



Integrity ★ Service ★ Excellence

Aerothermodynamics & Turbulence

Date: 09 03 2012

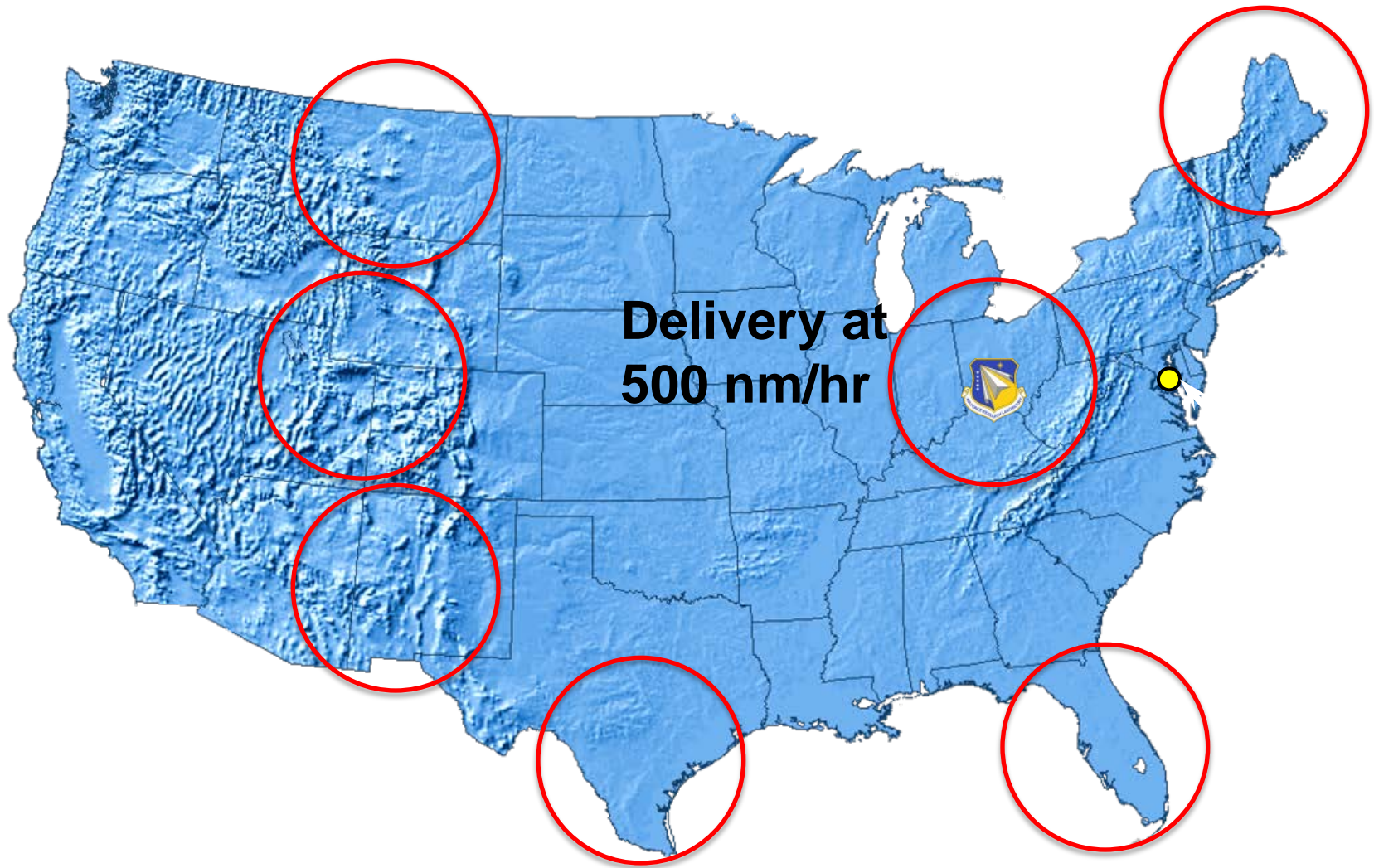
**John D. Schmisser
Program Manager
AFOSR/RSA**

Air Force Research Laboratory

AFRL Pizza 15 Minutes or Less



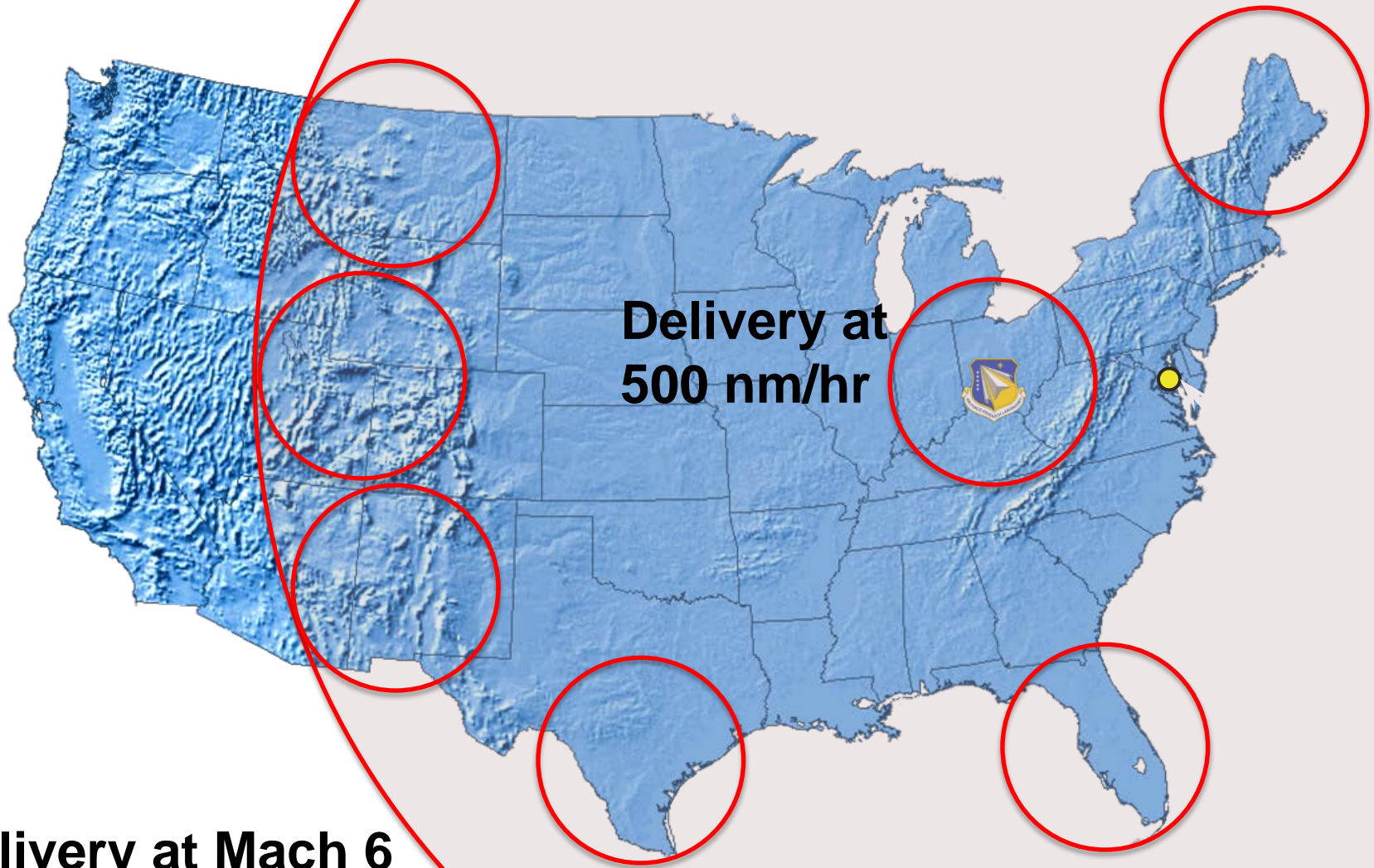
AFRL Pizza 15 Minutes or Less



AFRL Pizza



15 Minutes or Less

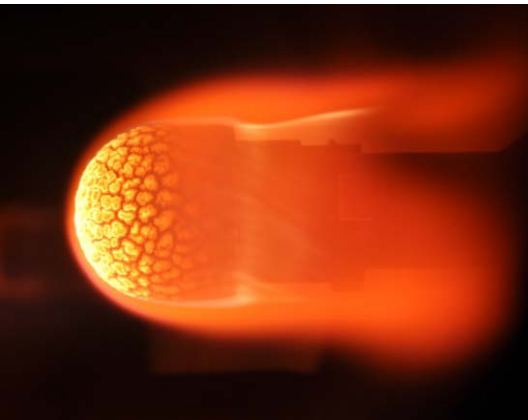


**Delivery at Mach 6
~50 X increase in
coverage**

Aerothermodynamics & Turbulence

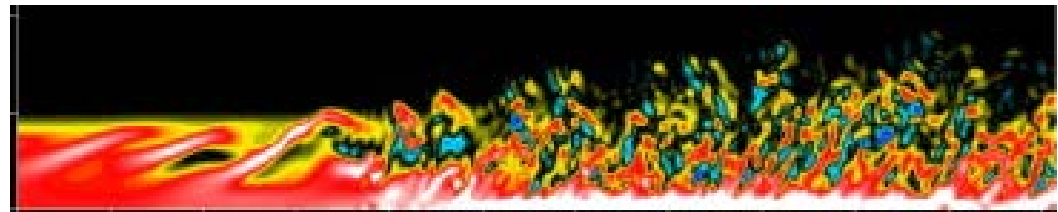
Energy Dynamics in High-Speed Flows

The Environment Around a High-Speed Vehicle is Dominated by Rate-Dependent Energetic Processes

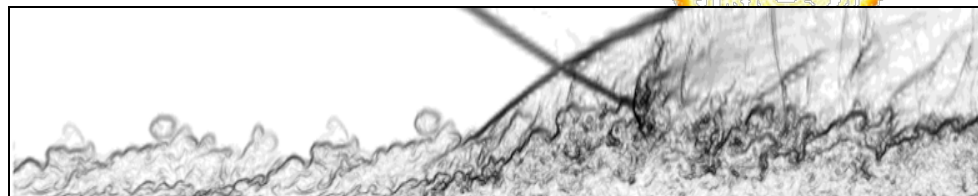
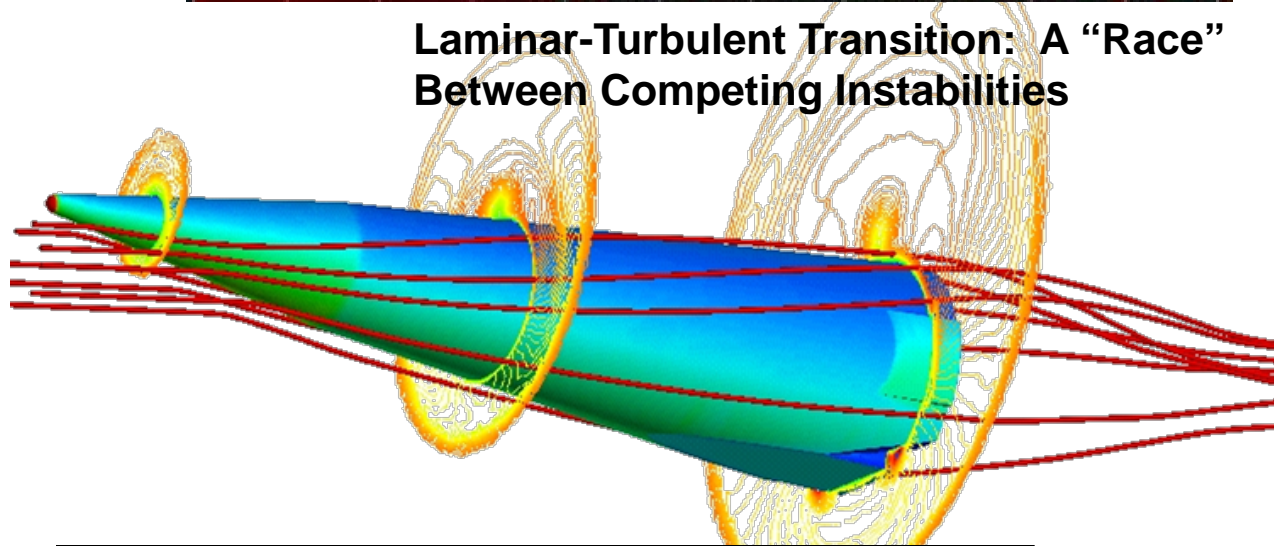


Shock-Excited Flow States and Gas-Surface Interactions are Driven by Reaction Rates

Turbulent and Shock-Interaction Heat Transfer: Transfer of kinetic to thermal energy poorly understood



Laminar-Turbulent Transition: A “Race” Between Competing Instabilities



2012 AFOSR SPRING REVIEW

2307/A Aerothermodynamics and Turbulence

NAME: John D. Schmisser

Aerothermodynamics & Turbulence

BRIEF DESCRIPTION OF PORTFOLIO:

Identify, Model and Exploit critical physical phenomena in turbulent and high-speed flows

- emphasis on energy transfer

Sole DoD basic research program in this area

SUB-AREAS IN PORTFOLIO:

- Boundary Layer Physics
- Shock-Dominated Flows
- Gas Thermophysics
 - Gas-Surface Interactions
- Turbulence and Transition

Partners



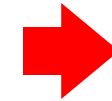
National Hypersonic
Foundational Research
Plan



Sandia
National
Laboratories



Joint Technology
Office -
Hypersonics



Assessment of
SOA and Future
Research
Directions



Jet Noise



Arnold
Engineering
Development
Center



Tech
Transition

Outline

- **Scientific Challenges**

- **The Big Picture**

- **Portfolio Management**

- **Evolving Research Directions**

- **Research Highlights**

**Leading the
International
Research Community**

**Identifying and
Responding to New
Opportunities**

Scientific Challenges in Aerothermodynamics

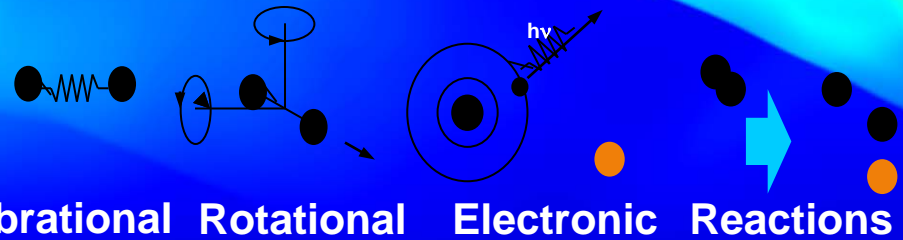
The intersection of shock waves,
turbulence, thermophysics and
chemistry

$M=10$, $Re = 2$ Million
Temperature Gradient

Bartkowicz/Candler
U Minn

AT

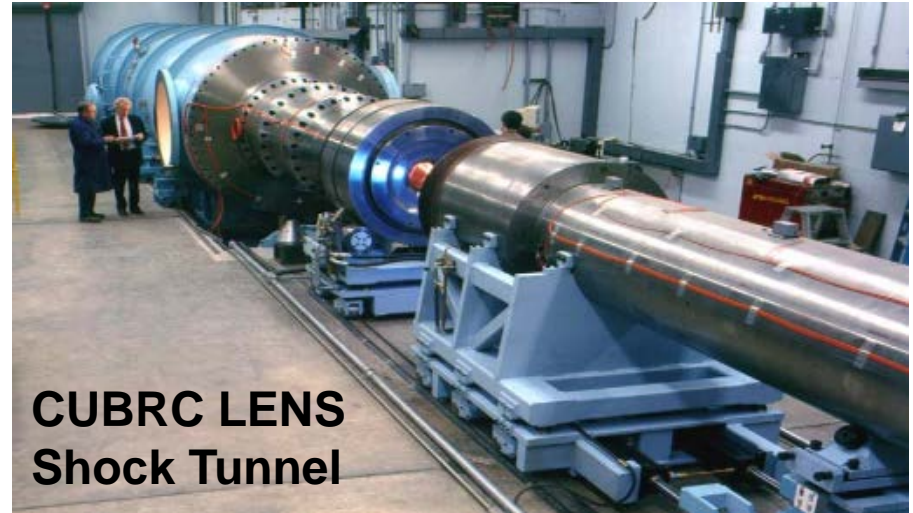
Rate-Dependent Energy
Transfer Processes are
Critical – yet poorly understood



~~A~~ The Challenging Environment

High-Speed Flight Environments Cannot Be Duplicated in Ground Facilities

- Test gas velocity of 10,000 mph
 - Half of orbital velocity!
- Few hundred millionths of a second test time
- Measure chemical species



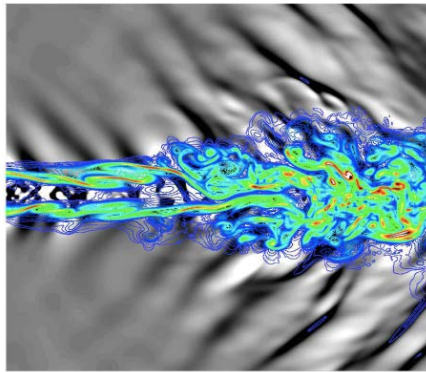
**CUBRC LENS
Shock Tunnel**



**U. Illinois
Expansion
Tube**

Unprecedented Opportunities

Large-Scale Computing and Optical Diagnostics Provide Incredible Insight into Critical Microscale Phenomena

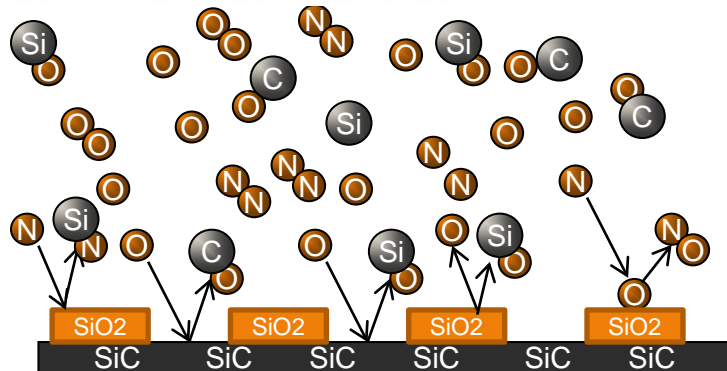


Model-Free
Sim. of
Noise
Generation
in Jet

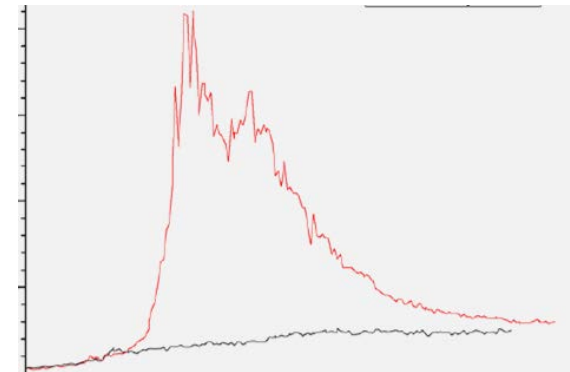
There is No Mature Industry Base for Hypersonic Systems

- *Opportunity to rapidly transition science breakthroughs for integration into emerging systems!*

Spectroscopic
Measurement of
Transient Material
Response

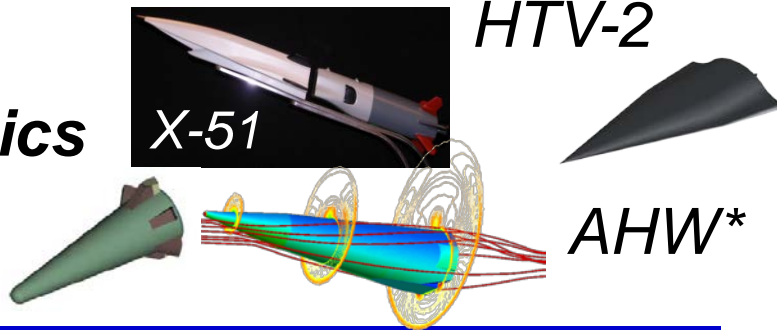


Molecular
Dynamic Sim.
Of Gas-
Surface
Interaction



Perspective from Reentry Altitudes

**Marquee
Hypersonics**
Demos and
Systems



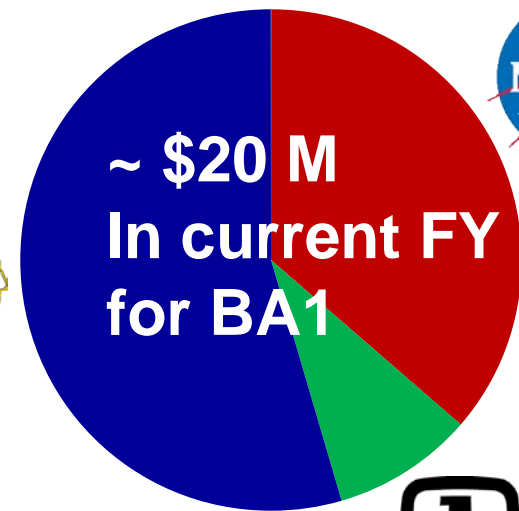
**Rough Estimate – A Billion
Dollar Total National
Investment**

**DoD Joint Technology Office on
Hypersonics - JTOH**

**Foundational
Research**

BA 1 and
early BA 2

- AFRL, NASA, Sandia
- AFOSR is only DoD investment in basic science



**National Hypersonic Foundational
Research Plan –
AFOSR Led, Adopted by JTOH**



**Sandia
National
Laboratories**

**Foundational
Research
Efforts**

NHSC

- Aerothermo
- Propulsion
- Materials



HARP

Coord. of Major
Academic Centers



**International
Collaboration**



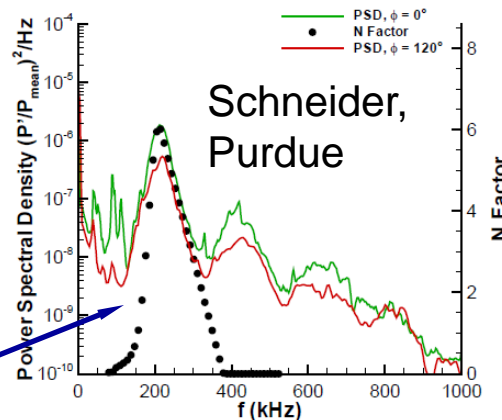
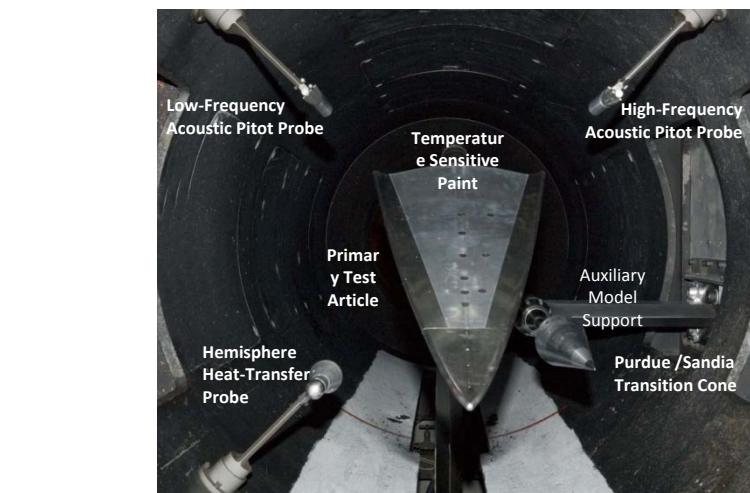
Transitioning Science: New Testing Capabilities



Integrated Computations and Experiments predict and verify instabilities and assess the surface thermal load...

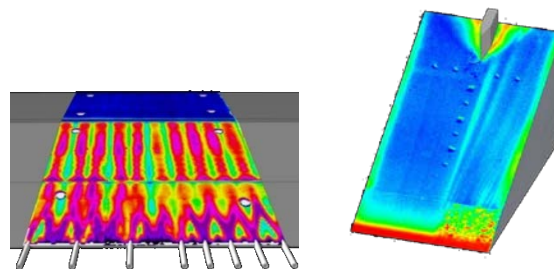
Focused schlieren image of BL transition obtained on 7° transition cone at Mach 10, $Re/L = 2.0 \times 10^6/ft$

... resulting in an unprecedented capability for the test and analysis of high-speed systems



Tunnel 9, $Re/m = 6.5 \times 10^6$, $x = 0.490$ m.

Breakthrough method for instability measurement



Temperature-Sensitive Paint provides global heating

AEDC Tunnel 9

DISTRIBUTION STATEMENT A – Unclassified, Unlimited Distribution



AFOSR as a Catalyst

NASA Environmentally Responsible Aerospace (ERA) program seeks new efficient transport designs



Surprising Designs for Eco-friendly Airliner



Guy Norris

Jan 13, 2012

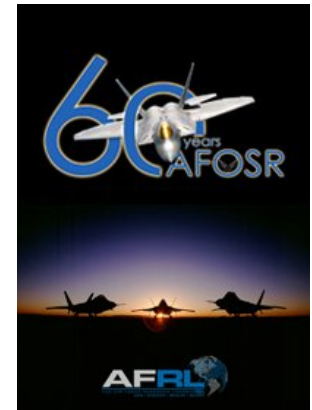
AMC-NASA connections result from AFOSR Workshops July and Dec 2010

AFOSR/NASA/SNL Ablation workshop (2008-2012) becomes a Gordon Conference in 2013 – Reentry Physics

**JTOH Workshop
Emerging Capabilities for the
Design and Analysis of High-Speed/
Hypersonic Systems
March 27-28, 2012
Arlington, VA**



**AIAA
HyTASP PC**



Dialog on the opportunities and challenges for transition of maturing scientific capabilities to engineering practice

World-Class Researchers

- Members of the NAE (6)
- NSSEFF Fellow
- DoD Advisory Boards
 - AF SAB
 - JASON
 - Def. Studies Group
- AIAA Fellows (~~11~~) 12
- PECASE (2)
- NSF CAREER (4)
- OSR Young Investigator (4)
- AIAA Past President (2)
- AIAA Awards
 - Thermophysics Award (2)
 - Fluid Dynamics Award (4)
 - Ground Test Award
 - Aero. Measurement Tech.
 - Plasmadynamics and Lasers
 - Atwood Educator Award
- APS Frenkiel Award (2)
- AF Chief Scientists (2)
- Prior PM: Dr. S. Walker

Accomplishments

- **Dream Team of world-class Principal Investigators**
- **Strong Connections to the Applied Research and Test Community**
- **Research Breakthroughs are being transitioned and guiding technology maturation programs**
- **Portfolio is leading the international research community in aerothermodynamics**

World-Class Researchers

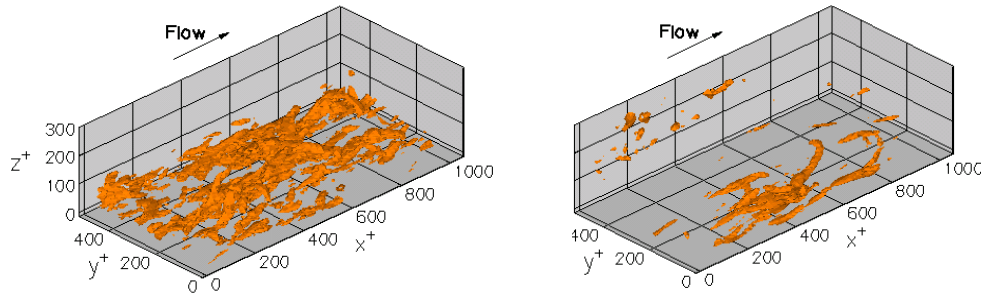
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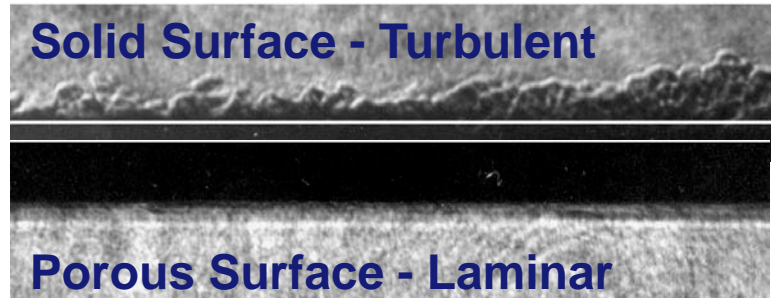
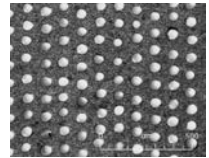
Time for a change?

Notable Past Highlights

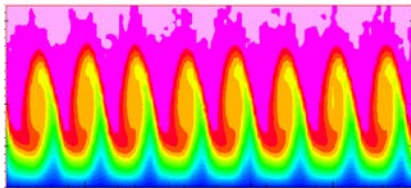
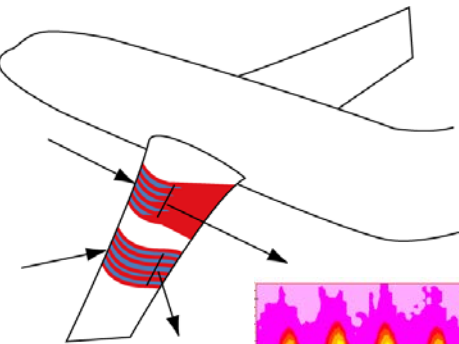


Candler and Martin - Turbulence Dampening Through Endothermic Reactions

Malmuth and Hornung - Transition Control via acoustic absorptive surface

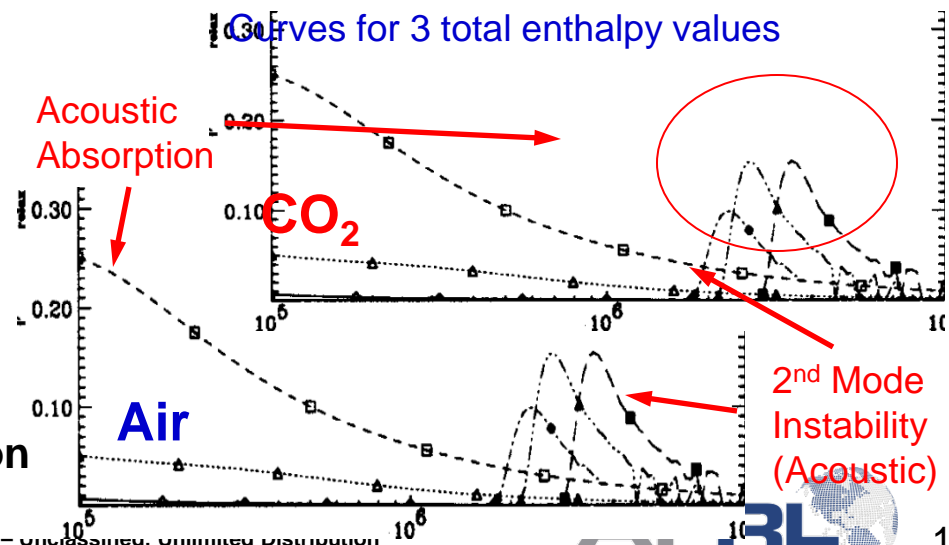


Saric – Crossflow transition delayed by promoting growth of more stable instabilities

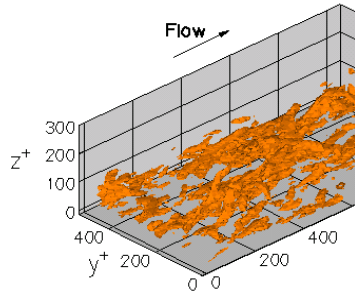


Leyva and Shepherd – Transition delay via internal energy absorption

For CO₂ internal energy and acoustic instability modes overlap



Notable Past Highlights

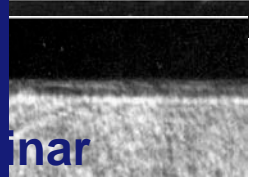
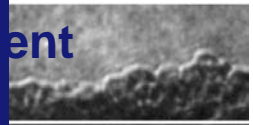
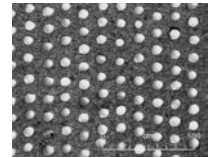


Candler and M
Through Endo

Energy transfer at the micro- and molecular scales drives the macroscopic flow behavior

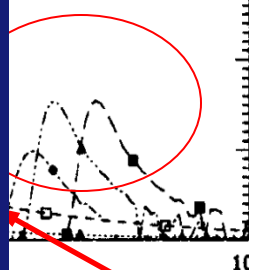
Imagine if we could control the transfer of energy within the various states (kinetic, thermodynamic, internal and chemical)

Transition delay via internal energy absorption



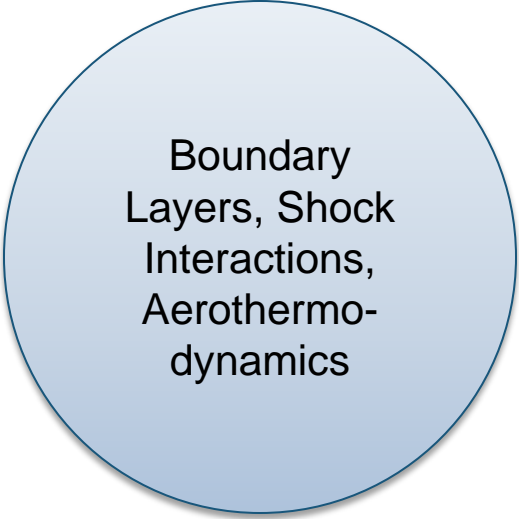
Acoustic

values



2nd Mode Instability (Acoustic)

Extending the Vision of Aerothermodynamics & Turbulence



Boundary
Layers, Shock
Interactions,
Aerothermo-
dynamics

**Aerodynamics-
Driven Focus**

Extending the Vision of Aerothermodynamics & Turbulence

Key: PI corp must start considering and communicating their work within this context

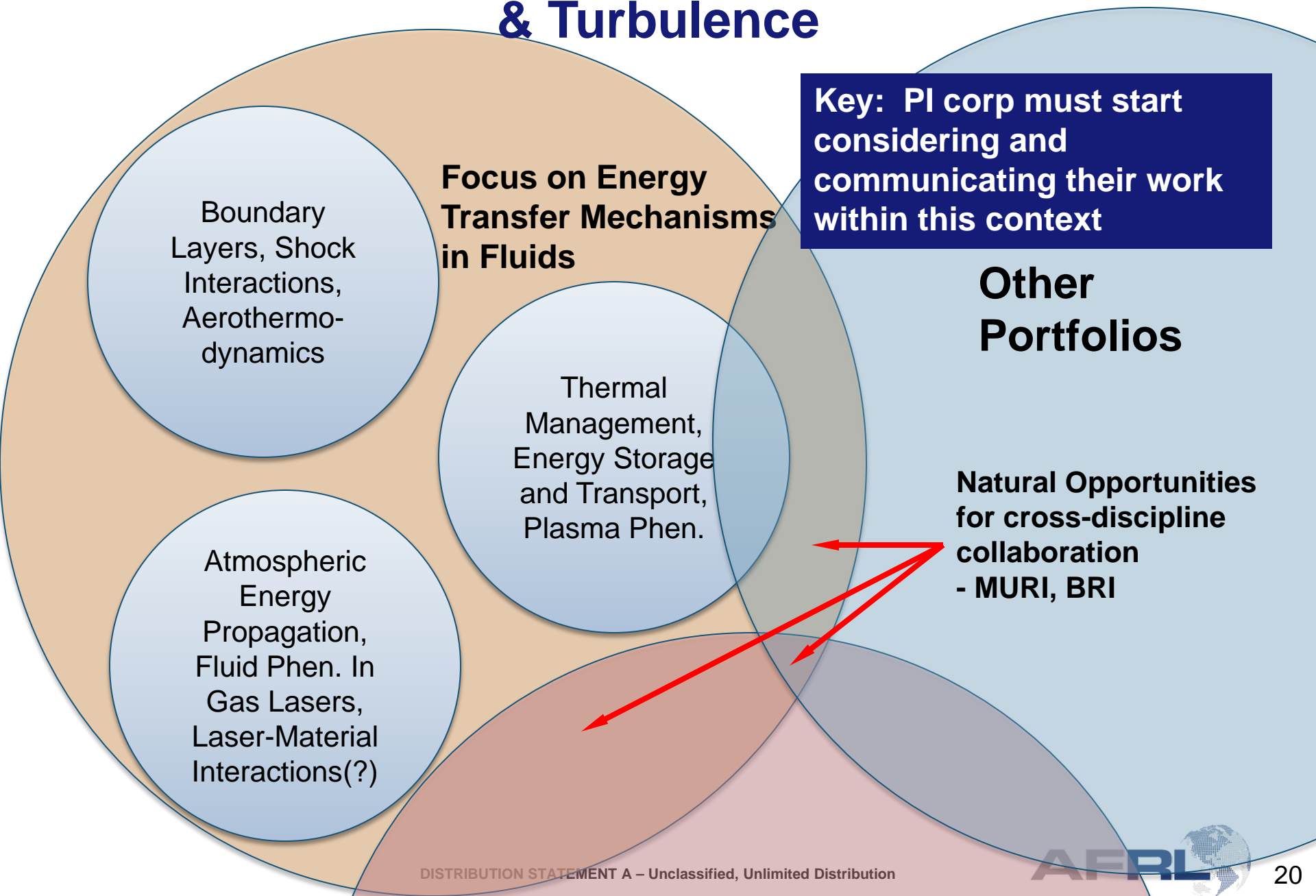
Focus on Energy Transfer Mechanisms in Fluids

Boundary Layers, Shock Interactions, Aerothermodynamics

Thermal Management, Energy Storage and Transport, Plasma Phen.

Atmospheric Energy Propagation, Fluid Phen. In Gas Lasers, Laser-Material Interactions(?)

Extending the Vision of Aerothermodynamics & Turbulence



Outline

- Scientific Challenges
- The Big Picture
- Portfolio Management
- Evolving Research Directions
- Research Highlights

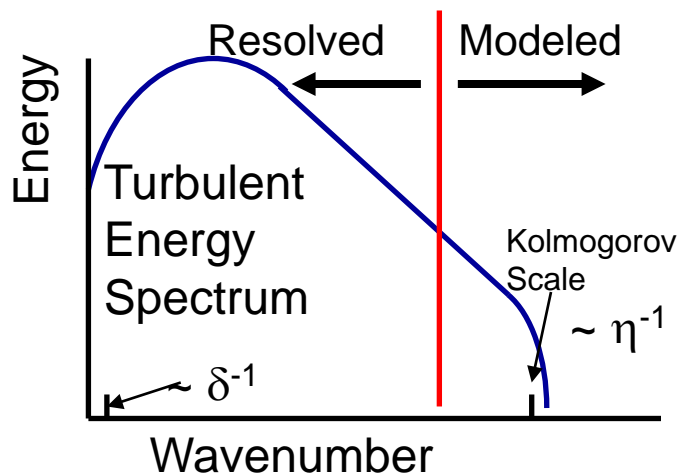
**Presented in terms of new portfolio emphasis:
energy transfer mechanisms**

Kinetic Energy Transfer in Turbulent Flows

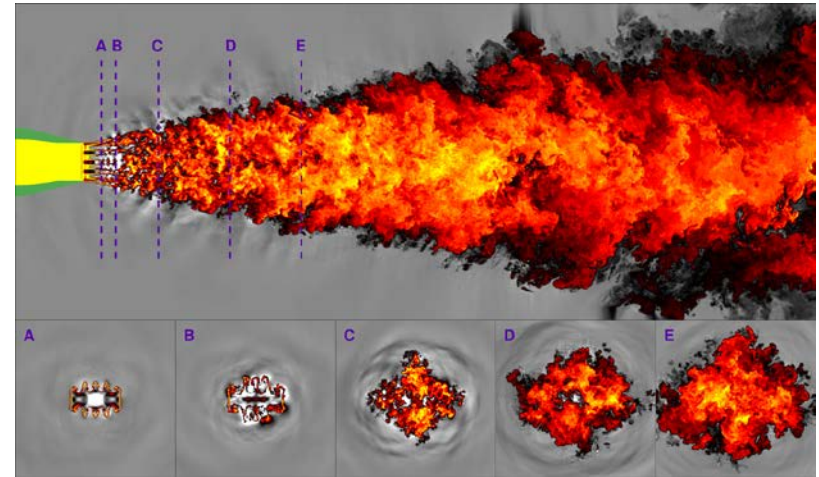
How does the flow of energy between the turbulent spectrum and other flow structures shape macroscopic flow dynamics?



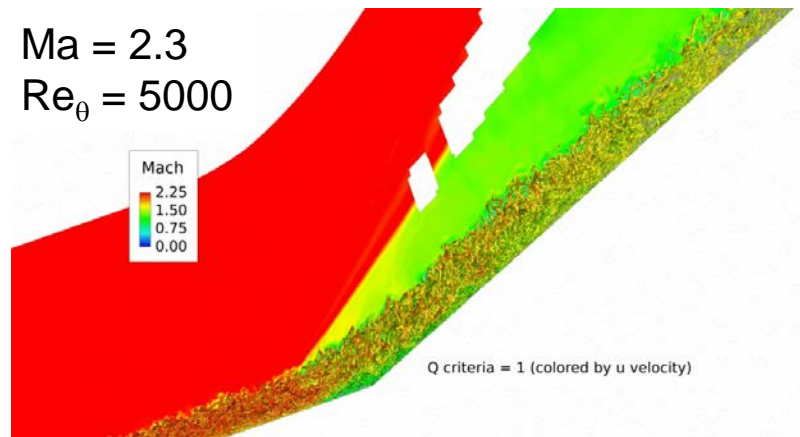
Modeling Turbulent Flows



RANS LES DNS
Eng. Tool First Principles
Increasing Fidelity and Cost



CharLES code simulations of supersonic rectangular jet - P. Moin, Stanford



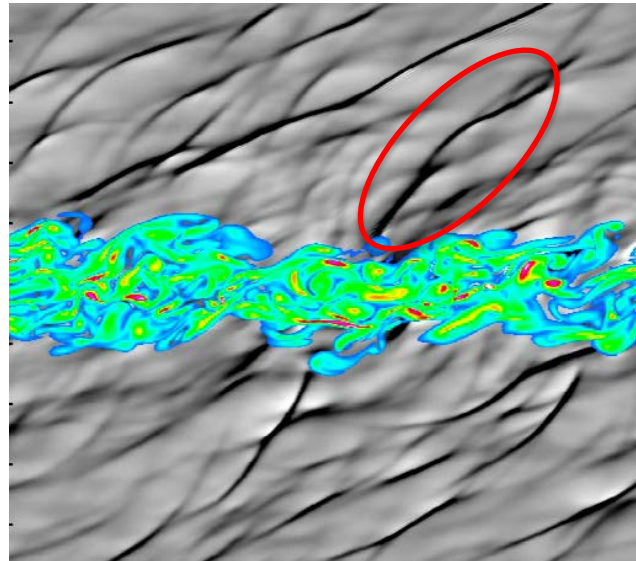
Large-Eddy Simulation of Compression Corner Shock/Boundary Layer Interaction
- J. Poggie, AFRL/RB

Kinetic Energy Transfer in Turbulent Flows

Jet Crackle

An intense form of acoustic radiation

- Distinguishing feature of sound on military platforms - fighters and rockets
- Mechanisms are unclear, particularly source of its peculiar signature
- Direct numerical simulation (no turbulence model) integrated with nonlinear propagation theory explores root mechanisms of *jet crackle*
- Model simulations have for the first time reproduced crackle --- a key step toward understanding and reducing



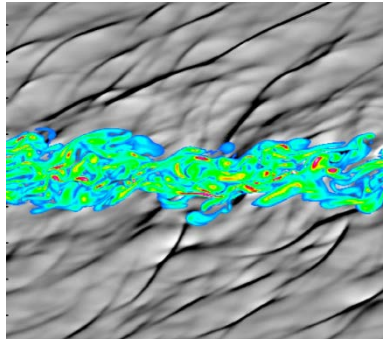
Prof. Jonathan
Freund
*Kritzer Faculty
Scholar*

- Mechanical
Science &
Engineering and
Aerospace
Engineering
- Fellow American
Physical Society
- APS/DFD Frenkiel
Award (2008)
- Associate Fellow
AIAA

Kinetic Energy Transfer in Turbulent Flows

Long-Range Propagation of Crackle Waves

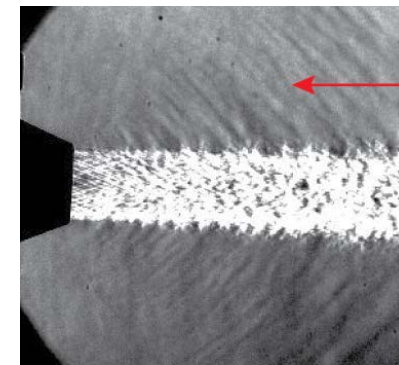
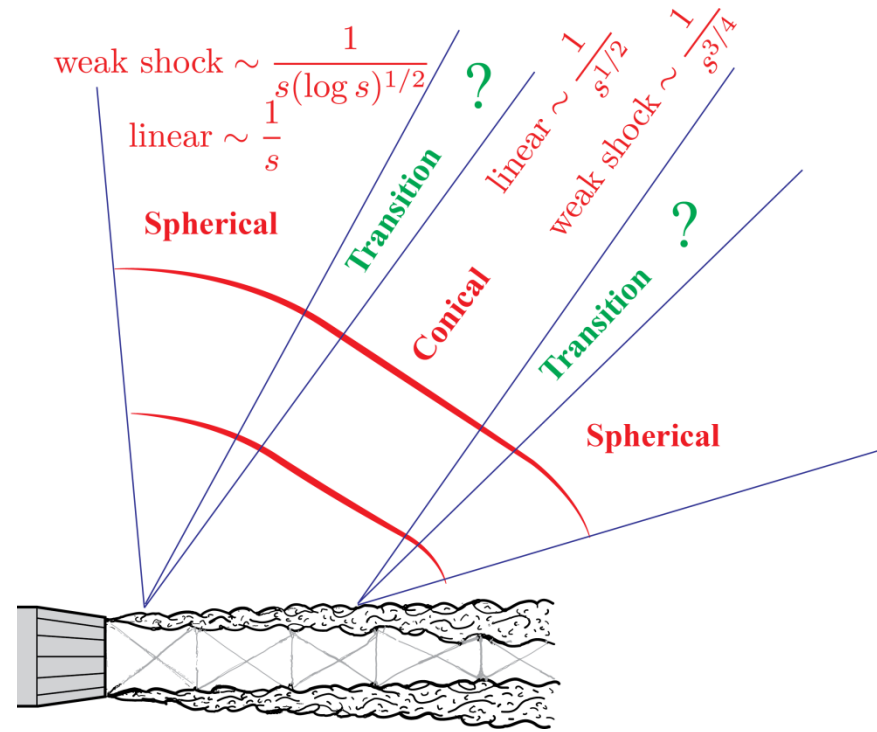
We now have a DNS model source:



Identified key factor: how the Mach waves transition from conical to spherical behavior

Spherical decay is much faster- strongly affects the mid- and long-range peak amplitudes

Length of conical portion depends on dynamics of large turbulent eddies in the jet



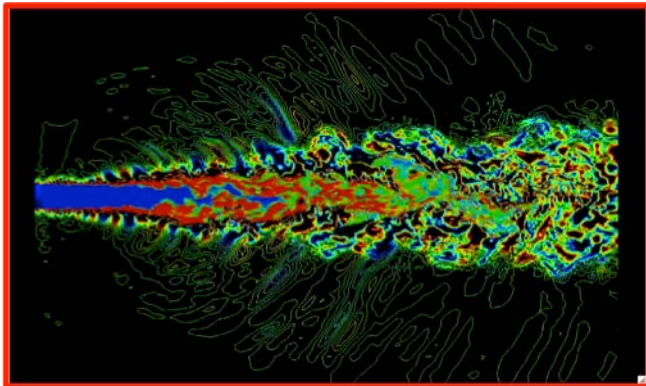
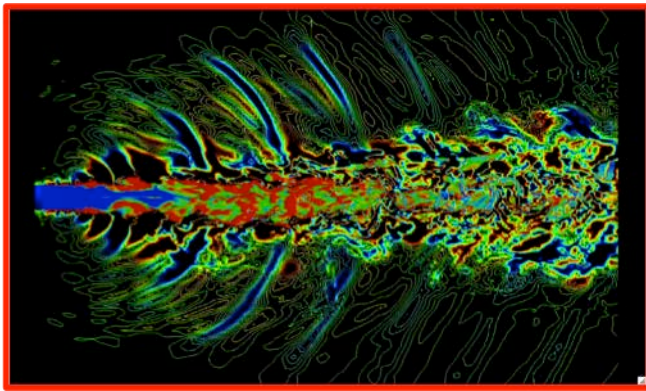
Near-field Mach-wave-like radiation associated with far-field jet crackle



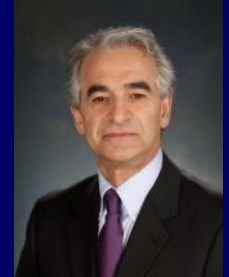
Fontaine, Austin, Elliott, Freund
University of Illinois Facility

Kinetic Energy Transfer in Turbulent Flows

High frequency actuation reduces near field
jet sound by inhibiting coherent structures
Synergy between CFD and experiment pays off



- Experiments reveal small high-frequency actuation can reduce jet noise
- But how do high-frequency techniques actually affect the structures that generate noise?
- This research suggests that the signals inhibit the growth of coherent structures in the near field, which in turn affects the far field noise



Prof. M. Samimy
Nordholt Professor

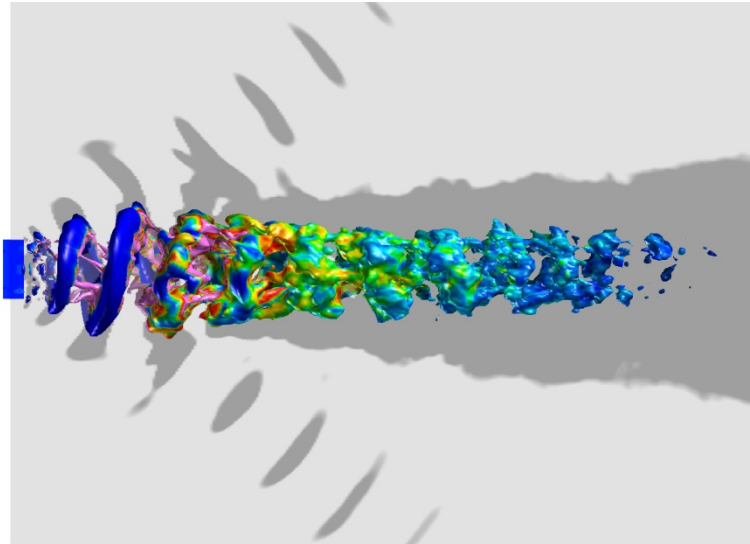
- Fellow AIAA, APS, AAAS, ASME



Prof. D. Gaitonde
Glenn Professor

- Fellow AIAA, AFRL

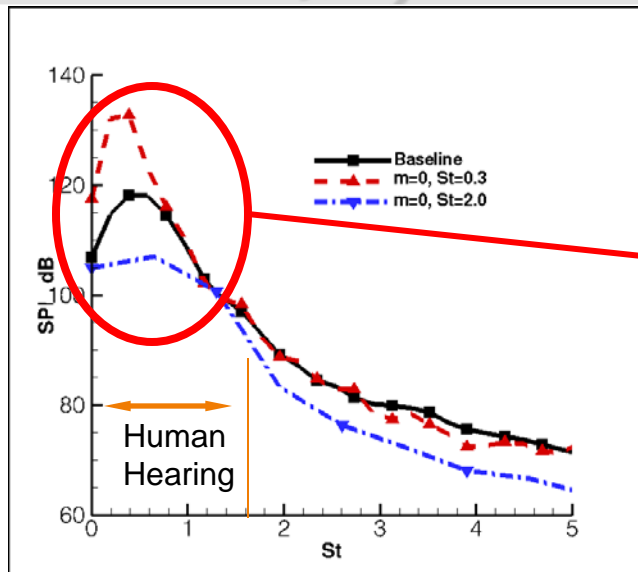
Kinetic Energy Transfer in Turbulent Flows



Experiments and simulations coordinated as never before to enhance understanding

Three dimensionality of structures of various scales influences wave generation and propagation

Near field provides best opportunity to implement feedback control



Impact of actuation: higher-frequency excitation disrupts formation and evolution of larger-scale structures

Kinetic Energy Transfer in Turbulent Flows

FLEET — Femtosecond Laser Electronic Excitation Tagging Provides New Insight Into Turbulent Flows

Princeton University



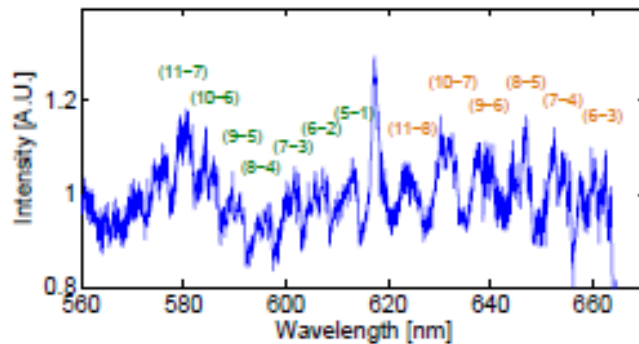
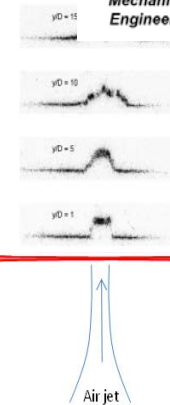
Mechanical & Aerospace
Engineering Department

- FLEET excites and tracks selected N_2 molecules
- Spatial resolution – tens of microns to 1m
- Temporal resolution - tenths of a microsecond
- Temperature range from condensation to greater than 2000K.

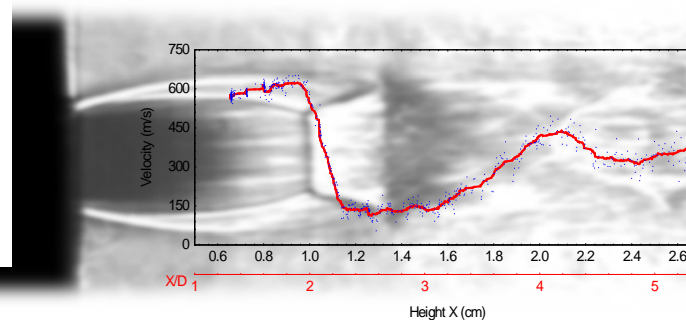
Lines are written by the laser and imaged with a fast gated camera.

F sec laser

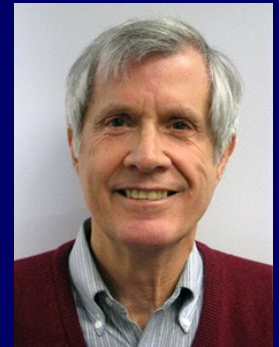
FLEET



Spectrum of FLEET emission in air. Spectral lines are associated with the nitrogen First Positive system



FLEET measurements of the centerline velocity in a supersonic jet



Dr. Richard B. Miles

*Robert Porter Patterson
Professor of Mechanical
and Aerospace
Engineering*

- Member of the National Academy of Engineering
- Fellow of the AIAA and the OAS
- 2001 recipient of the AIAA Aerodynamic Measurement Technology Award

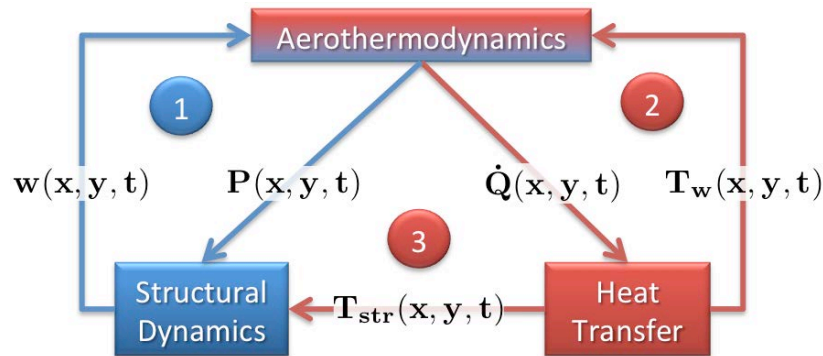
Kinetic Energy Transfer in Turbulent Flows

Paradigm Change in Fluid-Thermal-Structural Interaction Modeling

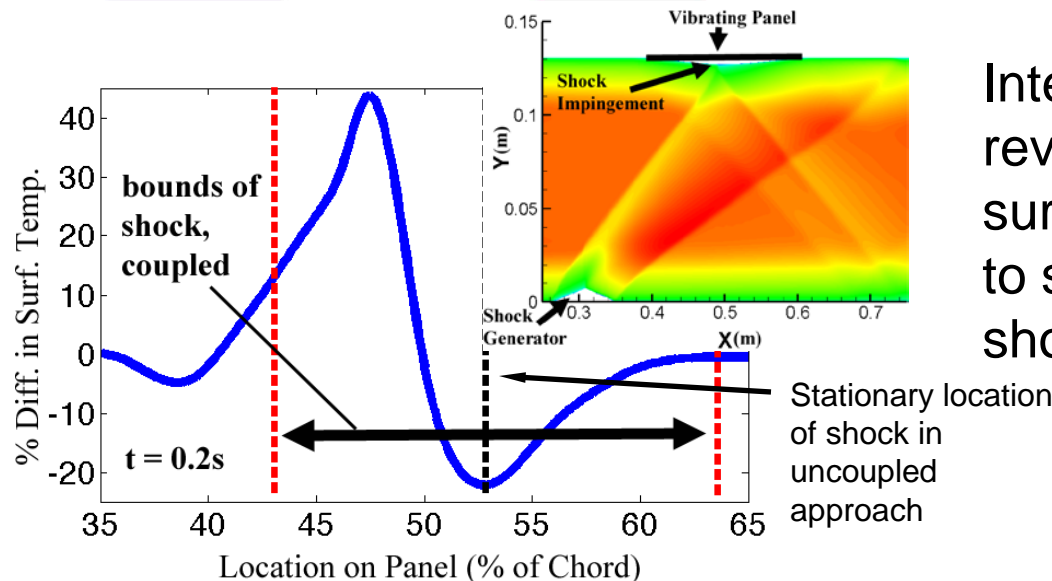


Dr. Jack McNamara
Assistant Professor

- Mechanical & Aerospace Engineering
- Senior Member AIAA
- 2011 Recipient of AFOSR YIP Award



Coupling of fluid, structural analysis reveals interactions unseen in prior uncoupled approaches



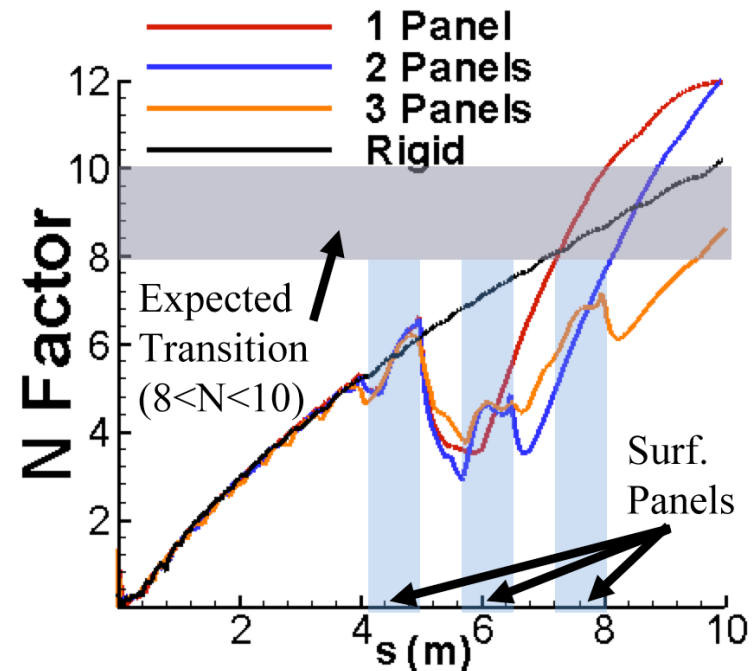
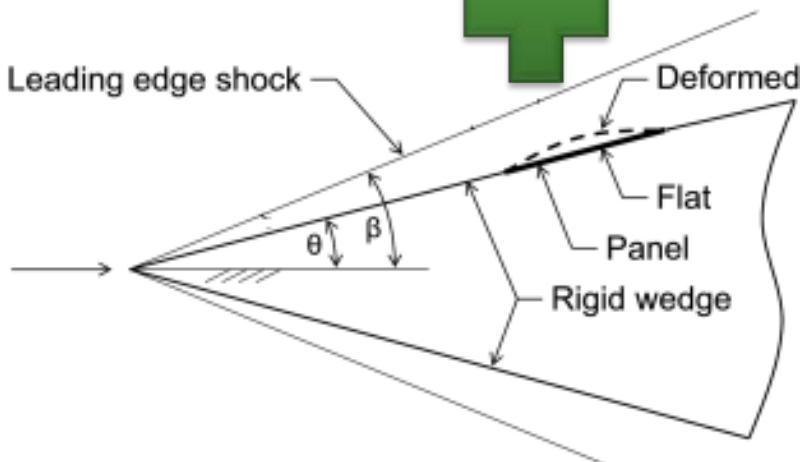
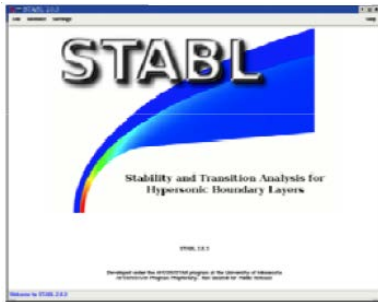
Integrated analysis reveals change in surface heating due to structure-driven shock motion

Kinetic Energy Transfer in Turbulent Flows

Lighter, More Compliant Surface Panels May Actually Reduce Aerodynamic Heating

First of a kind studies reveal a new strategy for simultaneously mitigating vehicle weight and aerodynamic heating

- **Series of thermally buckled panels predicted to delay transition**
- **Does change in boundary layer base state disrupt instability growth (?)²**



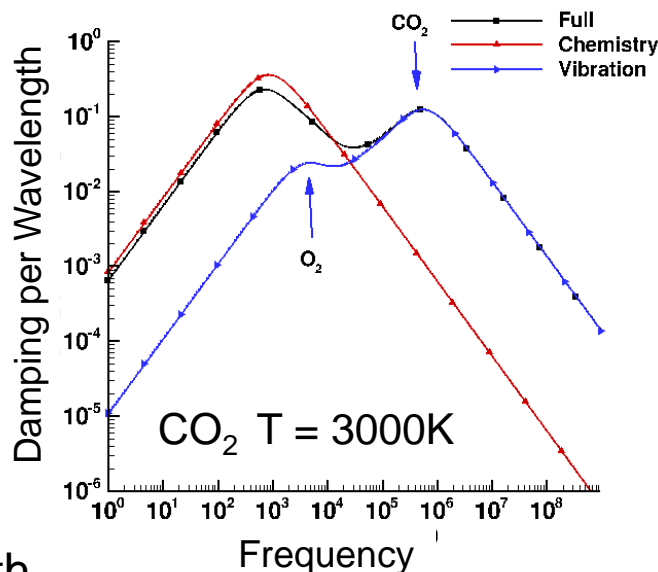
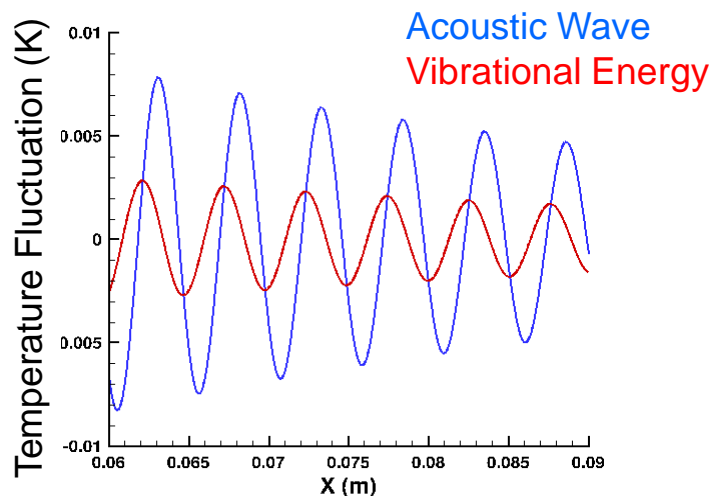
²Riley, Z., McNamara, J., and Johnson, H., "Hypersonic Boundary Layer Stability in the Presence of Thermo-Structural Compliance," 53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, April 2012.

Intermodal Energy Transfer in Laminar Flows

Direct Numerical Simulation of Vibrationally Active Gas Flows



- Vibrational energy absorption can attenuate acoustic disturbances – delaying laminar-turbulent transition
- Simulations provide a physics-based understanding of how and why this occurs to enable novel flow control strategies



Damping is caused by the interaction of the acoustic wave with the relaxation qualities of a molecule

Simulations allow isolation of effects of vibrational absorption and chemistry on instability attenuation



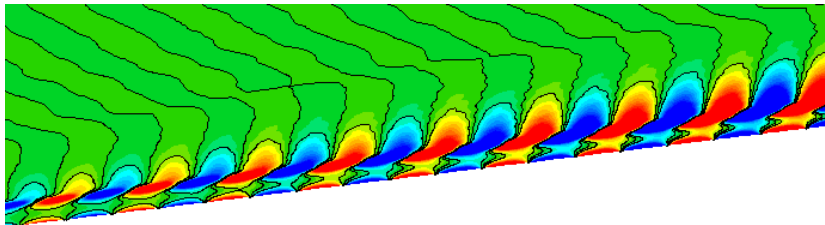
Dr. Candler
McKnight
Presidential
Professor

- Fellow of AIAA
- 2009 NSSEFF
- 2007 AIAA Thermophysics Award

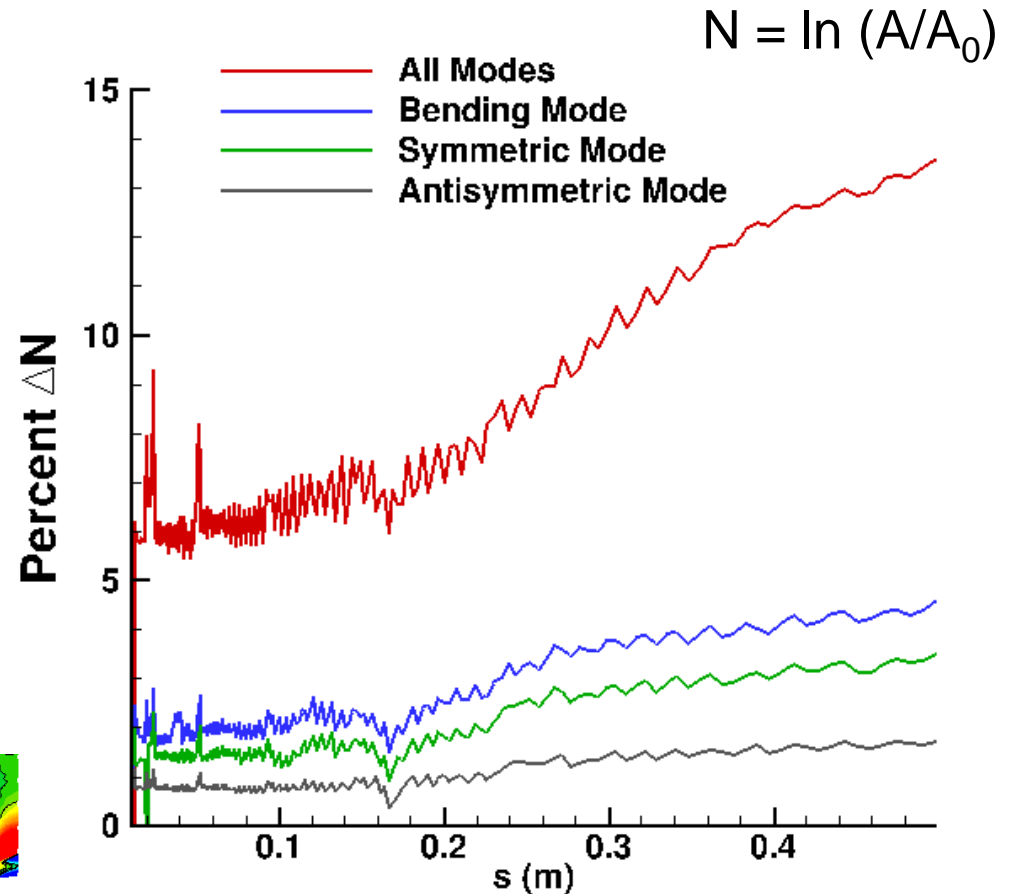
Intermodal Energy Transfer in Laminar Flows

Stability analysis reveals contributions of specific vibrational modes to instability attenuation

- Bending mode contributes most to disturbance damping
- Contribution increases with larger C_{vv}



Simulation of Mach 6 flow over a cone with Imposed acoustic wave with largest damping rate



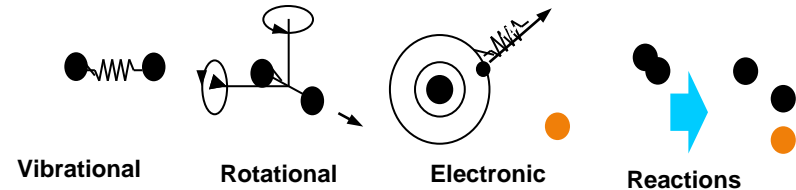
**Percent change in N factor
versus distance along the cone**

Understanding Nonequilibrium Energy Transfer In High-Enthalpy Flows

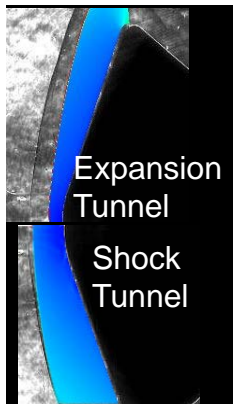
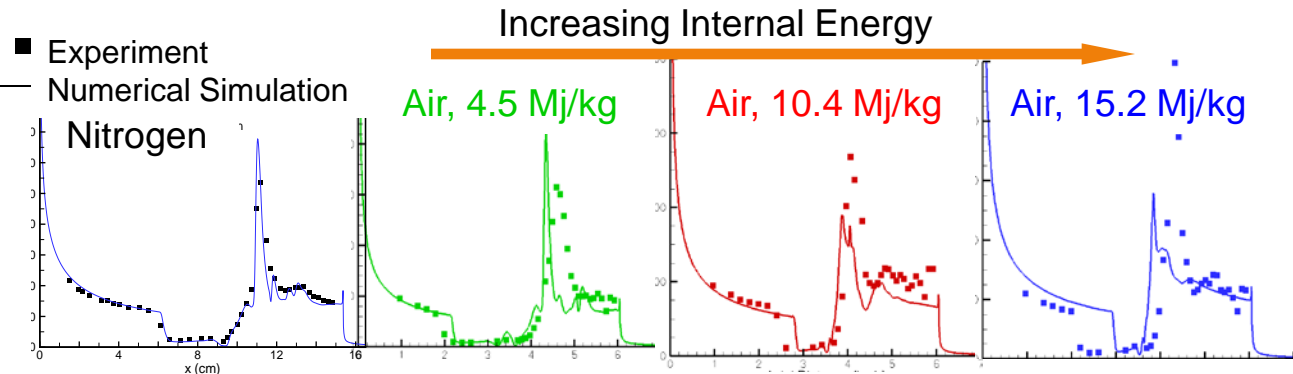
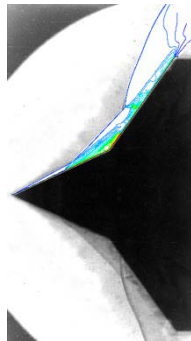


Sandia National Laboratories

For high-enthalpy flows energy transfer between the flow, thermodynamic and chemical processes becomes significant



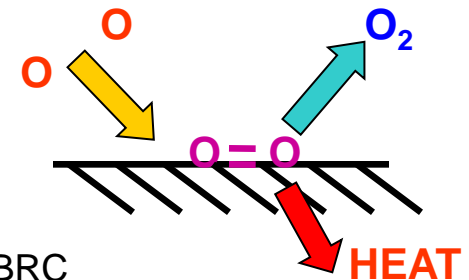
Predictions Fail as Chemical Complexity Increases
Candler, U. Minn
NSSEFF, CII



Excited States Impact Macroscopic Behavior
CO₂ at 5 MJ/kg freestream enthalpy:
- Shock Tunnel excites internal modes
- Expansion Tunnel does not

Surface reactions will be driven by available species in nonequilibrium environment

Ex: Catalytic Heating



M. MacLean and M. Holden, CUBRC

Goal: Characterize, Model and Exploit Nonequilibrium Processes

Understanding Nonequilibrium Energy Transfer In High-Temperature Flows

Dissecting the Anatomy of Shock-Boundary Layer Interaction in Hypervelocity Flow

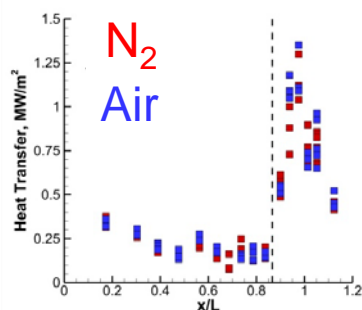
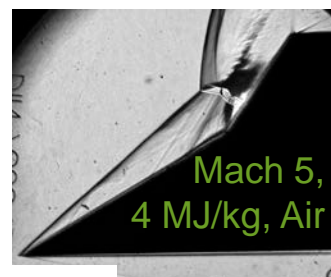
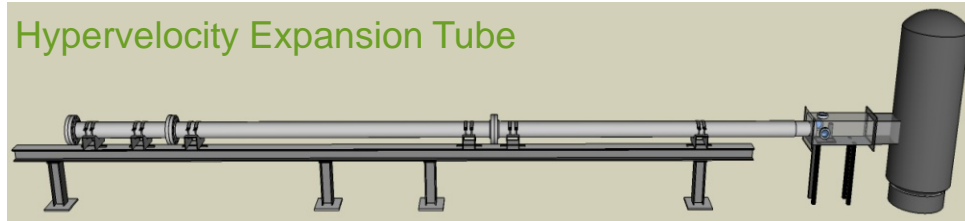


Goal: "Tune" the thermochemical activity to identify critical transitions between perfect and real gas flows. Made possible by novel facility built at Illinois under AFOSR support.



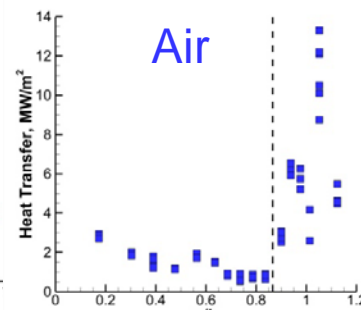
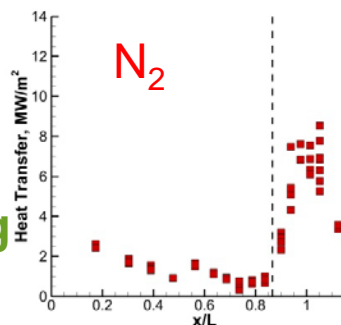
Joanna M Austin

- AFOSR Young Investigator Program Award
- NSF CAREER Award
- Associate Fellow, AIAA
- AIAA Fluid Dynamics Best Paper Award
- Xerox Award for Faculty Research Excellence



Mach 7.1
2 MJ/kg

8 MJ/kg



- Current dataset chosen for simulation by NATO RTO AVT 205 group.

Swantek and Austin, Int. Shock Wave Symp., July 2011

Swantek and Austin, AIAA ASM Meeting, Jan. 2012

CONTRIBUTION SPONSORMENT A – Unclassified, Unlimited Distribution



Understanding Nonequilibrium Energy Transfer In High-Temperature Flows

Optimization approach enables computation of high-temperature chemistry rates for all relevant processes based on reduced number of evaluations¹

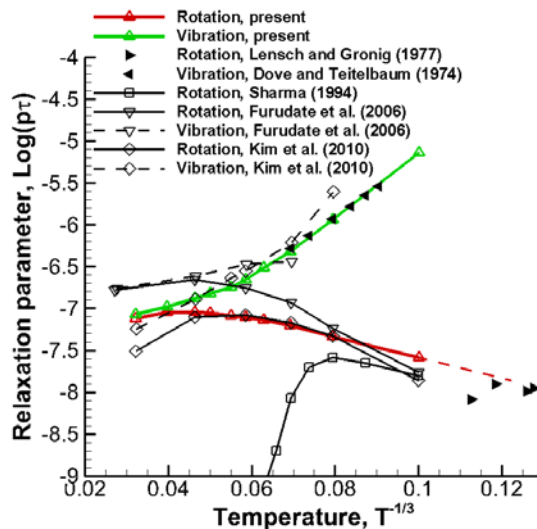
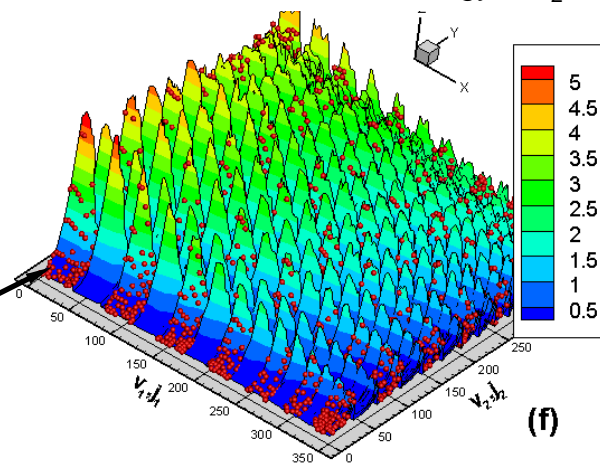
Quasi-Classical Trajectory method employed to compute cross sections that are integrated to find the rates (red dots) - 1800 collision states

Kriging approach used generate cross section surface representing 60,000 collision states

Computed relaxation rates agree well with measured data

- Reveal convergence of rates at high temperatures – contrary to conventional view

Transition cross section as a function of rotational and vibrational energy – H_2



Iain D. Boyd
James E. Knott
Chair of
Engineering

- Fellow of Am. Inst. Aero. Astro. (AIAA)
- 1998 AIAA Lawrence Sperry Award
- 2011 AIAA Thermophysics Best Paper Award
- AFSAB member

Understanding Nonequilibrium Energy Transfer In High-Temperature Flows

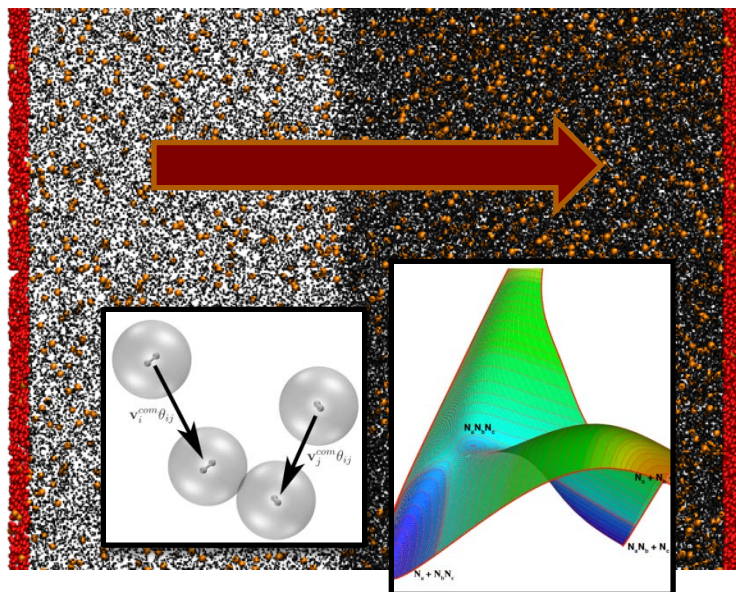
Pure Molecular Dynamics Simulation of Shock Waves Is Now Possible

New tool to study internal energy transfer in hypersonic flows

- No equation of state, transport models, or rate models required
- Inter-atomic forces provided by computational chemists are the sole model, directly linking chemistry and aero communities
- Dominant internal energy transfer mechanisms can be analyzed and reduced models formed
- Enabled by large-scale computing¹ and a novel numerical method²

¹Valentini and Schwartzentruber, *Physics of Fluids*, 21 (2009)

²Valentini and Schwartzentruber, *Journal of Computational Physics*, Vol. 228, No. 23 (2009)



Dr.
Schwartzentruber

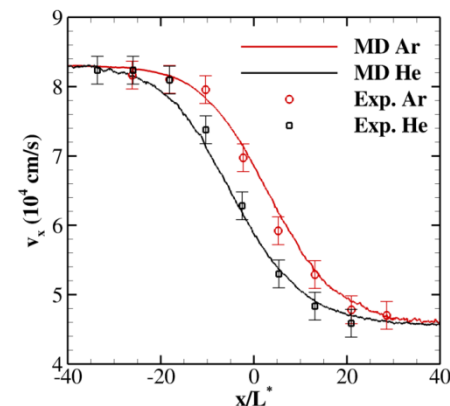
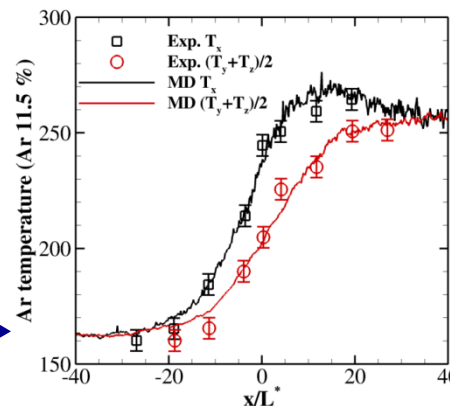
*Assistant
Professor*

- 2011 Visiting Professor, von Karman Institute
- AFOSR Young Investigator Award (2009)
- 2007 AIAA Orville and Wilbur Wright Award

Understanding Nonequilibrium Energy Transfer In High-Temperature Flows

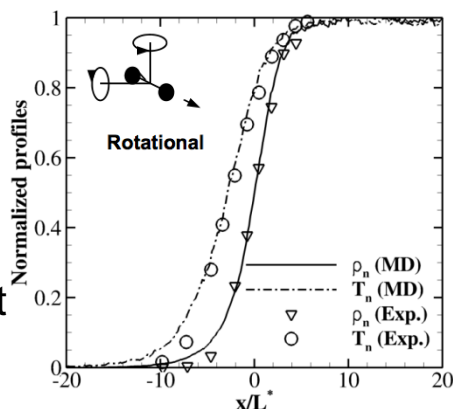
Translational nonequilibrium study (viscosity and mass diffusion) complete and validated with experiment.

- Species separation in an Argon-Helium Mixture shock wave vs. experiment



Rotational nonequilibrium study reveals new insights.

Rotational excitation in a N₂ shock vs. experiment



Rotational de-excitation ($T_{rot} > T_{tr}$) is slow

Rotational excitation ($T_{rot} < T_{tr}$) is fast

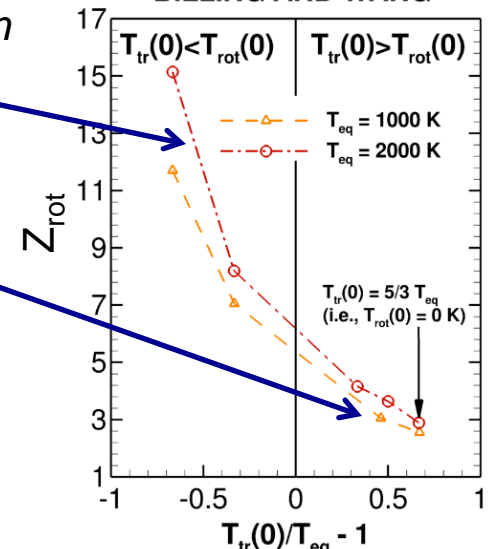
Current model:

$$Z_{rot} = \text{const or } Z_{rot} = f(T_{tr})$$

New model:

$$Z_{rot} = f(T_{tr} \text{ and } T_{rot})??$$

BILLING AND WANG



Vibrational excitation and dissociation study underway.

Vibrational Reactions



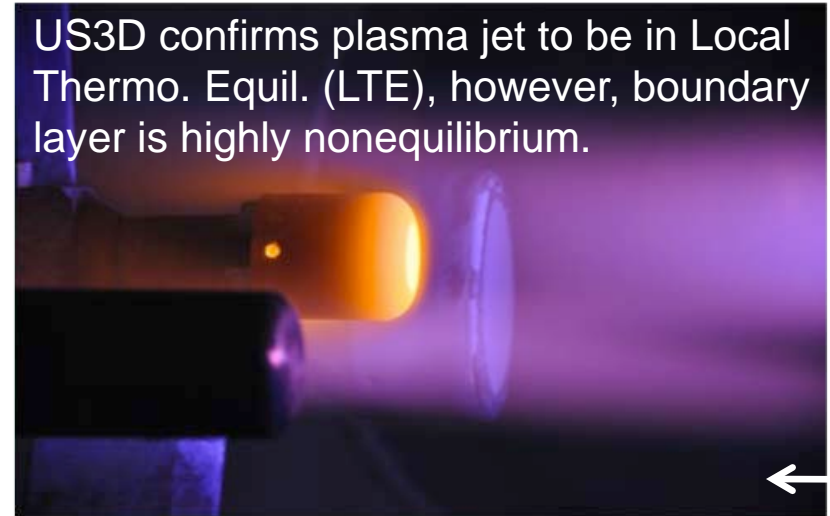
Understanding Nonequilibrium Energy Transfer In High-Temperature Flows



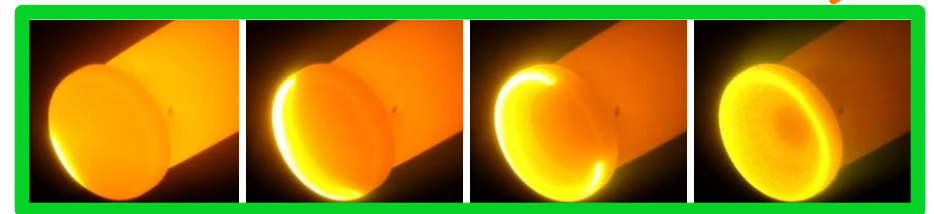
New High-Fidelity Modeling of Subsonic Plasma Flow Facilities Integrated Experimental-Numerical Collaboration

- *Boundary layer in subsonic plasmatron flow requires modeling* to extrapolate to hypersonic conditions
- Current modeling valid only for stagnation line heat flux
- Combine *Minnesota's leading-edge modeling* capabilities with *high-quality data from VKI's Plasmatron*
- This effort could drive a new level of understanding and form *new predictive models for gas-surface reactions for real TPS*

US3D confirms plasma jet to be in Local Thermo. Equil. (LTE), however, boundary layer is highly nonequilibrium.



Experimental images of passive to active oxidation of a UHTC sample



No current modeling capability.

MURI: Fundamental Processes in High-Temperature Hypersonic Flows

Graham V. Candler, Don Truhlar, Adri van Duin, Tim Minton, Deborah Levin
Tom Schwartzentruber, Erica Corral, Dan Kelley and Paul DesJardin



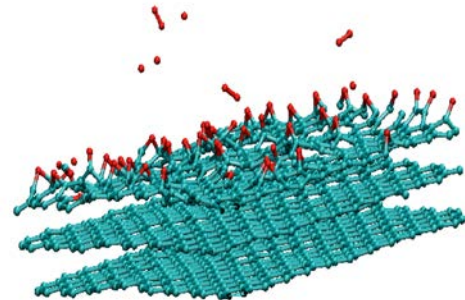
MURI Explores Molecular scale Kinetic Processes to Advance Simulation of Vehicle Scale Phenomena

Integration of Aerothermodynamics, Chemistry and Materials Research to develop advanced models for gas-surface interactions

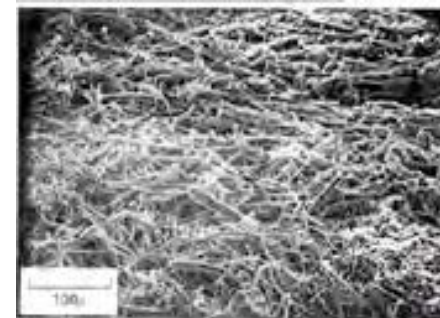
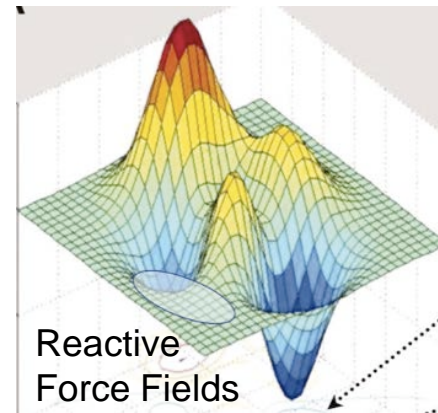
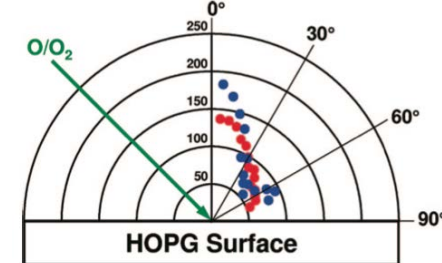
Approach

- Use detailed quantum mechanics to develop accurate force fields for key processes
- Train reactive force field for MD simulations of post-shock wave flows and gas-surface interactions
- Extend to continuum models with DSMC models and state-specific simulations
- Perform experiments at all scales to provide validation data for model generation

Molecular Dynamics

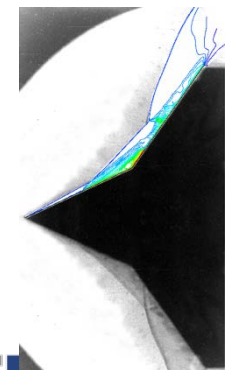
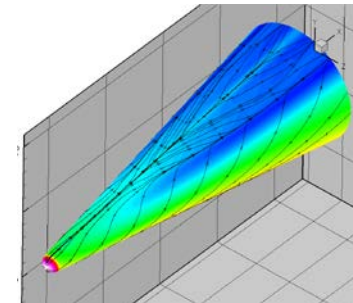


Reaction Dynamics Experiments



Material Surface Effects

High-Fidelity, Large-Scale CFD



Understanding Nonequilibrium Energy Transfer In High-Temperature Flows

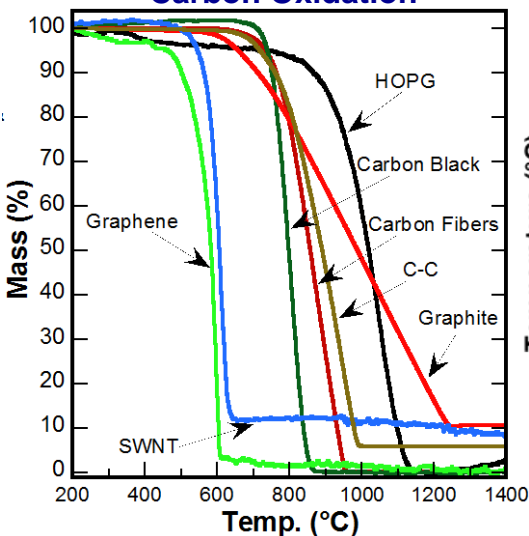
Novel Measurements of Carbon Oxidation Rates Under Controlled Conditions

Carbon ablation models rely on oxidation rate data; previous measurements were obtained under poorly controlled conditions, making it difficult to interpret the data. The University of Arizona team has developed a new approach to reduce these uncertainties and provide accurate data.



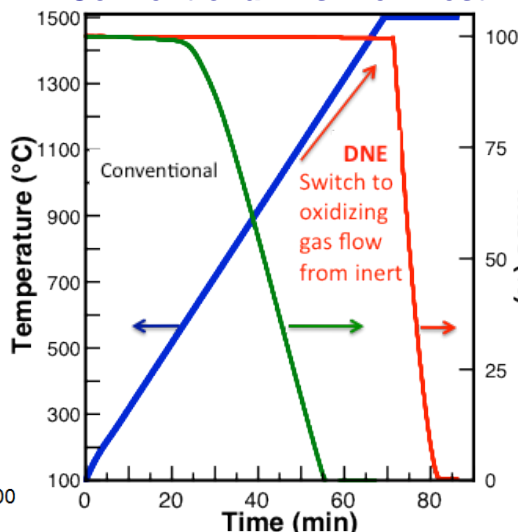
Dr. Erica Corral,
Assistant Prof.,
Univ. of Arizona
• AFOSR YIP
• NSF CAREER
• Member of AFOSR
MURI team

Carbon Oxidation



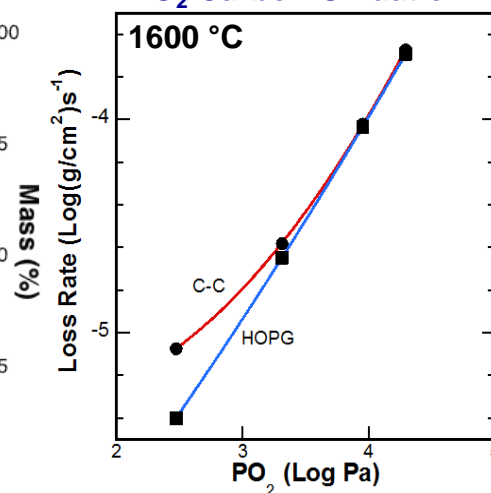
Conventional Approach:
Large variation in rate data; T
changes during measurement

Conventional" vs. New Test



NDE-TGA Approach: Pre-
heat sample under inert gas;
take data at constant T

PO₂ Carbon Oxidation



Oxidation rate data at 1600 °C is ONLY possible
using the new test method and will be used for
gas-surface interaction models; less variation
with form of carbon.



Outline



- **Motivation**
 - **Scientific Challenges**
 - **The Big Picture**
 - **Portfolio Management**
 - **Evolving Research Directions**
 - **Research Highlights**
- **AFRL Pizza - high-speed systems provide *efficient* coverage**
 - **Intersection of thermophysics, turbulence and chemistry**
 - **Portfolio plays a leading role in international research**
 - **Lessons from Skeet Shooting: New approach may increase “hits”**
 - **Energy transfer at small scales drives macroscale behavior**
 - **Portfolio PIs are conducting exciting, world-leading research**



Integrity ★ Service ★ Excellence

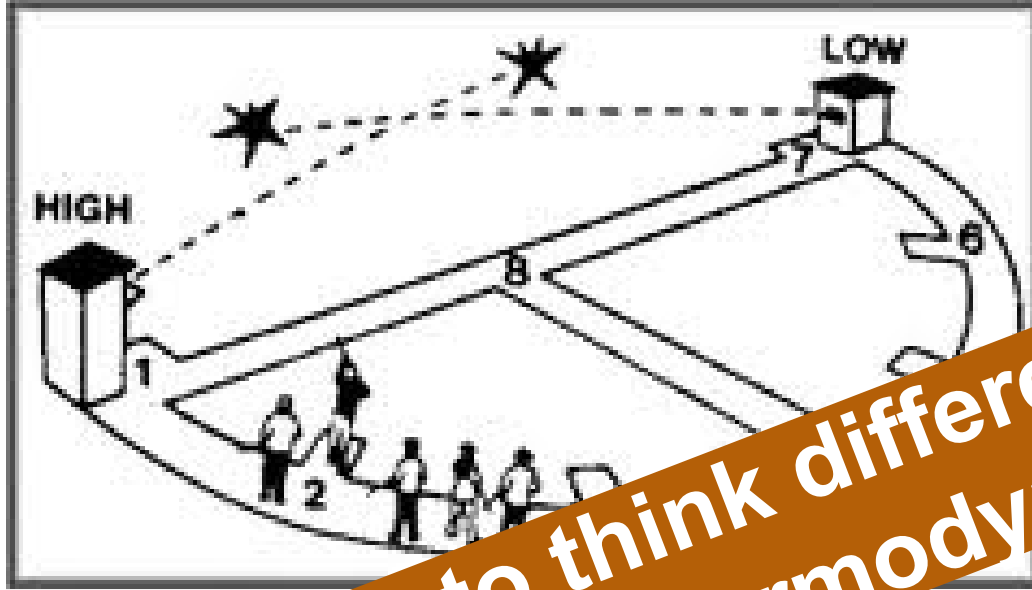
Pizza, Skeet Shooting and the Future of Aerothermodynamics

Date: 09 03 2012

**John D. Schmisser
Program Manager
AFOSR/RSA**

Air Force Research Laboratory

What Skeet Shooting Has Taught Me About Program Management



**Time to think differently about
Aerothermodynamics!**

- Keep your eyes open
- Know which way the wind is blowing and stay in front of the target



- How you think about the target effects your approach (and ability to hit it!)