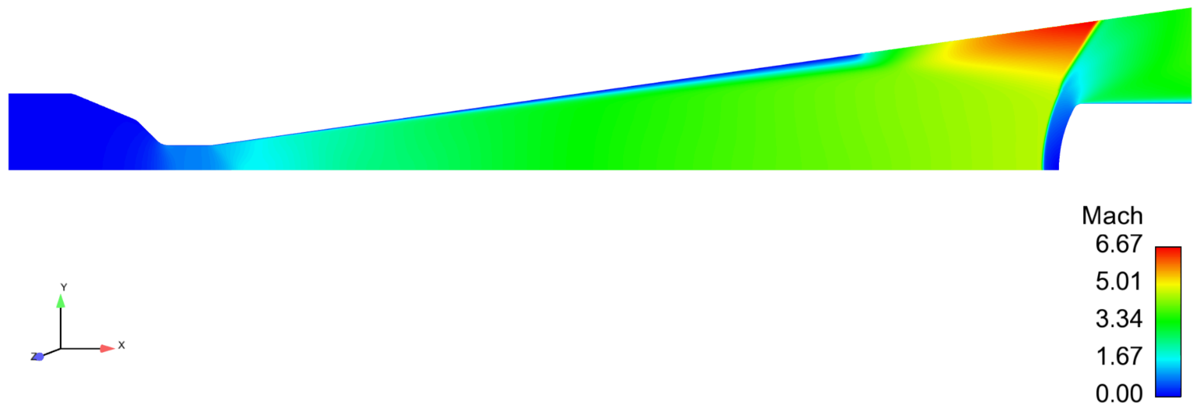
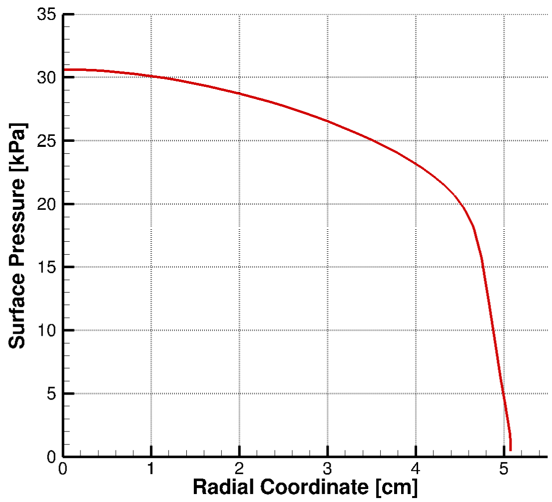
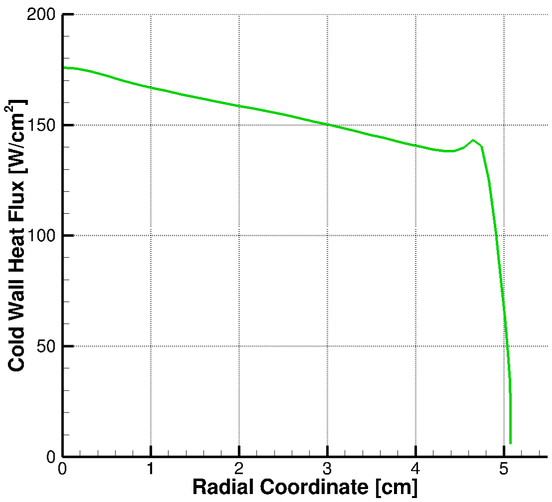
Arc-Jet Simulations Using US3D and SPARC

- **CFD Simulation of NASA Ames AHF**

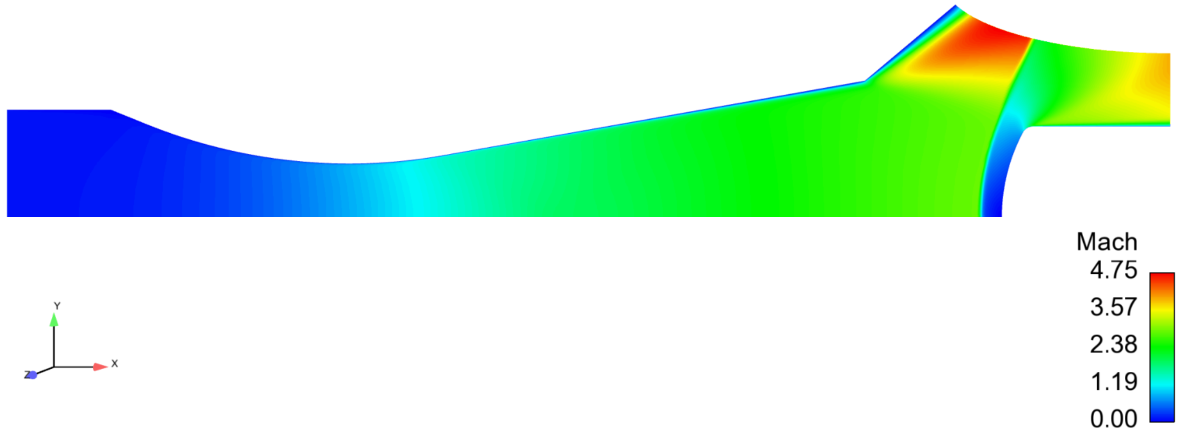


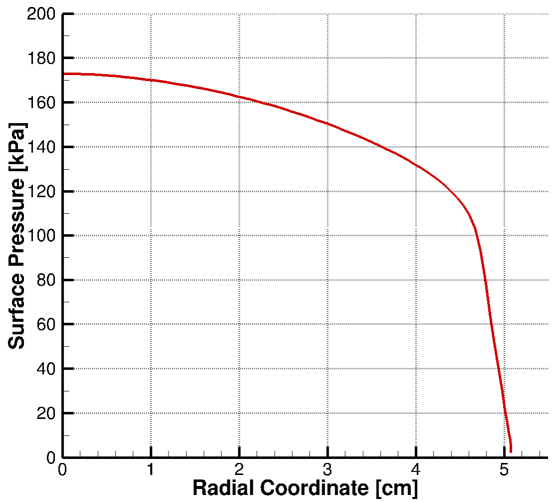


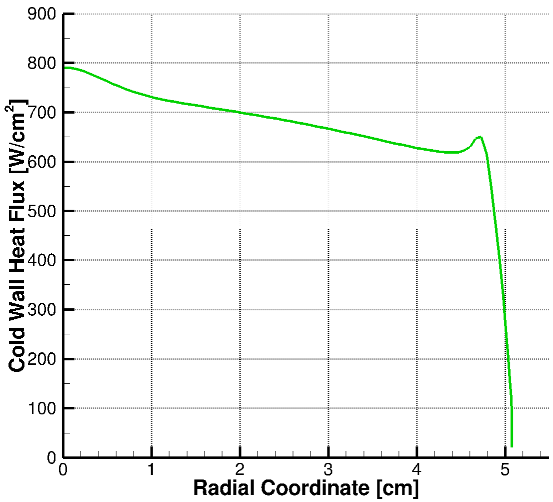


Arc-Jet Simulations Using US3D and SPARC

- **CFD Simulation of NASA Ames IHF**

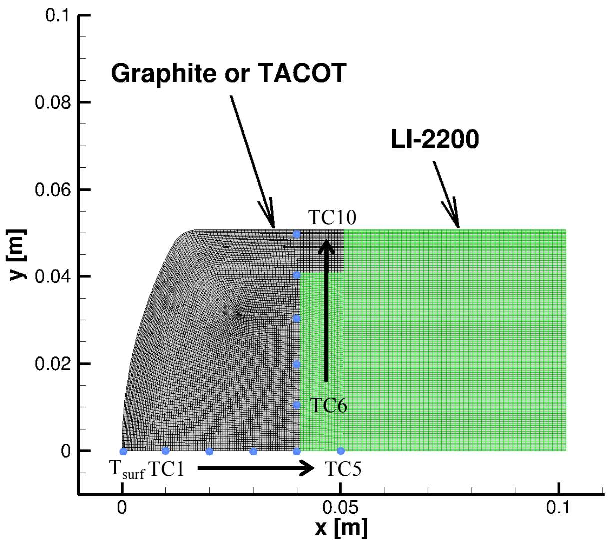






Arc-Jet Simulations Using US3D and SPARC

- **Ablation Simulation of Iso-Q Models**
  - **2-D axisymmetric arc-jet/Iso-Q ablation test**
    - **Both non-decomposing (graphite) & decomposing (TACOT) ablators**
    - **LI-2200 insulating model holder material**
    - **CFD-based arc-jet flowfield heating on the ablating surface**
      - **Post-process CFD solution for $\rho_e u_e C_H$, h_r, and p_e**
      - **Interpolate data to a "surface transfer file" (not necessarily matching the CFD grid)**
      - **60 second heat up, 240 second cool down**



Case 1: Graphite Iso-Q in AHF
(P_{stag} = 30.4 kPa, q_{stag}= 174 W/cm^2)

Case 2: Graphite Iso-Q in IHF
(P_{stag} = 171 kPa, q_{stag}= 780 W/cm^2)

Case 3: TACOT Iso-Q in AHF
(P_{stag} = 30.4 kPa, q_{stag}= 174 W/cm^2)

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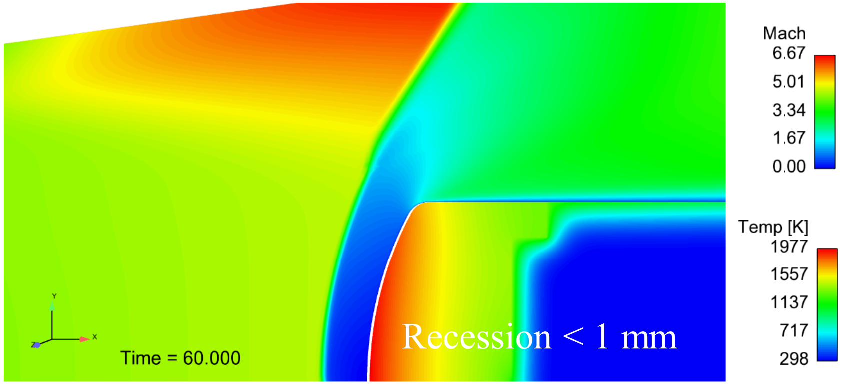
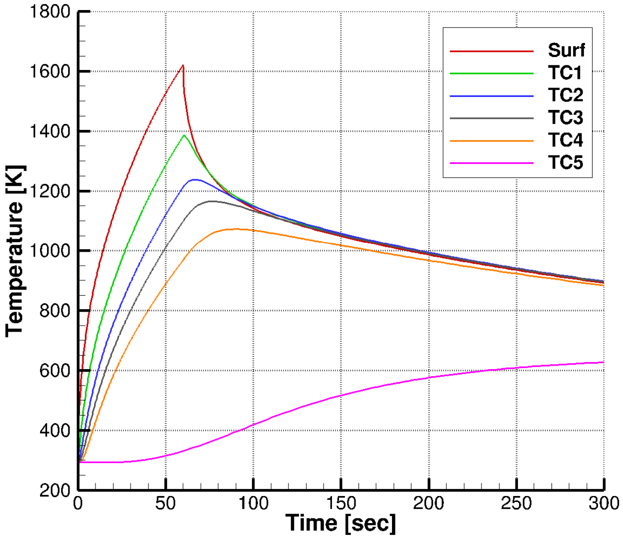
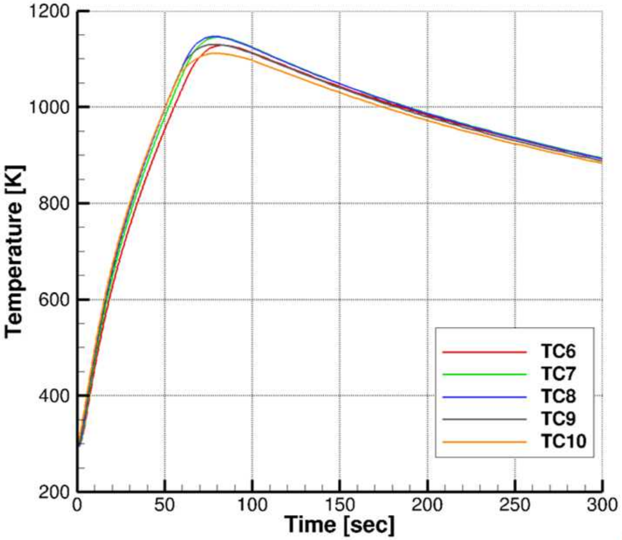
Arc-Jet Simulations Using US3D and SPARC

- **Graphite Iso-Q – AHF Simulation**

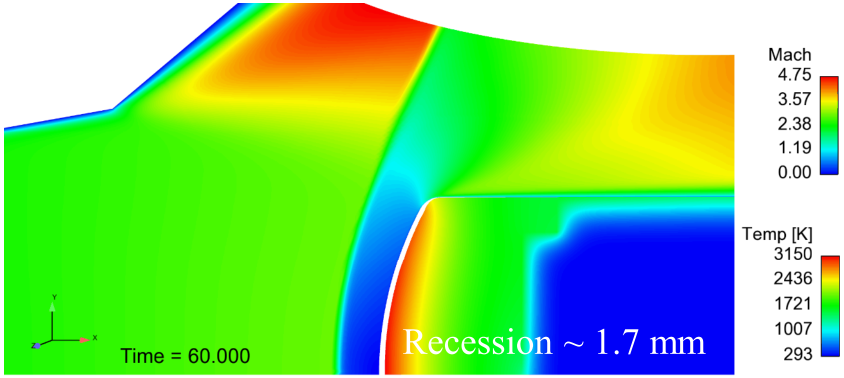


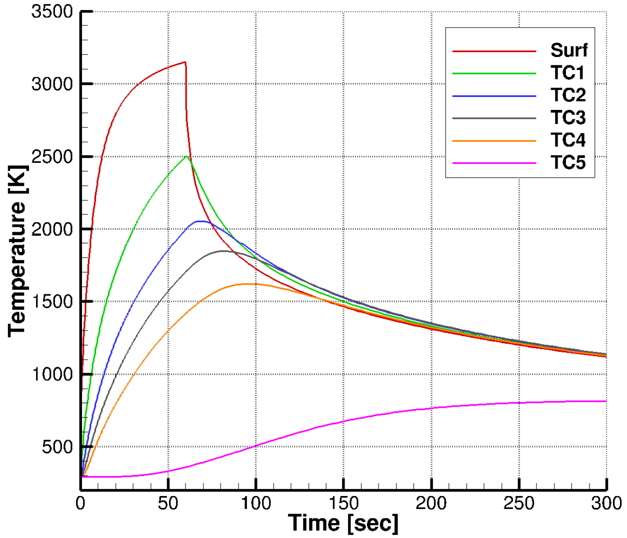


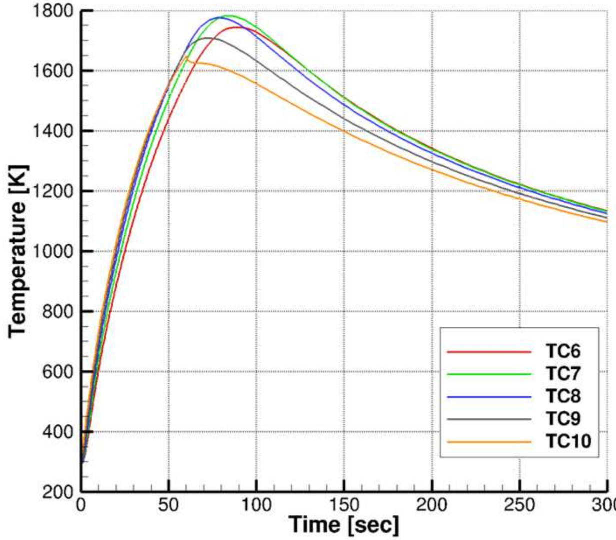


Arc-Jet Simulations Using US3D and SPARC

- **Graphite Iso-Q – IHF Simulation**

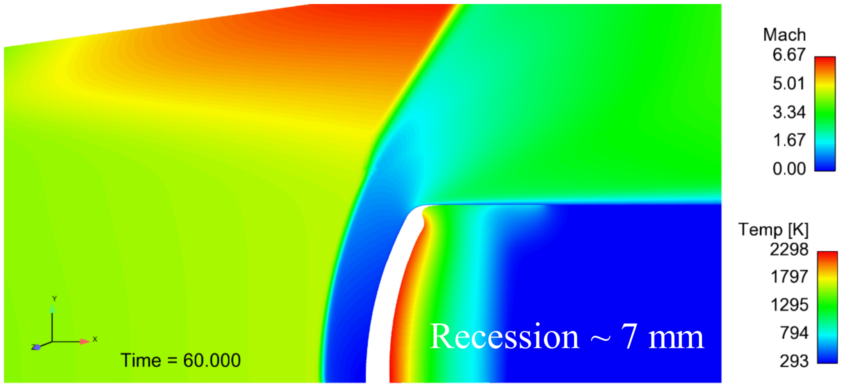


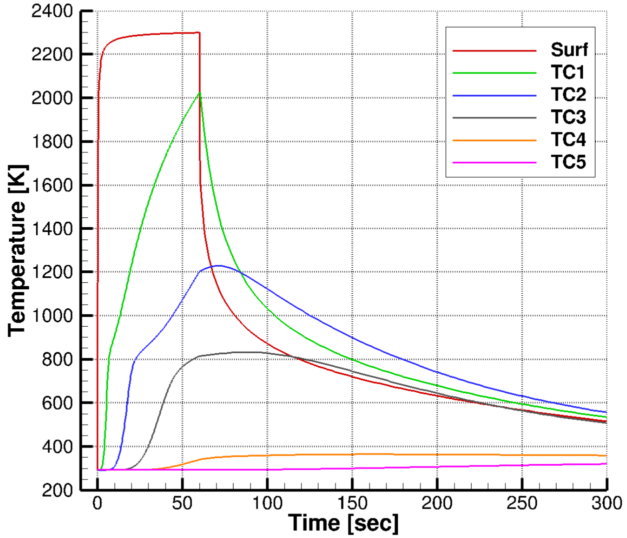


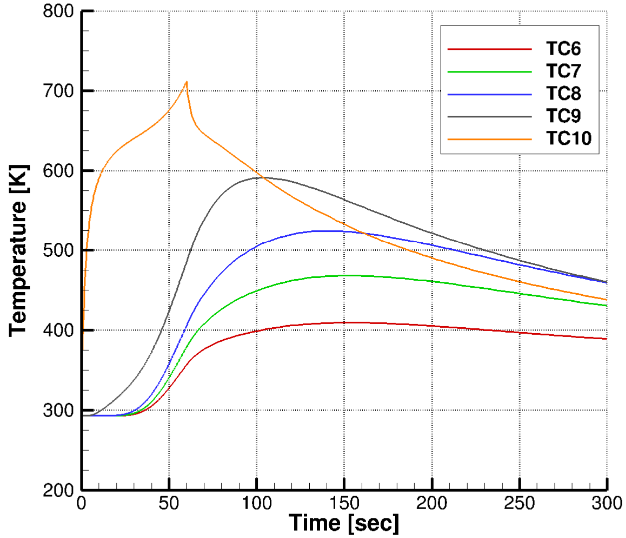


Arc-Jet Simulations Using US3D and SPARC

- **Tacot Iso-Q – AHF Simulation**

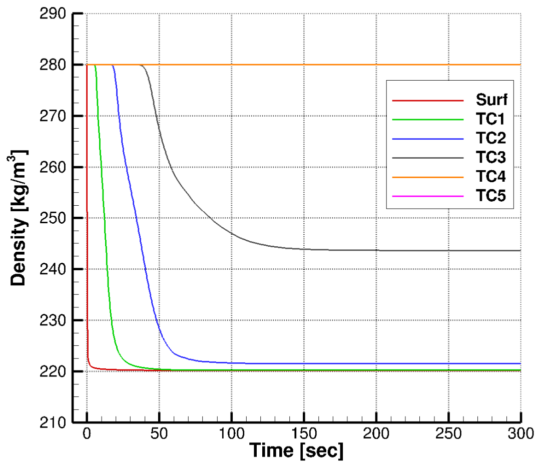


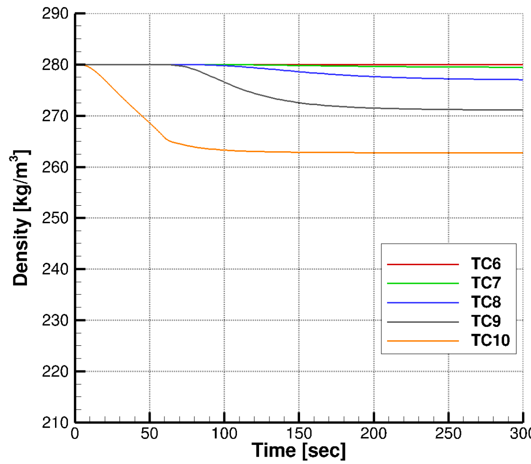


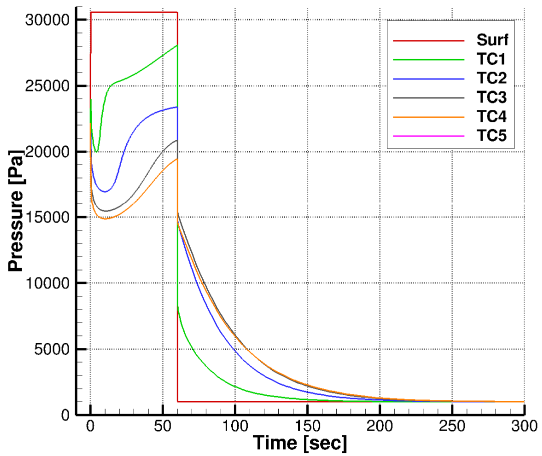


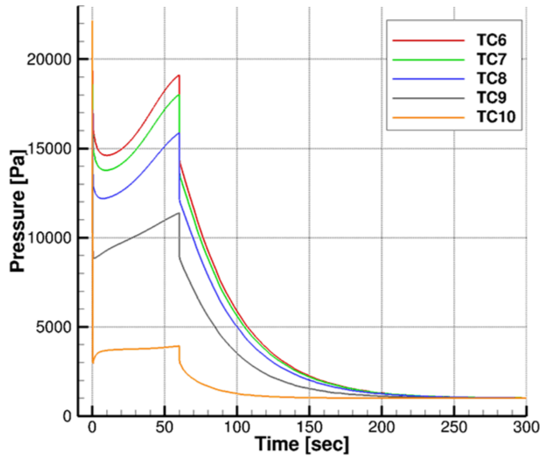
Arc-Jet Simulations Using US3D and SPARC

- **Tacot Iso-Q – AHF Simulation**









Summary

- Sandia has multiple Aeroheating and Material Thermal Response codes used in the design and analysis of hypersonic flight vehicles.
- The choice of tools depends on the particular vehicle being analyzed and the type of thermal information needed.
- Development of additional 3-D ablation modeling capabilities, motivated by increasingly complex flight vehicles, continues.
  - Numerical test problems have demonstrated the capability.
  - Code-to-code comparisons have shown relatively good agreement.
- Efforts Recently Underway
  - Development of a fully-coupled aerodynamic-aerothermodynamic capability.
  - Development of CFD codes compatible with upcoming computer architectures.

Questions?