University of Colorado Boulder

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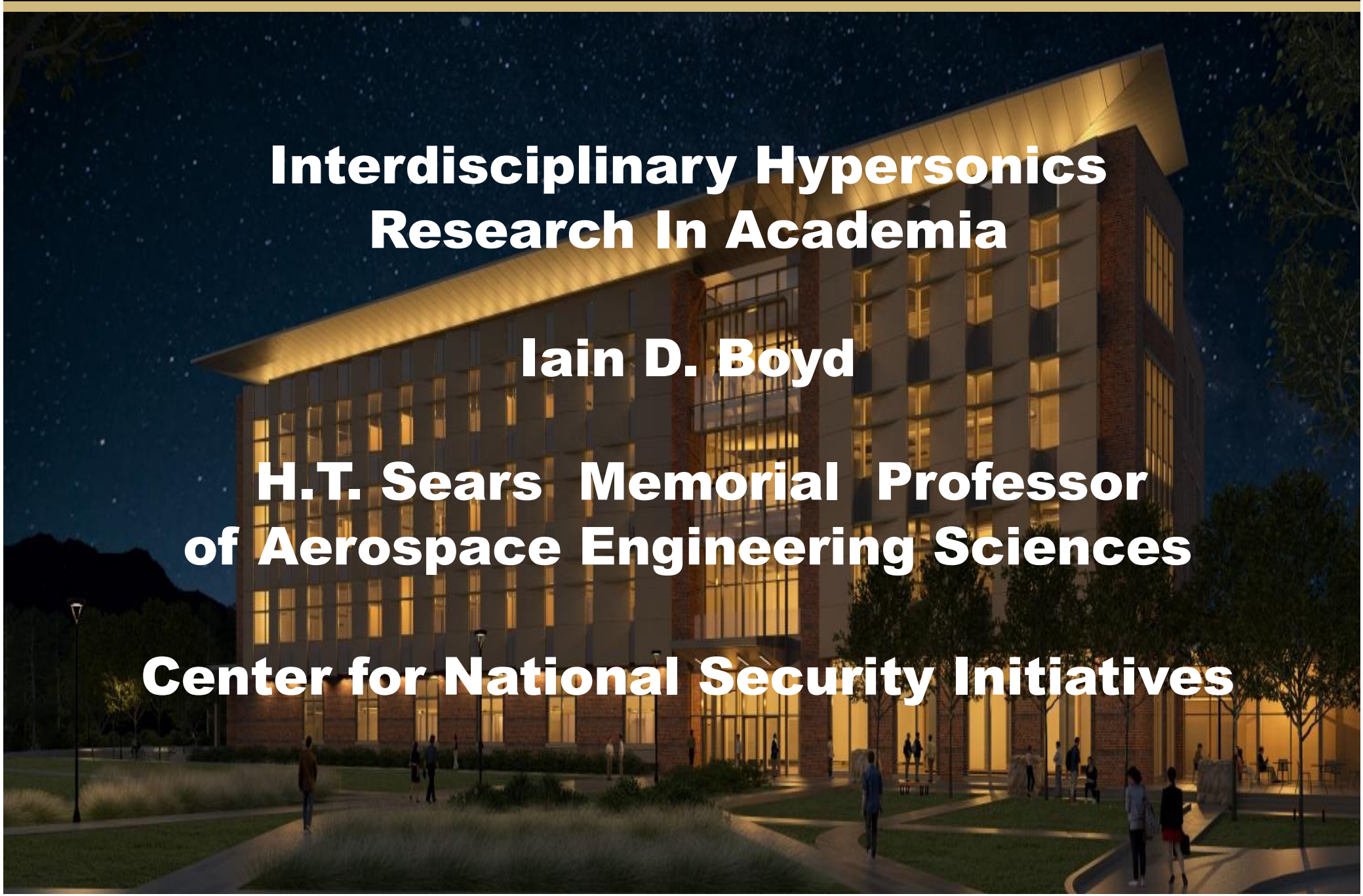

Interdisciplinary Hypersonics Research In Academia

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Center for National Security Initiatives

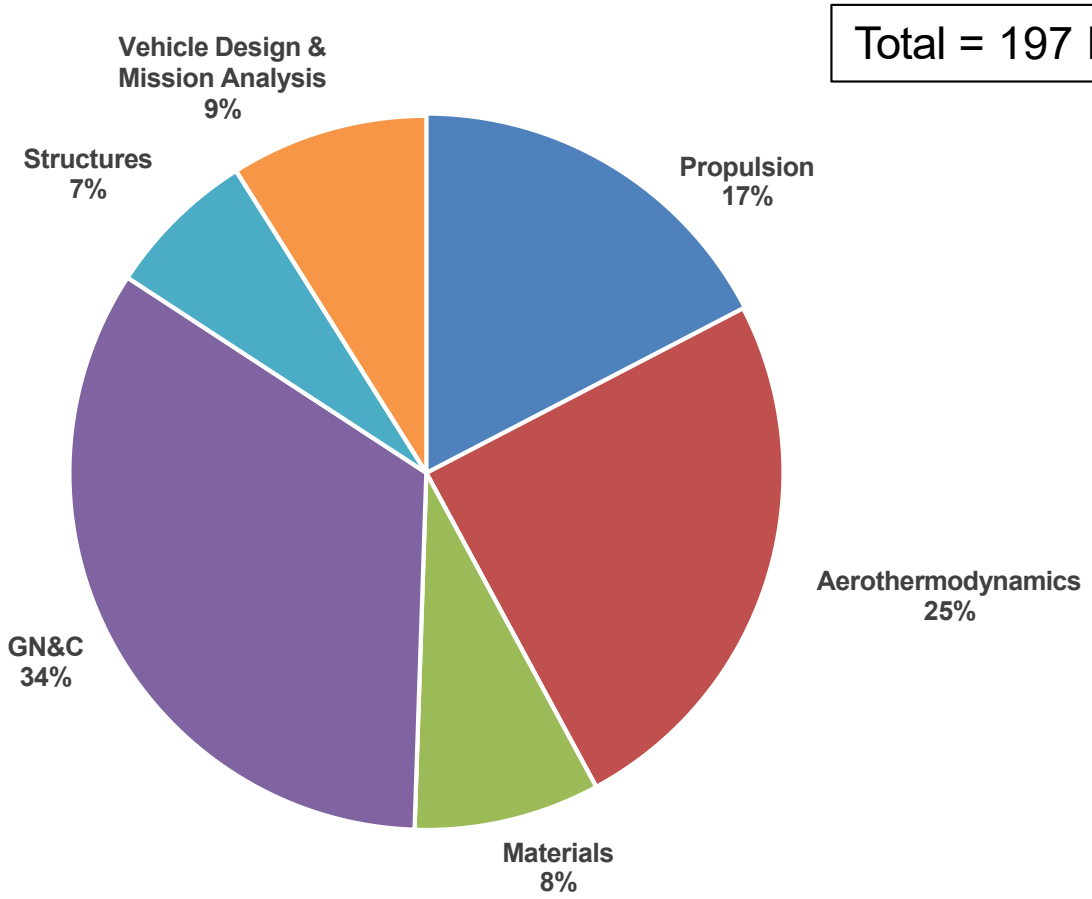
Outline

- Status of U.S. university hypersonics research
  - Comparison with China
  - New directions for U.S. academia
- Needs for **interdisciplinary** research in hypersonics
- Components of **interdisciplinary** analysis
  - Flow, surface phenomena, material response
  - Examples
    - Thermal management, shape optimization
- Summary

Efforts at Chinese Universities: Buildup in Hypersonics

- China has taken several steps to develop its hypersonics academic community
  - Infrastructure (e.g., many new wind tunnels)
  - Funding students and postdocs to study and research at U.S. universities
    - 140,000 Chinese students studied in STEM fields at U.S. universities in 2015-2016
  - Return home of Chinese nationals from United States
- Hosted the 2017 AIAA Hypersonics Conference

China Hypersonics Journal Articles: Research Topics (2017)

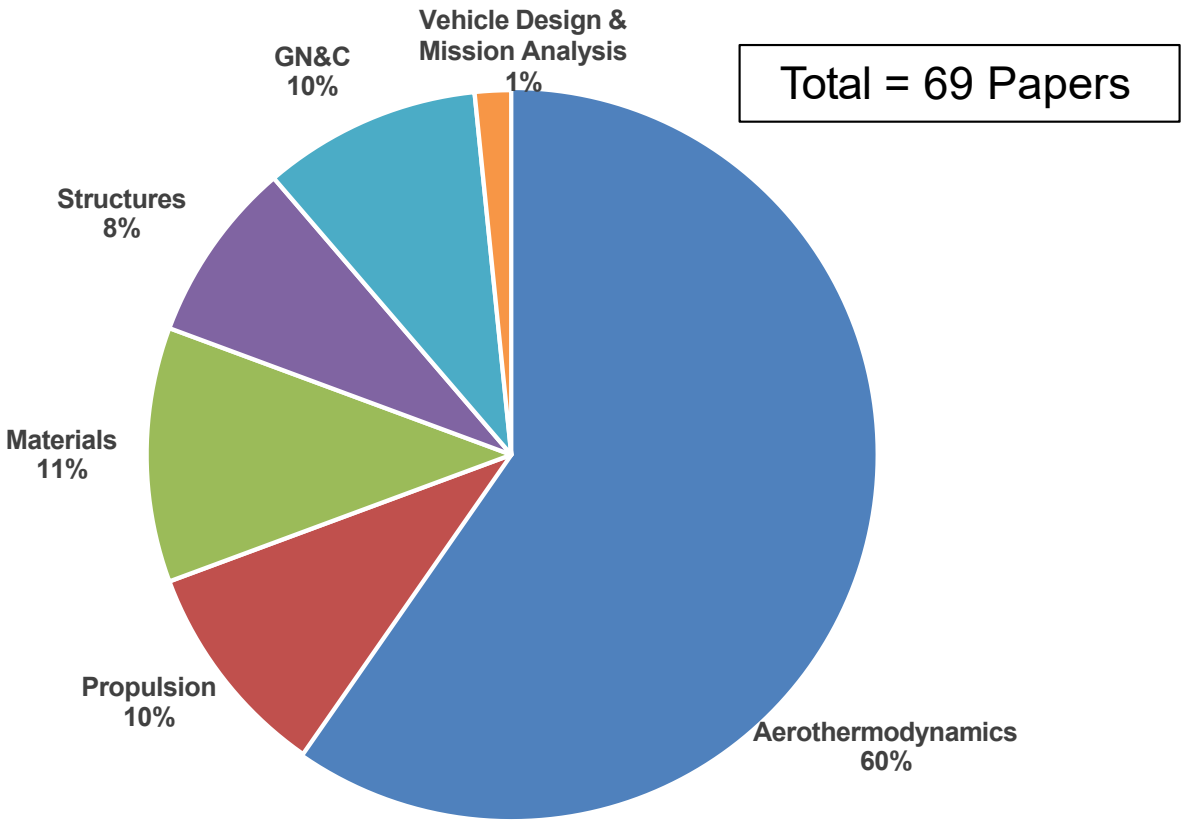


* Boyd, I.D. & Miller, R.K., Science & Technology Policy Institute, July 2017

U.S. University Hypersonics: Summary (2017)

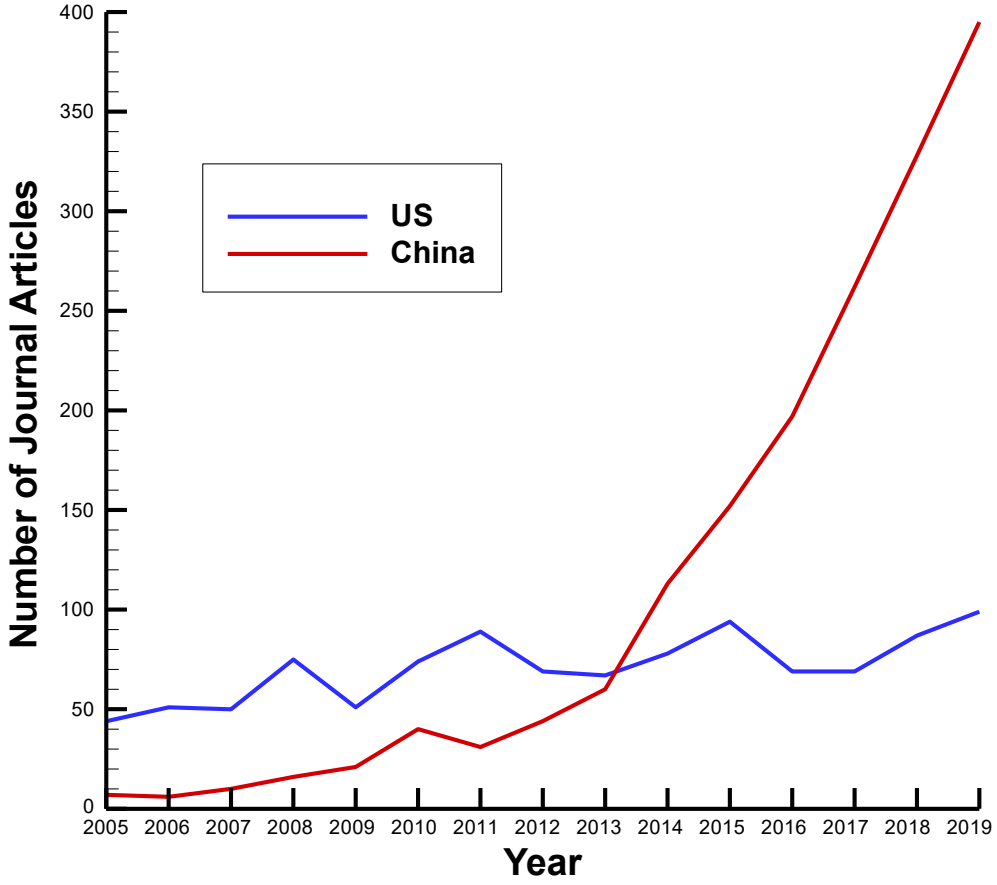
- Total federal funding around $20 million/year
  - Mostly single investigator grants
  - Low levels of industry support
- Heavily focused on aerothermodynamics
- Many top-ranked engineering schools conducting hypersonics research
- No Centers of Excellence
  - There were 3 funded by AF/NASA in 2010-2015

U.S. University Hypersonics: Published Research Topics (2017)



* Boyd, I.D. & Miller, R.K., Science & Technology Policy Institute, July 2017

Hypersonics Journal Articles: China's Rise (2019)



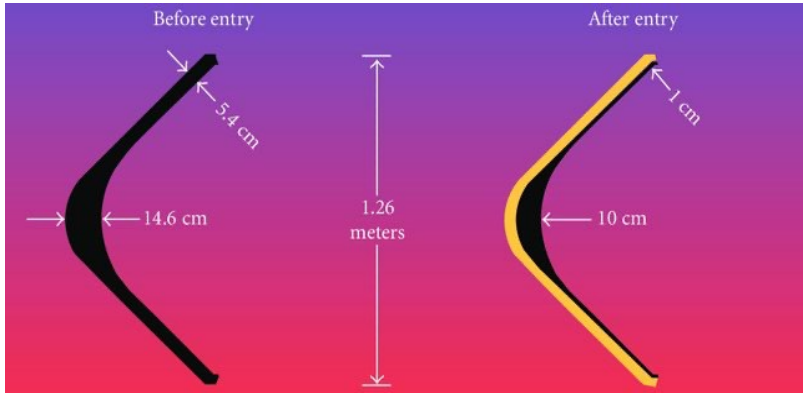
Web of Science database; topic="hypersonic*"; Chinese journals excluded

New Approaches for U.S. Academia

- University Consortium for Applied Hypersonics - UCAH:
  - About $17M/year from OSD - JHTO
  - Managed by Texas A&M University
- Increased and broader engagement:
  - New opportunities in GNC, materials, propulsion, structures
  - New emphasis on **interdisciplinary** research
- Increased interaction with industry:
  - Transition of advanced M&S capabilities
  - University test capabilities to complement national assets
  - Workforce development
    - Training, retraining, clearances

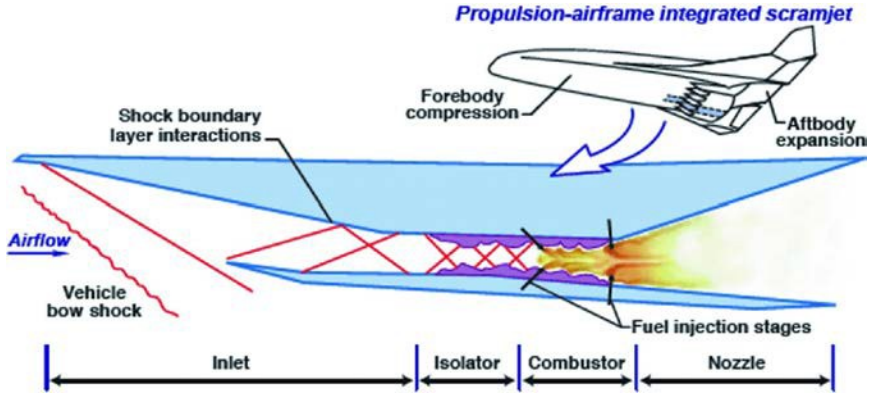
Needs for Interdisciplinary Research

Ablating Vehicle



- Hot flow ablates vehicle surface
- Shape change alters aerodynamics
- Aerodynamics affects GNC
- **Need**: Optimization across designs of vehicle and trajectory to take *advantage* of shape change

Deforming Hot Structure

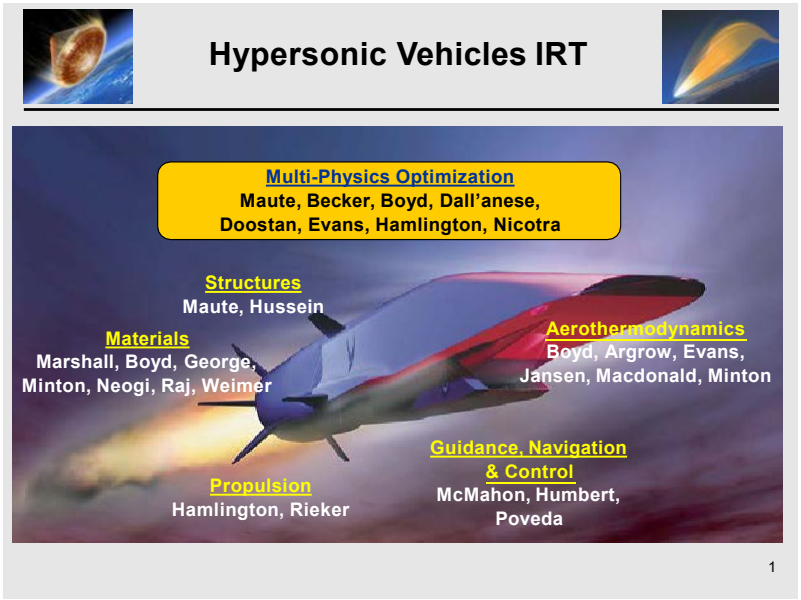


- Hot flow heats, deforms structure
- Deformation alters engine inlet
- Inlet controls scramjet performance
- **Need**: Optimization across designs of structure, propulsion, and controls to *maximize* performance

- **High-fidelity** predictive models of all subsystems
- Reliable interdisciplinary **optimization** approaches

CU Hypersonic Vehicles Interdisciplinary Research Team (HyVIRT)

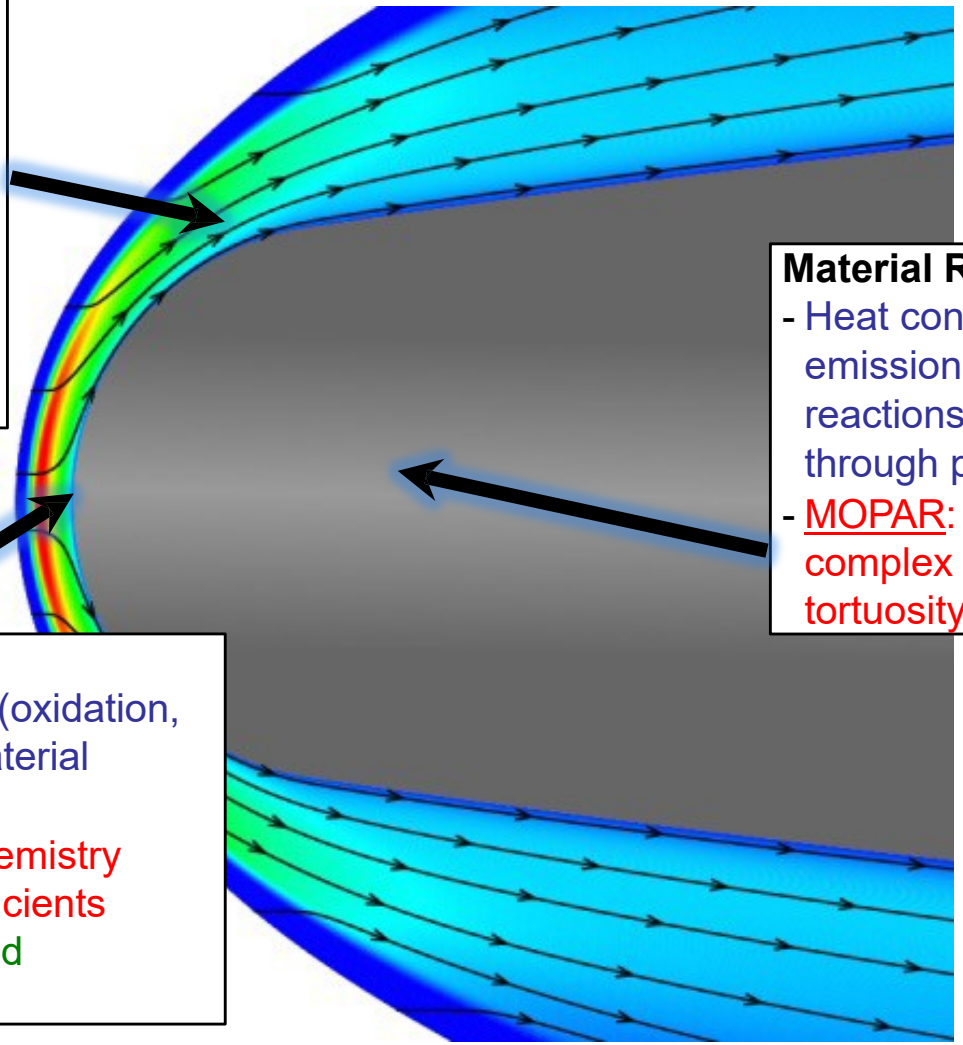
- College of Engineering at CU competes IRTs every 3 years
  - Internal investment to foster faculty collaboration
- HyVIRT selected for funding in July 2020
  - Focus on **multiphysics optimization** of hypersonic vehicles
  - Involves 22 faculty experts in hypersonics and optimization
- Leverage funds via external support
  - Fund student in academic year
  - Host student as summer intern
  - Research:
    - High-fidelity subsystem models
    - Optimization



https://www.colorado.edu/irt/hypersonic-vehicles/

Coupling of High-Fidelity Models for Interdisciplinary Hypersonic Analysis

Gas Flow
- Strong shocks, thermochemical nonequilibrium, boundary layer, etc.
- LeMANS: relaxation times, Arrhenius rate coefficients with two-temperature model



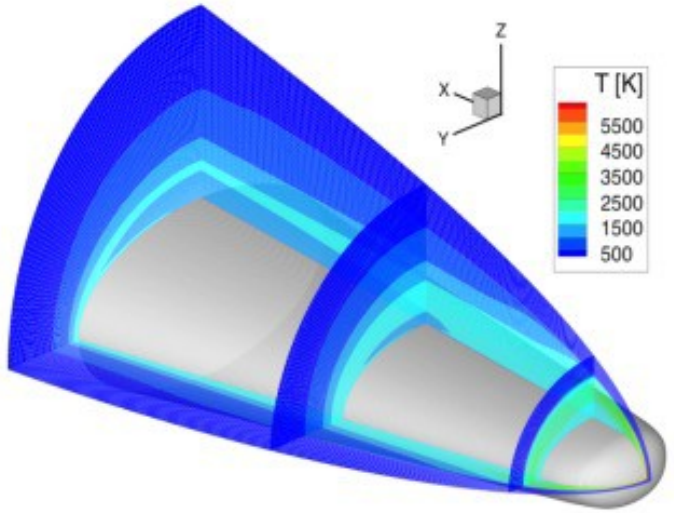
Material Response
- Heat conduction, radiative emission, internal chemical reactions (pyrolysis), gas flow through porous media, etc.
- MOPAR: physical properties of complex materials (conductivity, tortuosity…)

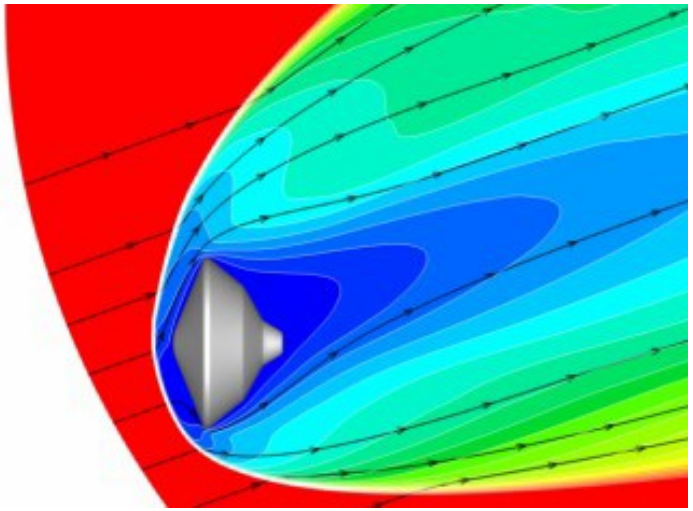
Surface
- Accommodation, ablation (oxidation, sublimation), catalysis, material structure evolution
- FRSC module: surface chemistry mechanism and rate coefficients
- Interface between CFD and material response

CFD Modeling of Hypersonic Flow

LeMANS:

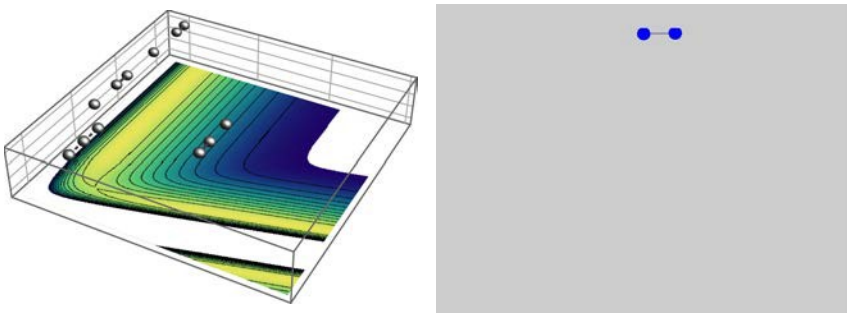
- 3D Navier-Stokes equations
- Nonequilibrium thermochemistry
  - Internal energy equation(s)
  - Species continuity equations
- RANS turbulence models
- Point/line implicit, parallelized
- Coupled via surface module to material response
- Verified using USG codes
- Validated using laboratory and flight measurements





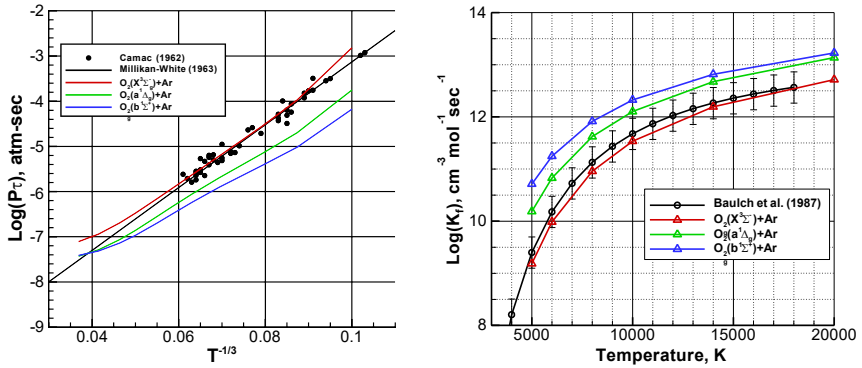
Flow Research: Aerothermodynamics

Computational Chemistry



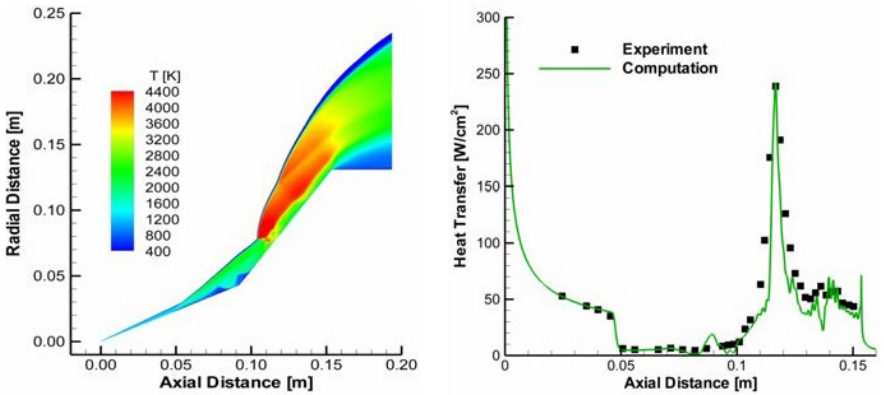
First principles analysis at molecular level

Evaluation of Rates



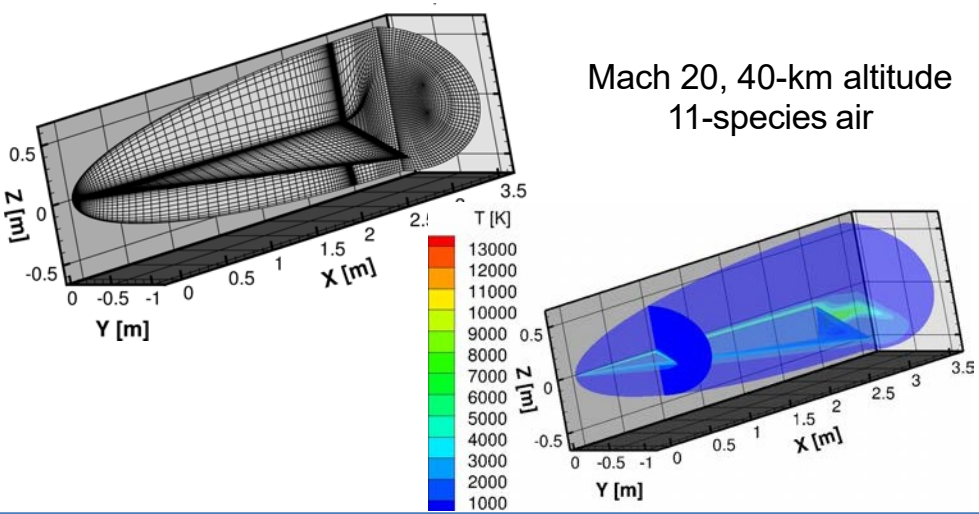
Nonequilibrium aerothermochemistry

CFD Validation



Mach 12 flow tested in shock tunnel

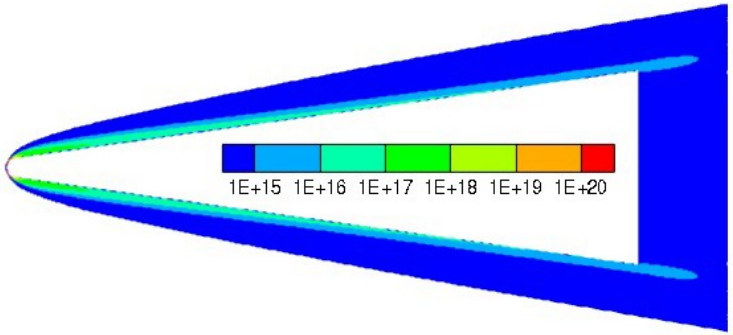
CFD Analysis of Vehicles



Mach 20, 40-km altitude
11-species air

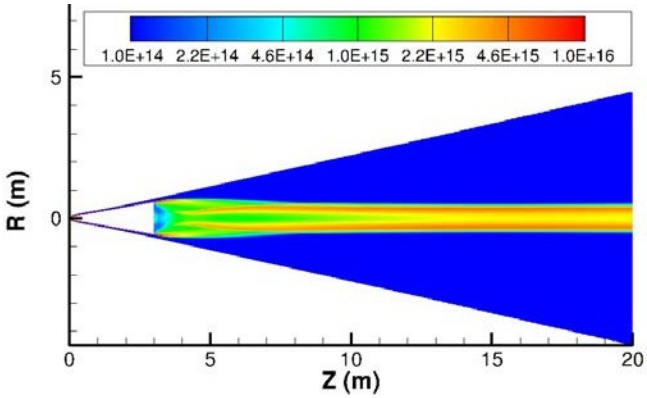
Flow Research: Plasma and Sensing

Communications Blackout



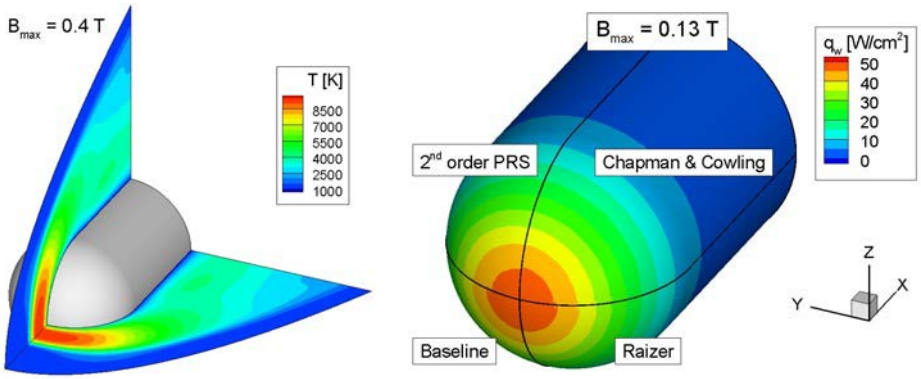
Plasma density to assess radio blackout effects

Wakes and Signatures



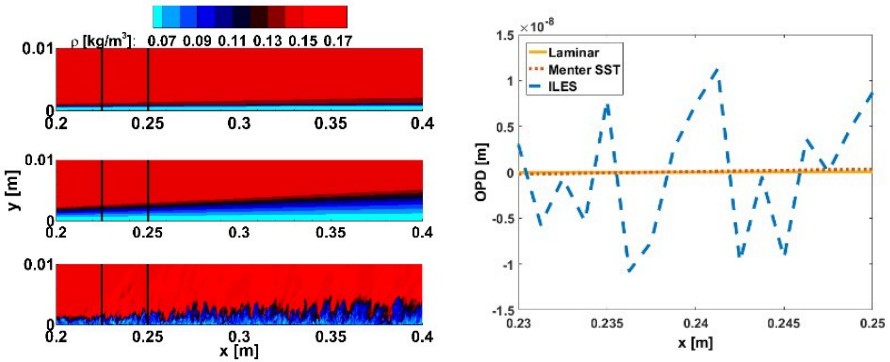
Boost-glide vehicle: Mach 16, 50 km

MHD Heat Shield



Manipulate plasma with a magnetic field to reduce heating

EO/IR Sensing



Effect of turbulence on EO sensing

Modeling of Surface Phenomena

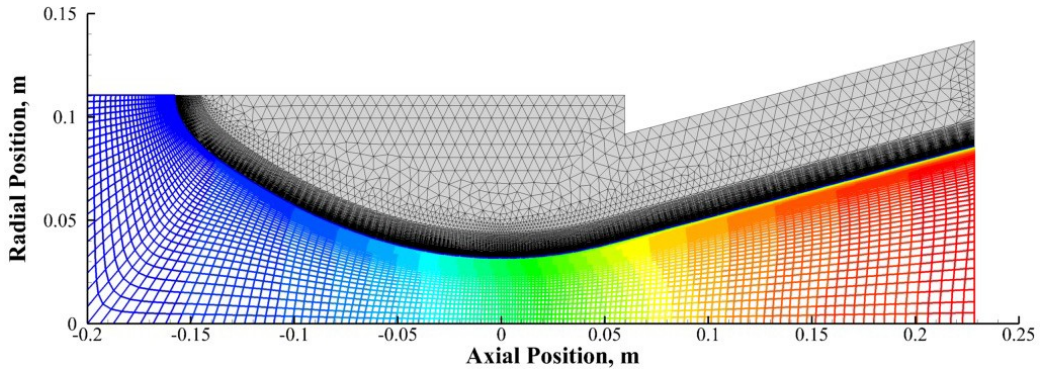
- **FRSC**: Finite rate surface chemistry module
  - Enables analysis of many surface processes

Adsorption/Desorption:	$A + (s) \leftrightarrow A(s)$
Eley-Rideal:	$A + B(s) \leftrightarrow AB + (s)$
Langmuir-Hinshelwood:	$A(s) + B(s) \leftrightarrow AB + 2(s)$
Oxidation/Reduction:	$A + (s) + B(b) \leftrightarrow AB + (s)$
Sublimation/Condensation:	$(s) + A(b) \leftrightarrow A + (s)$

  - Implemented in LeMANS as a surface boundary condition by solving a mass conservation equation for each species
  - Mechanisms and rates known only for simple materials (e.g., graphite)
- Equilibrium surface chemistry model (B' tables) also implemented

Modeling of Material Response

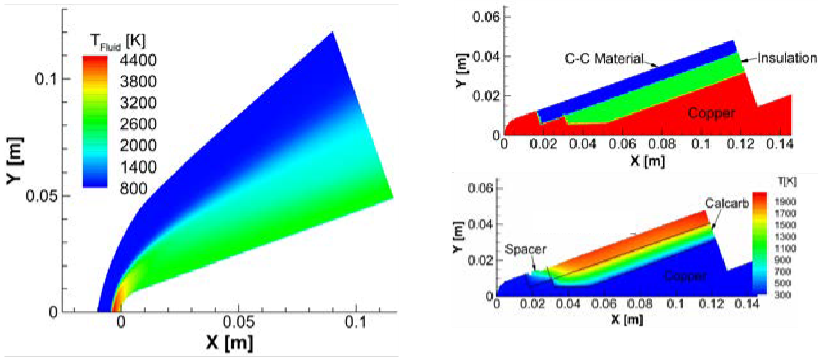
- **MOPAR**: material response model that accounts for anisotropic conduction, radiation, surface ablation, internal decomposition (pyrolysis) and gas flow through pores
- Solves momentum, energy, and density equations (solid & gas)
- Kinetic rates for pyrolysis
- Energy flow in material, pyrolysis gas blown from surface
- Coupled to LeMANS via surface module



Ablation of Carbon Phenolic Solid Rocket Motor Nozzle

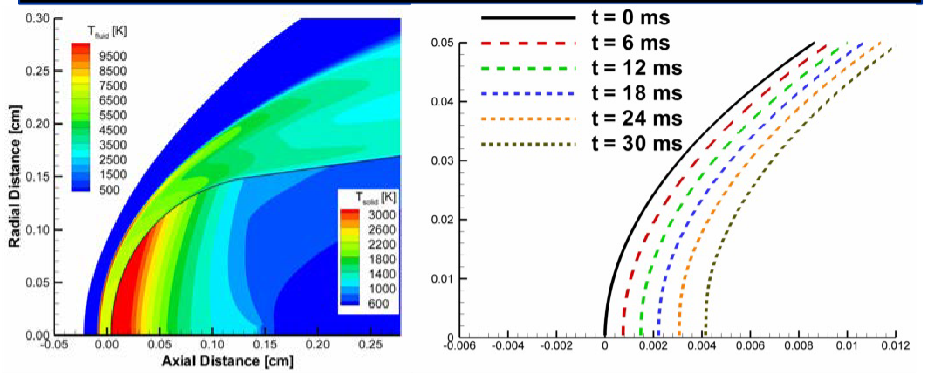
Interdisciplinary Research: Thermal Management (Flow + Materials)

Material Response



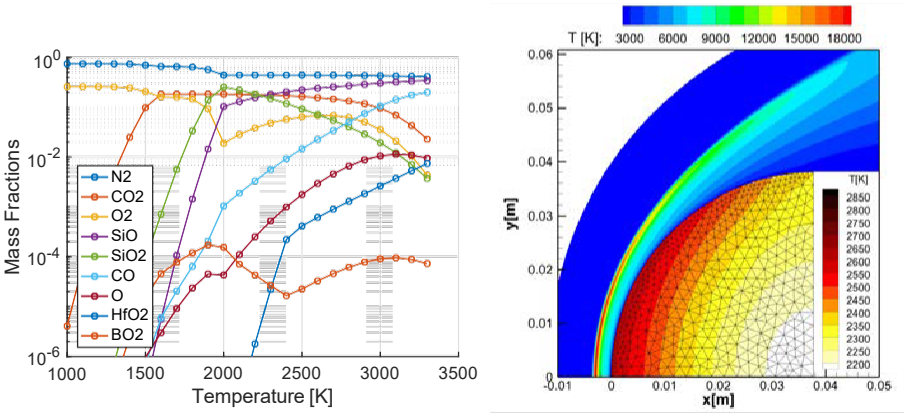
Convection/conduction/radiation/pyrolysis

Ablation



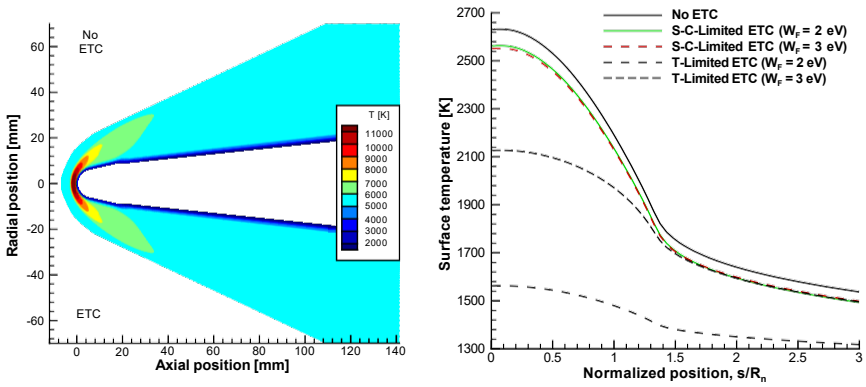
Material recession via surface chemistry

Ultra-High Temperature Ceramics



Analysis of HfB_2-SiC Arcjet test

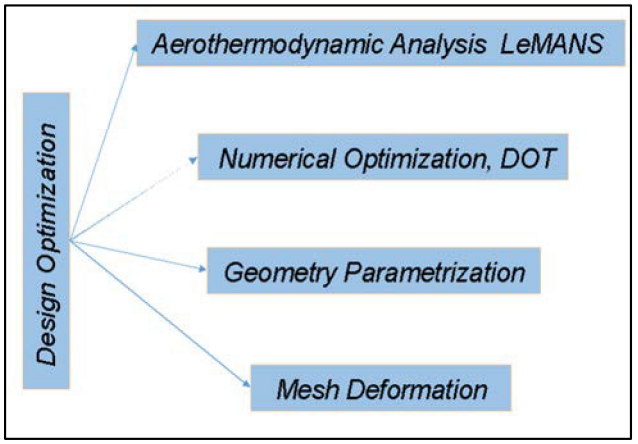
Electron Transpiration Cooling

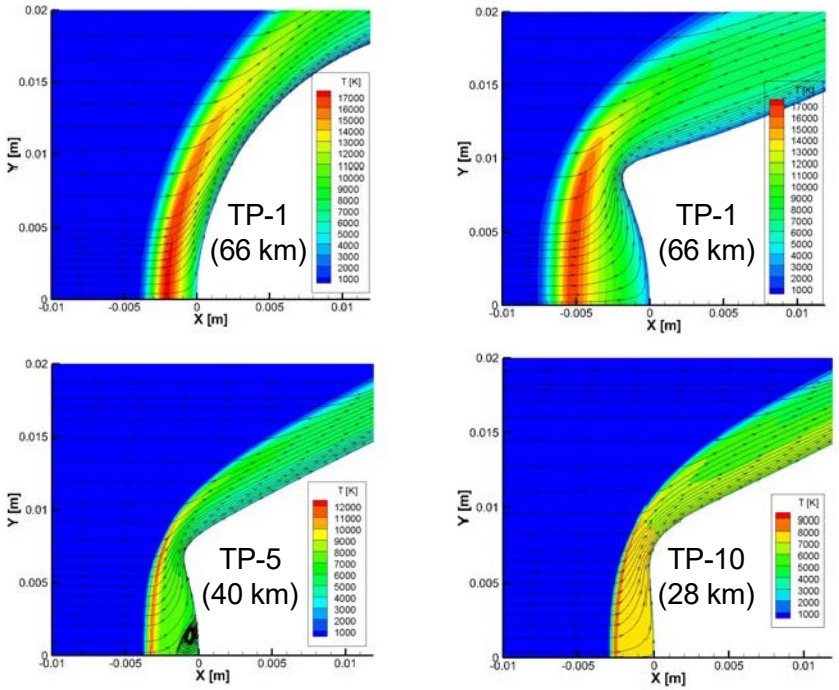


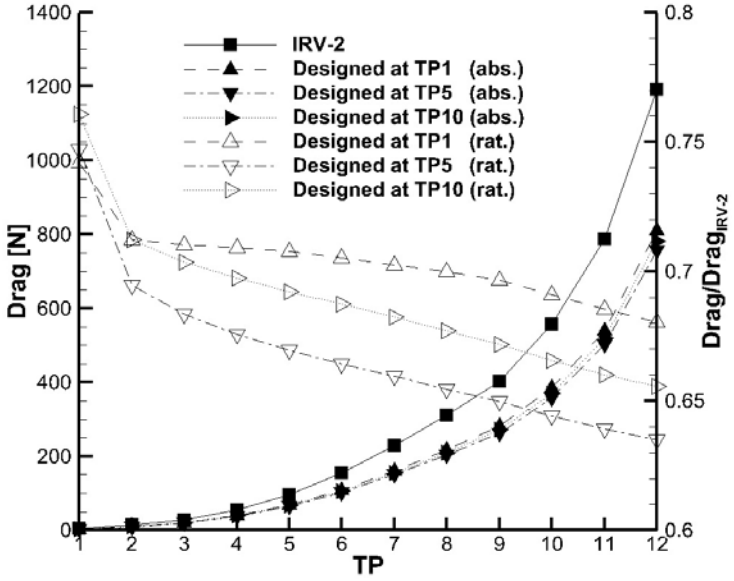
Evaluation of net cooling performance

Interdisciplinary Research: Vehicle Shape Optimization

- LeMANS used in optimization of hypersonic vehicle shapes to minimize drag and/or heat load
- Linked to DOT optimization library
- Geometry and mesh handling

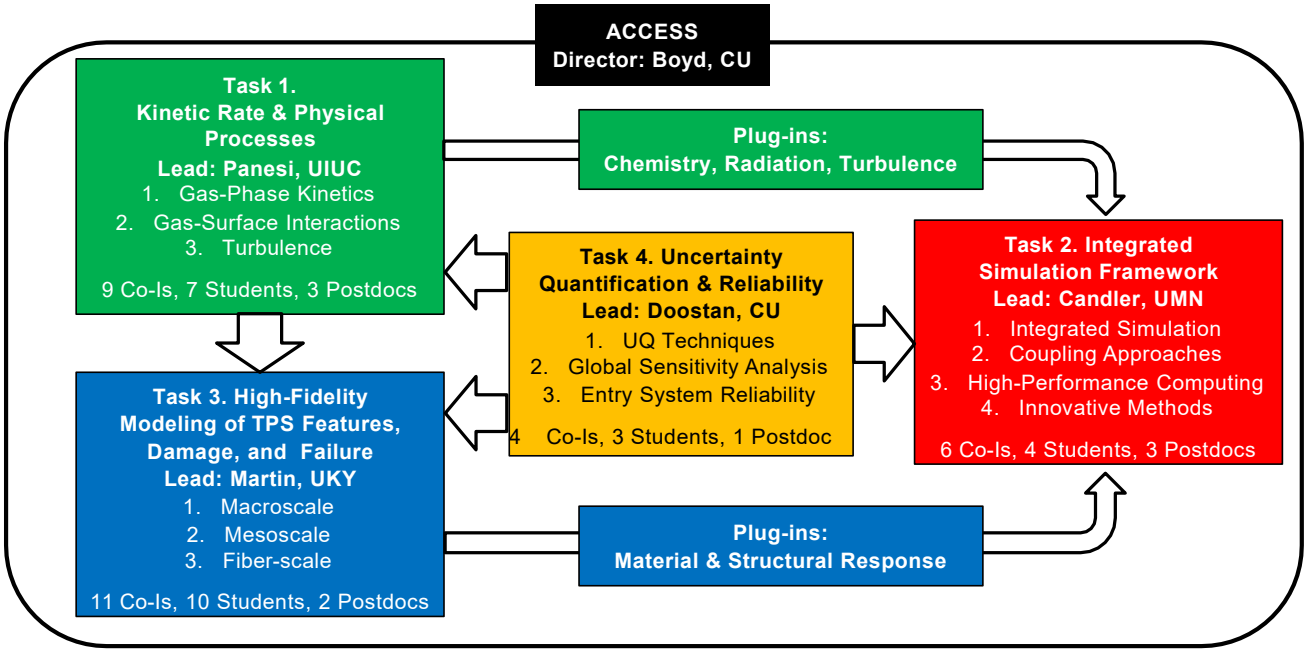






ACCESS (NASA Space Technology Research Institute)

- Led by CU, PI = Iain Boyd, starts October 2021; 5 years, $15M, 5 universities, 20 faculty
- Objective: Create simulation capability to assess **entry system reliability**
- Strongly interdisciplinary with key elements
  - Flow processes (chemistry, radiation, turbulence)
  - Material and structural response
  - Uncertainty quantification and reliability
  - Integrated simulation framework



Workforce Development

- A new educational program introduced at CU in Fall 2021 to develop a pipeline of engineers educated in hypersonics
- Graduate Hypersonics Certificate
  - Required: aerothermodynamics
  - Electives:
    - Materials, structures, GN&C, propulsion
    - Research, design
  - Endorsed by Lockheed, Sandia, APL, NASA
  - 75% of CU aero grad student population is United States
  - Can be taken by nondegree participants

https://www.colorado.edu/aerospace/academics/graduates/curriculum/certificate-programs/hypersonics-certificate

Summary

- United States is strengthening its academic hypersonic community
  - In response to national needs and China's rise
  - Applied research, broader coverage of topics, close engagement with industry
- Need for **interdisciplinary** research in hypersonics
  - Vehicle subsystems are tightly integrated; analysis needs to be coupled across subsystems to avoid surprises
  - **Optimization** across subsystems offers potential for performance enhancements
  - Requires **high-fidelity**, validated component models

Active Development of Interdisciplinary Approaches Will Enhance Performance of U.S. Hypersonic Systems