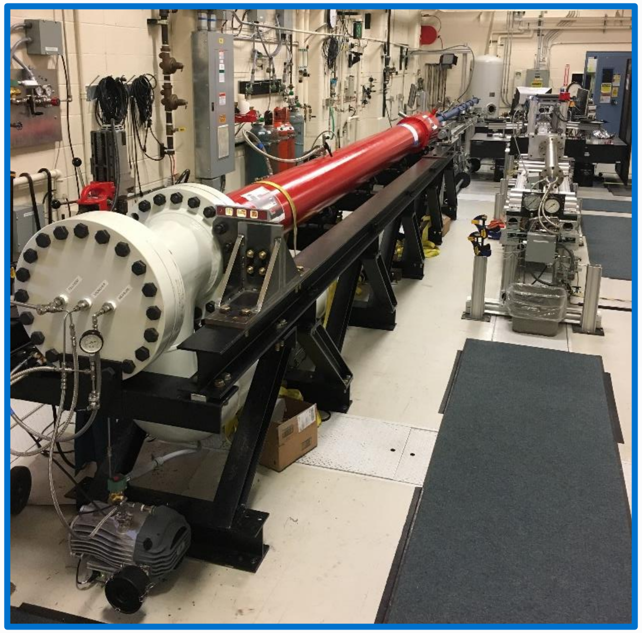
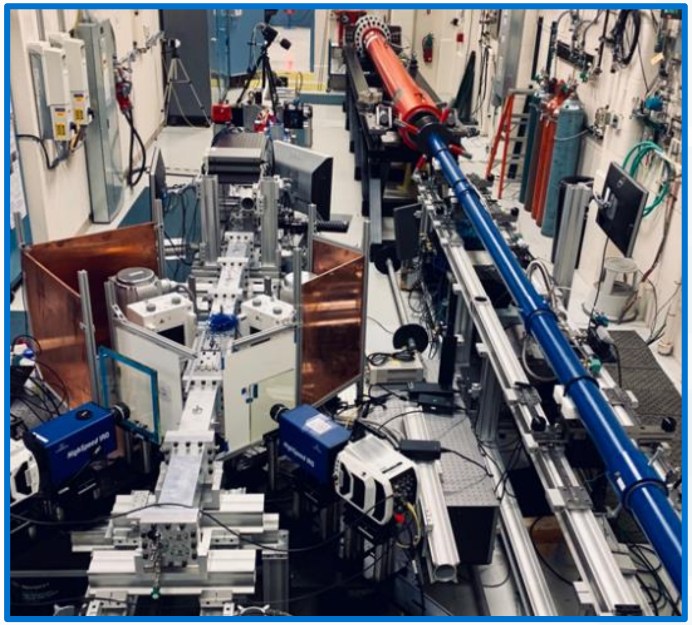
SAND2021-4055PE

Planned TPS Experiments in the Sandia Reflected Shock Tunnel





-March 30th, 2021

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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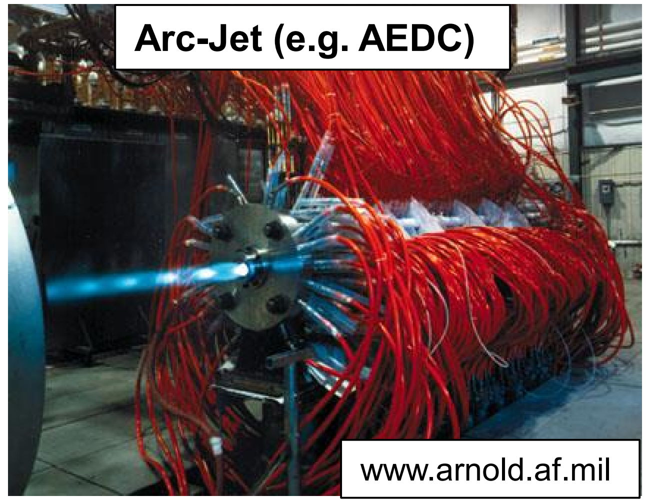
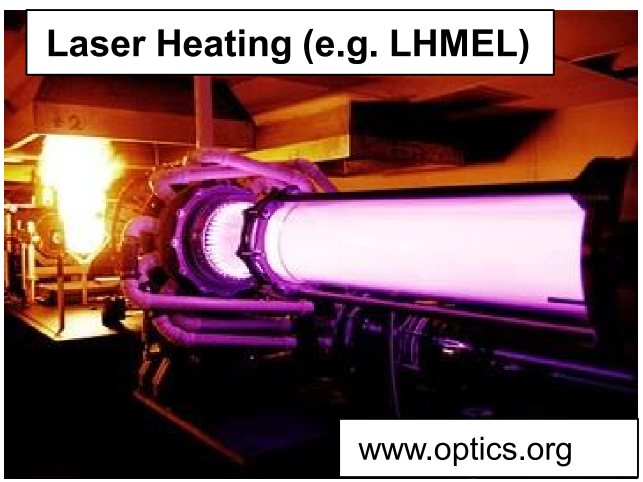
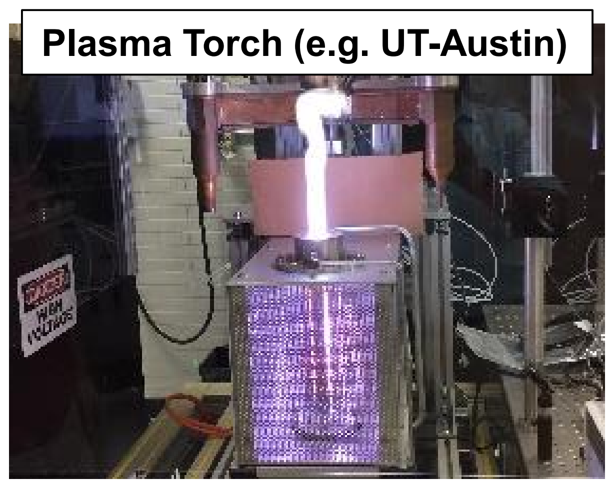
Established Methods for TPS Characterization







Summary

- Each method produces the correct heating over run times of several minutes.
- **These facilities cannot reproduce flight velocity, aerodynamic heating and the correct air chemistry concurrently.**

In hypersonic flight, fluid mechanics, gas chemistry and surface chemistry are critical to ablation and they are coupled!

Hypersonic Gas-Surface Interactions

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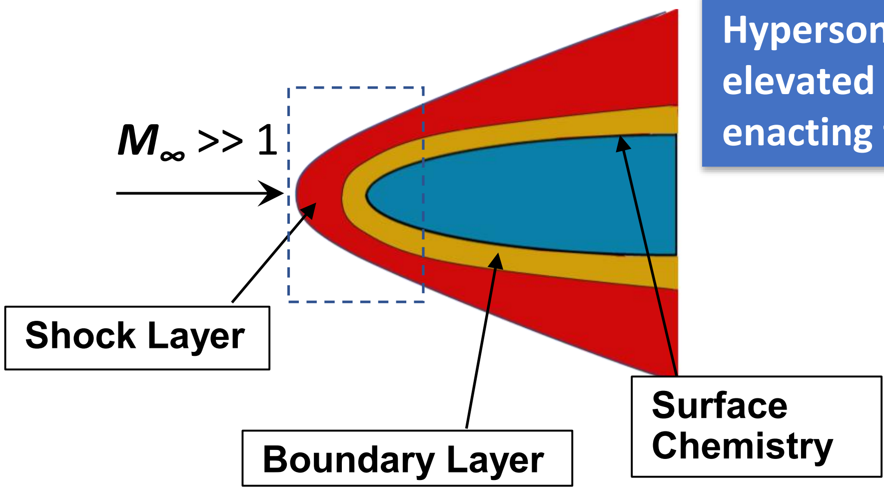
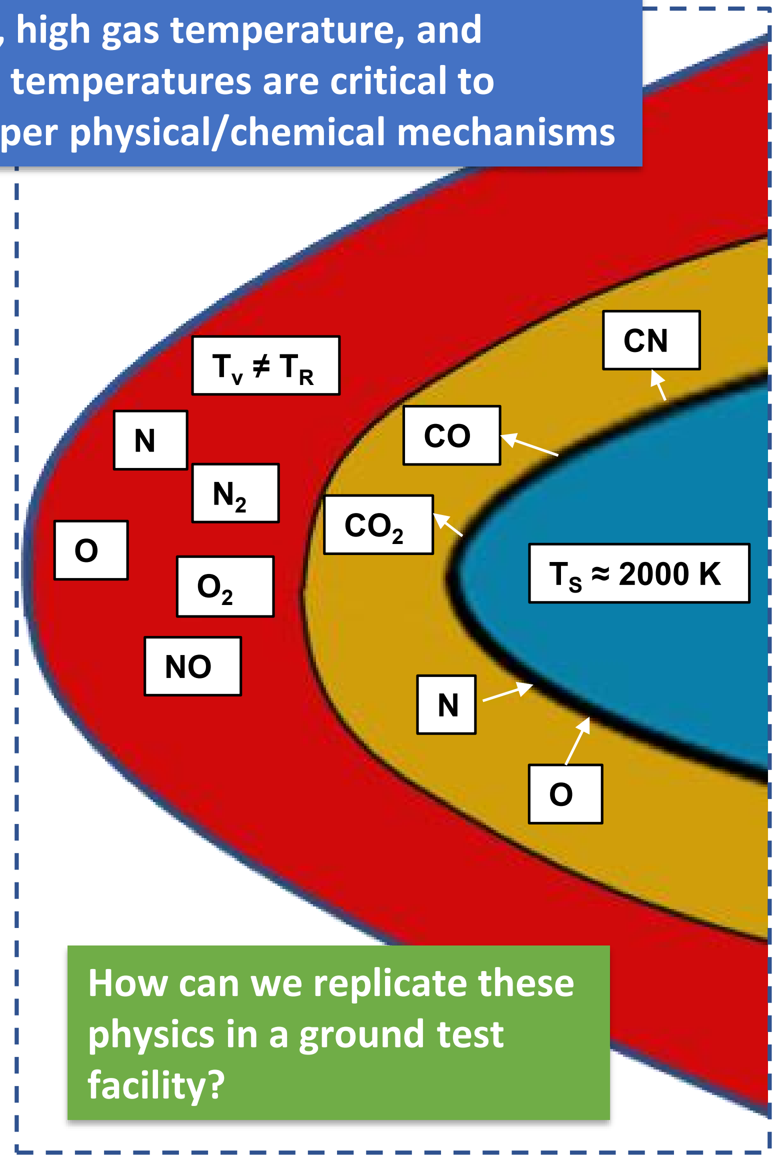


Hypersonic flow, high gas temperature, and elevated surface temperatures are critical to enacting the proper physical/chemical mechanisms



How can we replicate these physics in a ground test facility?

Shock Layer (Gas Chemistry)

- Species dependent thermodynamic nonequilibrium. Vibrational ≠ rotational temperature ($T_v \neq T_R$)
- Dissociation produces atomic N and O and formation of nitric oxide (NO)

Surface Chemistry

- N and O interact (adsorb) with surface.
- Oxidation and nitridation
- CO, CO_2 production.

Boundary Layer

- Diffusion of oxidization products
- Air chemistry
- Vibrationally excited species (N_2 , O_2)

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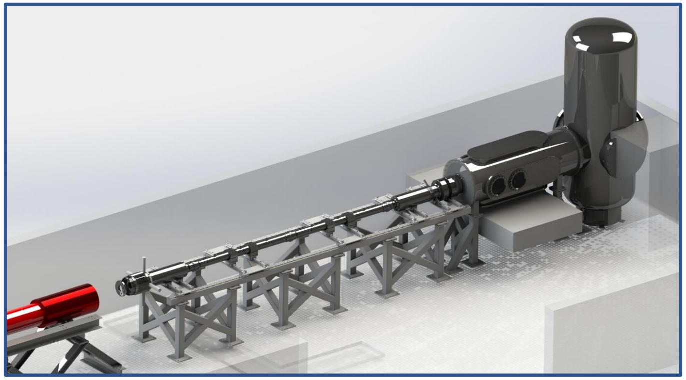
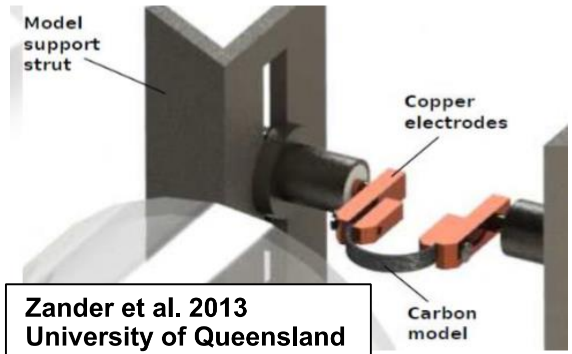
1. Experimental Facility Development and Requirements

Mach 8 Reflected Shock Tunnel



Surface Temperatures > 2000 K



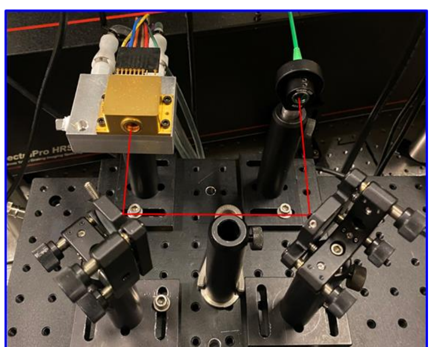
Zander et al. 2013
University of Queensland

Environment closely replicating surface chemistry in hypersonic flight

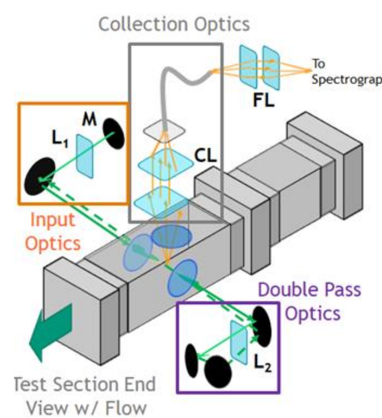
2. Diagnostics Development and Requirements

Optical Emission (O, N)

Laser Absorption (CO, NO)



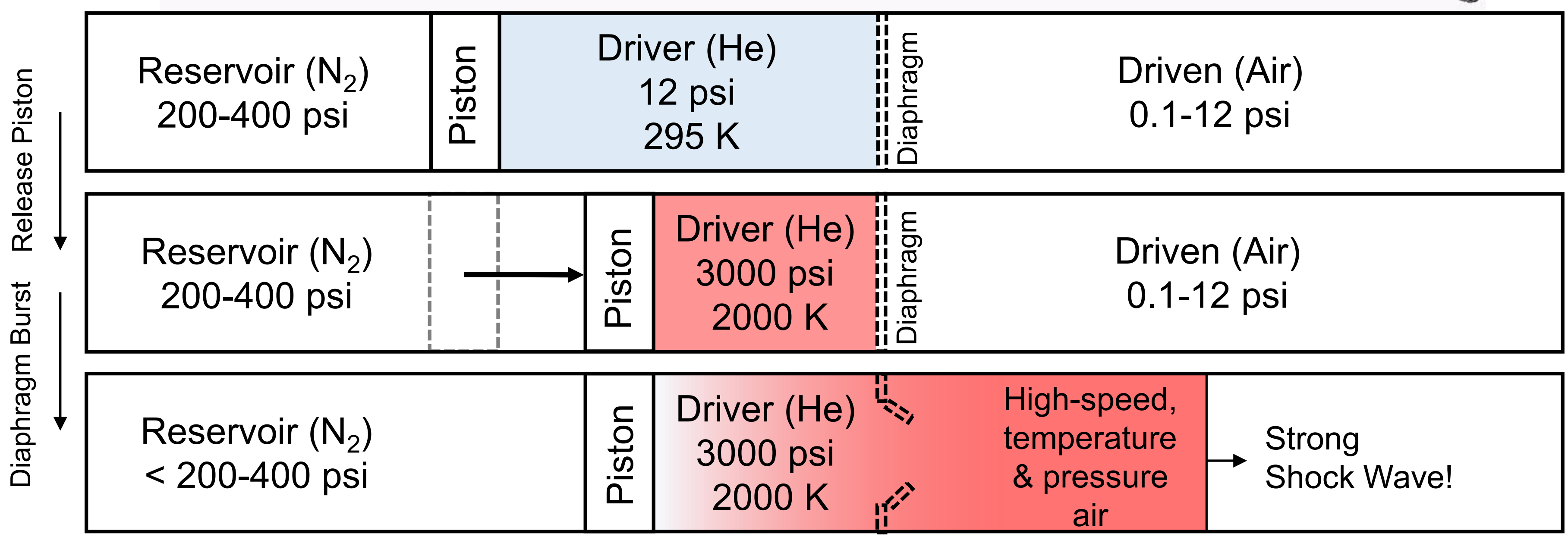
Raman Scattering (N_2, O_2)



Experimental data to address persistent surface chemistry modeling gaps

How do we Generate Our High Enthalpy Supply Gas?

Operating Principle of the Free-Piston Shock Tube



Air Luminosity Following Shock Reflection off the End Wall

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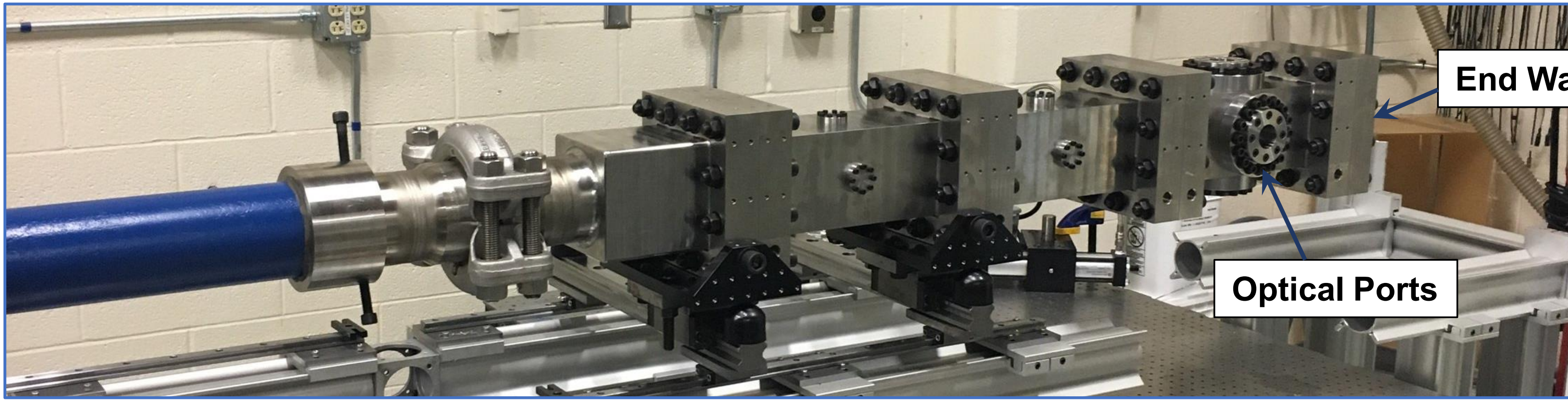
Shock Heated Air in the High-Temperature Shock Tube (HST) at 7000 K



The HST provides our shock tunnel supply gas at the required temperature and pressure to represent flight.

The Sandia Mach 8 Reflected Shock Tunnel (HST-8R)

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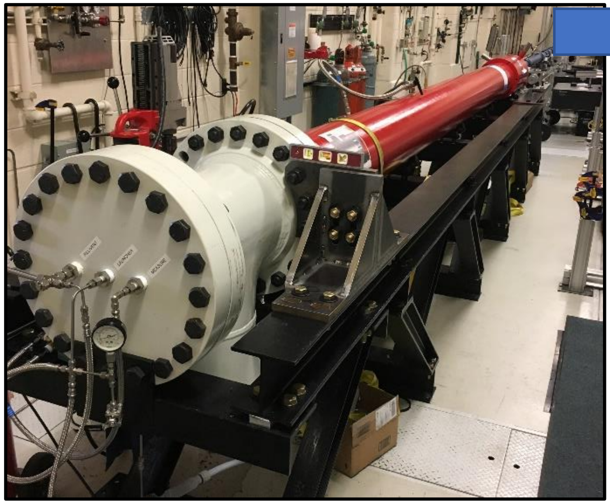
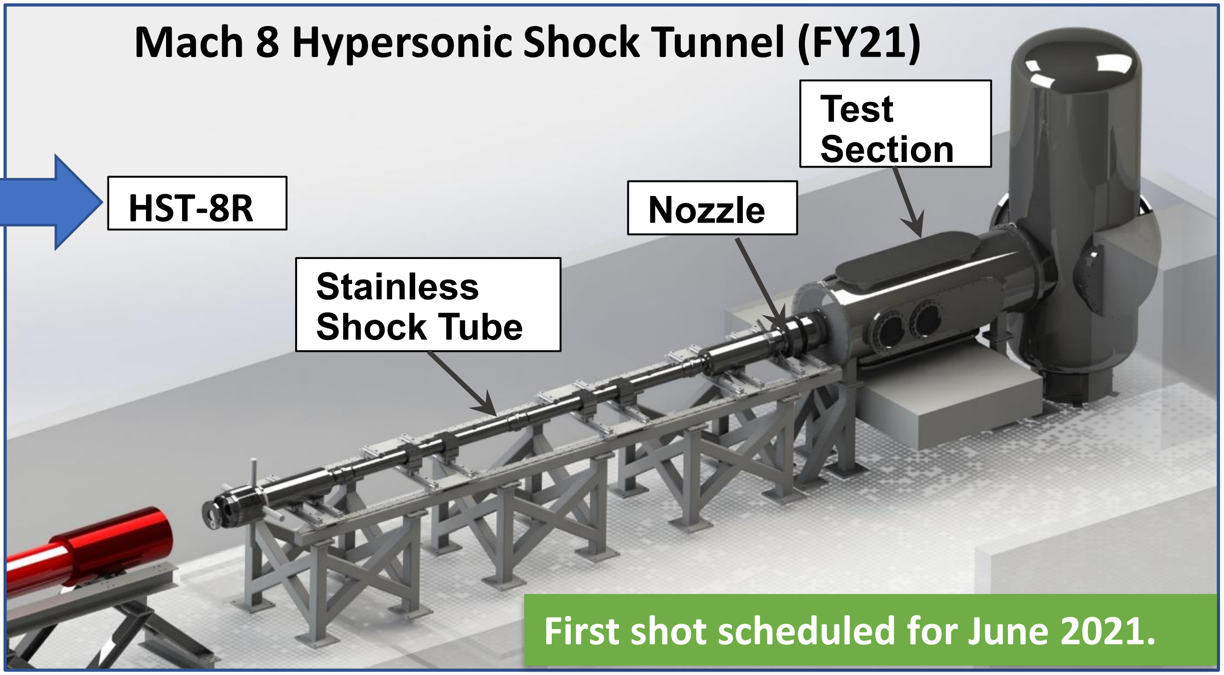
The free-piston shock tube is the front end of the shock tunnel.





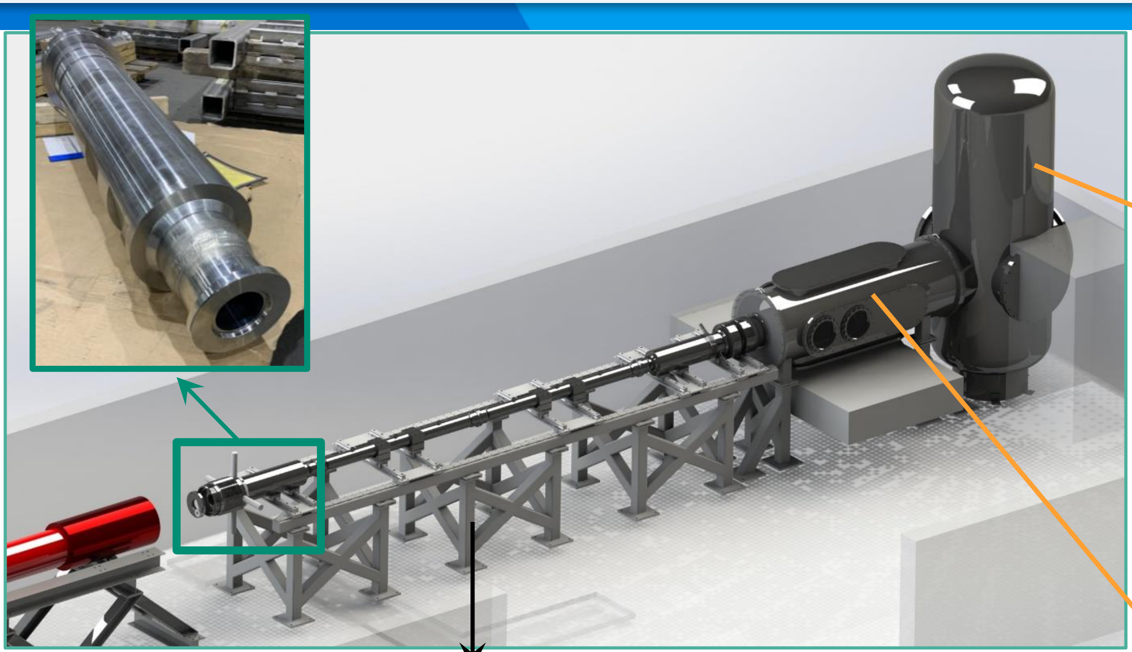
Tunnel Specifications

- Max stagnation pressure **P_0 ≈ 24.1** MPa (3500 psi)
- Max stagnation temperature **T_0 ≈ 7000 K**
- Test section diameter 0.5 m
- Run times of 1 – 20 milliseconds
- Research scale amenable to innovation

Combined Environments in the Tunnel

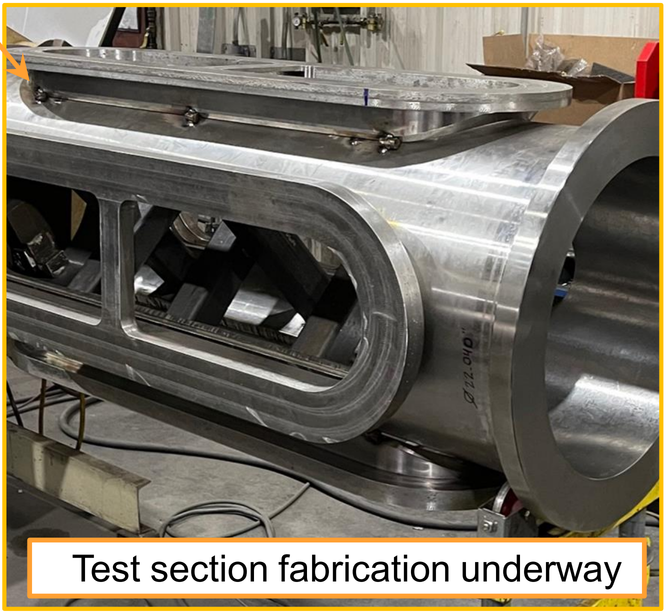
- High-temperature aerodynamics
- **Air thermochemistry including nonequilibrium**
- **Materials characterization and surface chemistry**

Tunnel Build Progress



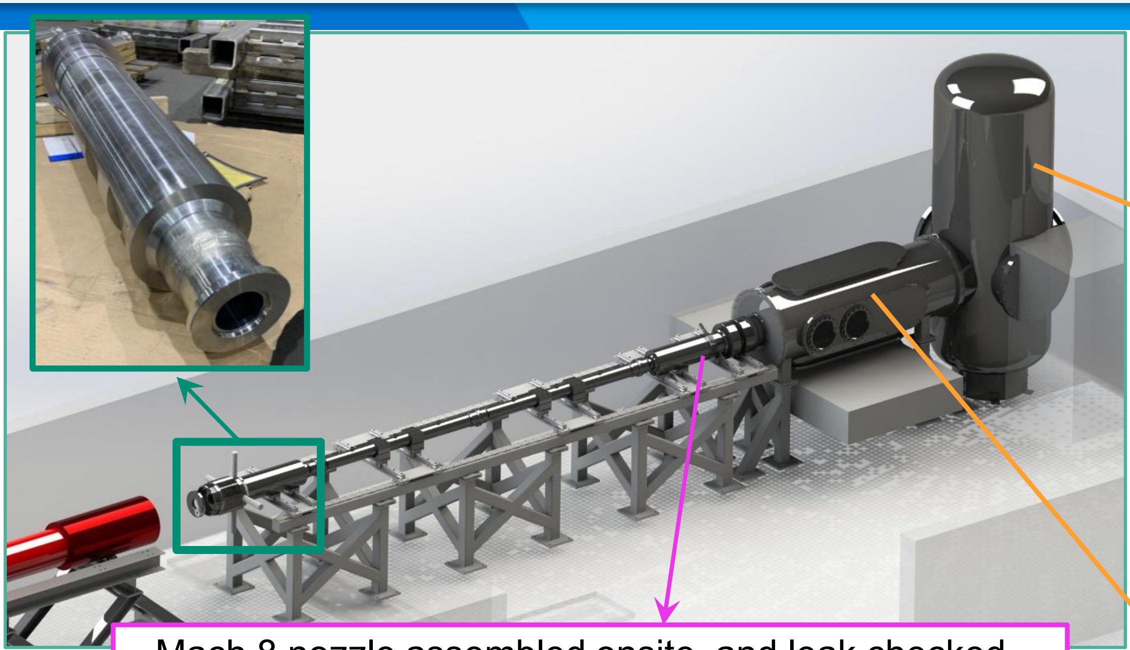
Support structure assembled onsite with data acquisition system

Vacuum tank in process

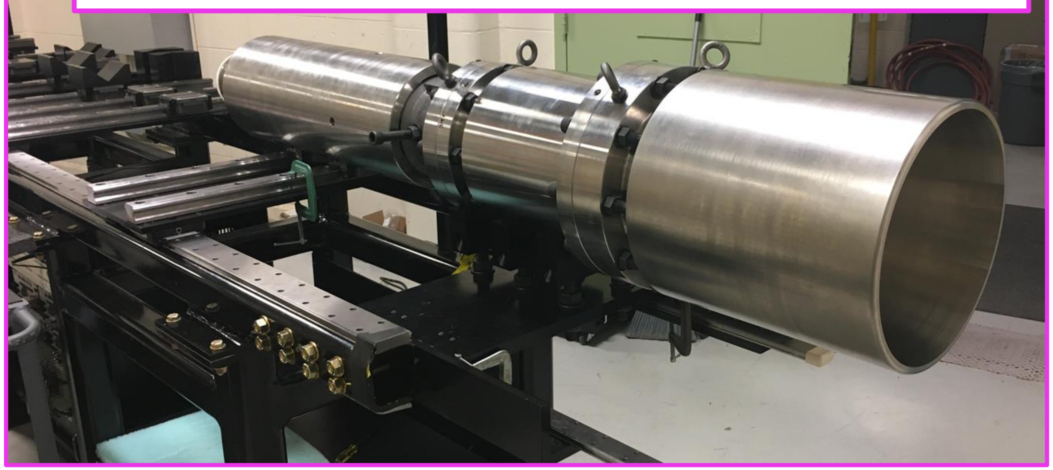


Test section fabrication underway

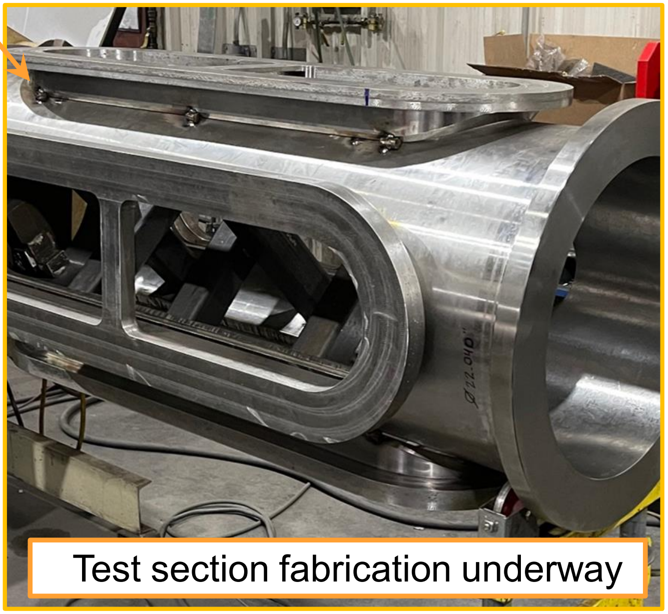
Tunnel Build Progress



Mach 8 nozzle assembled onsite, and leak checked

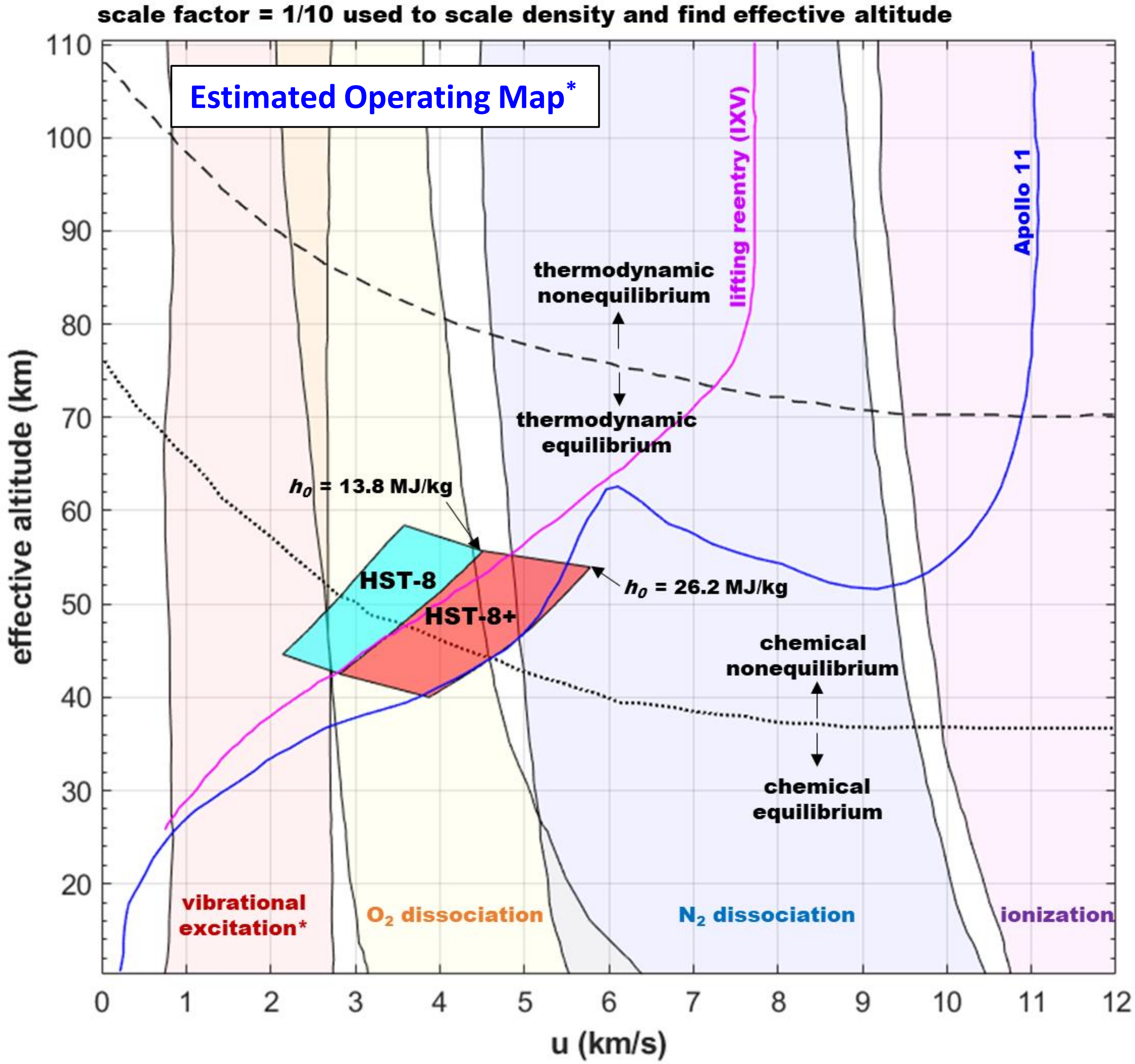


Vacuum tank in process



Test section fabrication underway

Notional Operational Map



*Regions of interest after Hanneman et al. 2016

Mach 8 Flight Enthalpy Condition

- H_0 = 4.0 MJ/kg (T_0 = 3300 K)
- U_∞ = 2.8 km/s, $\mathbf{T_\infty}$ **= 240 K**
- **O_2 dissociation minimal**
- Test time ≈ 10 ms
- **Pressure altitude = 35 km**

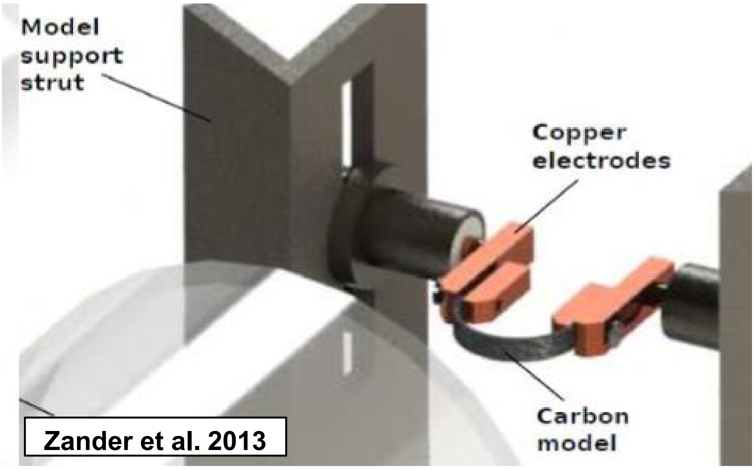
High Enthalpy Condition

- H_0 = 8.8 MJ/kg (T_0 = 5400 K)
- U_∞ = 4.1 km/s, $\mathbf{T_\infty}$ **= 800 K**
- **O_2 dissociation prevalent**
- Test time ≈ 5 ms
- Simulates higher Mach # enthalpy

The focus this year is demonstrating the flight enthalpy condition.

Preheat Plans

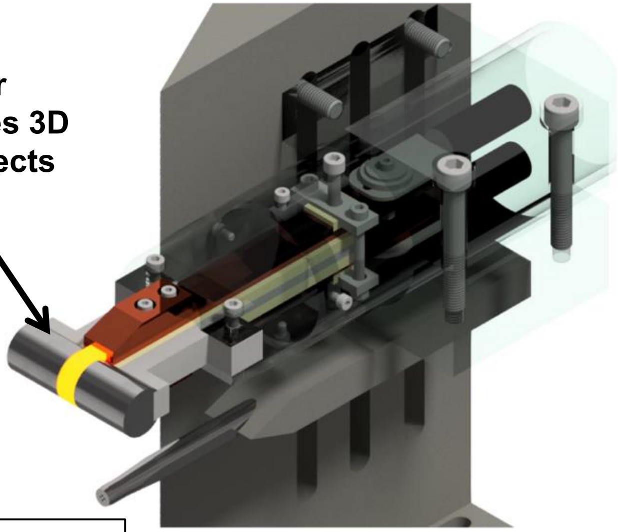
University of Queensland (UQ) Version 1.0



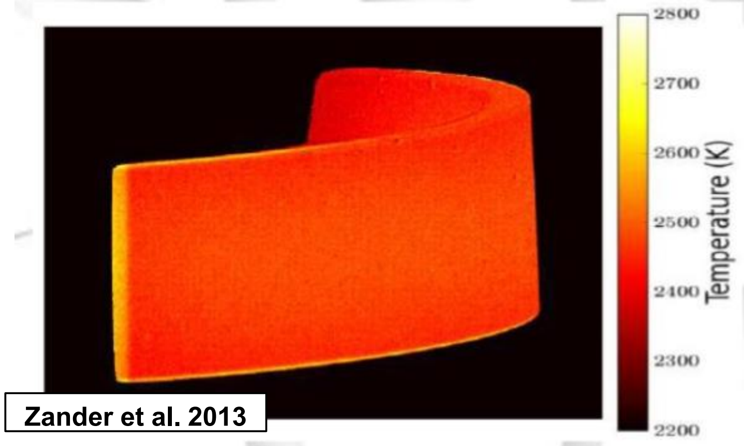
Zander et al. 2013

UQ Version 2.0

Cylinder mitigates 3D flow effects



Lewis et al. 2018



Zander et al. 2013

Resistive heating gives temperatures > 2000 K

Preheat Options

- Laser-based heating
- Electrical resistive heating
  - **Seems like the best option here.**

A design of the preheater and first experimental model is currently underway.

Presentation Overview

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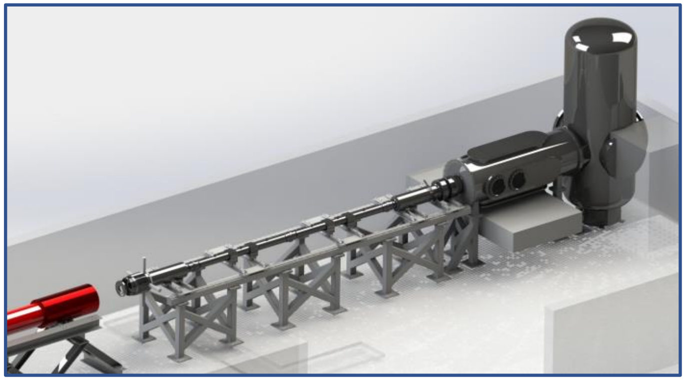
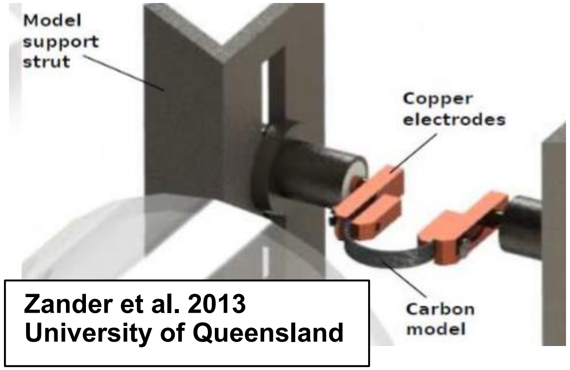
1. Experimental Facility Development and Requirements

Mach 8 Reflected Shock Tunnel + **Surface Temperatures > 2000 K**

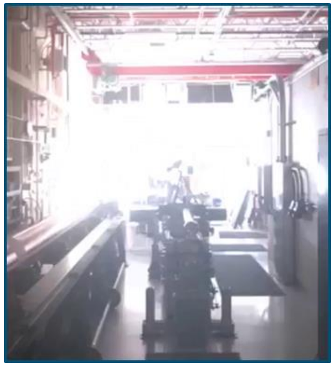


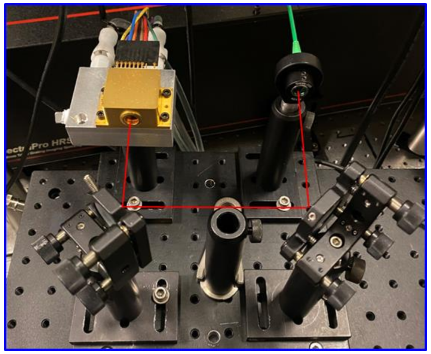


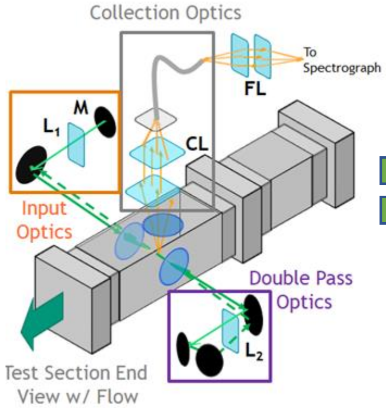
= **Environment closely replicating surface chemistry in hypersonic flight**

2. Diagnostics Development and Requirements

Optical Emission (O, N) + **Laser Absorption (CO, NO)** + **Raman Scattering (N_2, O_2)**







= **Experimental data to address persistent surface chemistry modeling gaps**

What Ablation Models Are Available?

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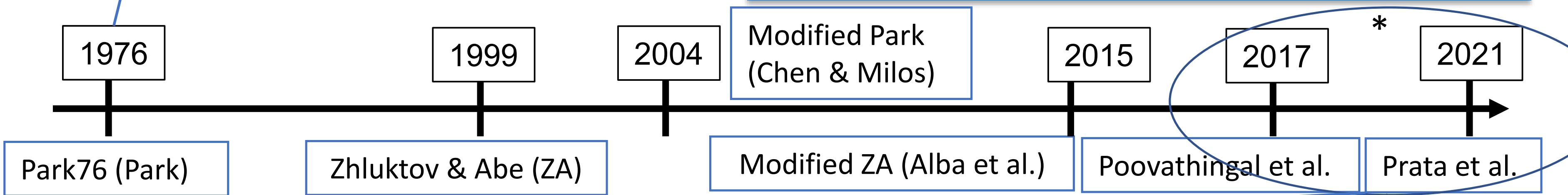
Table 5. Reactions and Rates for Park(1976) Model

	reaction	γ	E (kJ/gmol)
1	$O_2 + (s1) + C(b) \rightarrow CO + O + (s1)$	0.01	0
2	$O + (s1) + C(b) \rightarrow CO + (s1)$	0.63	9.644
3	$O + (s2) \rightarrow O(s2)$	0.63	9.644
4	$O + O(s2) \rightarrow O_2 + (s2)$	0.63	9.644

The last 45 years has seen detailed models emerge on air-carbon ablation with increasing complexity, but they have yet to be validated with detailed measurements under flight-like conditions.



R.No	Reaction	Reaction Rate	Rate Coefficient	Units
1.	$O + (s) \rightarrow O(s)$	$k_{O1}[O][(s)]$	$\frac{F_O}{B} * 0.3$	m^3 mol^{-1} s^{-1}
2.	$O(s) \rightarrow O + (s)$	$k_{O2}[O(s)]$	$\frac{2\pi m_O k_b^2 T^2}{A_v B h^3} \exp\frac{-44277}{T}$	s^{-1}
3.	$O + O(s) + C(b) \rightarrow CO + O + (s)$	$k_{O3}[O][O(s)]$	$\frac{F_O}{B} * 100 * \exp\frac{-4000}{T}$	m^3 mol^{-1} s^{-1}
4.	$O + O(s) + C(b) \rightarrow CO_2 + (s)$	$k_{O4}[O][O(s)]$	$\frac{F_O}{B} \exp\frac{-500}{T}$	m^3 mol^{-1} s^{-1}
5.	$O + (s) \rightarrow O^*(s)$	$k_{O5}[O][(s)]$	$\frac{F_O}{B} * 0.7$	m^3 mol^{-1} s^{-1}
6.	$O^*(s) \rightarrow O + (s)$	$k_{O6}[O^*(s)]$	$\frac{2\pi m_O k_b^2 T^2}{A_v B h^3} \exp\frac{-96500}{T}$	s^{-1}
7.	$O + O^*(s) + C(b) \rightarrow CO + O + (s)$	$k_{O7}[O][O^*(s)]$	$\frac{F_O}{B} * 1000 * \exp\frac{-4000}{T}$	m^3 mol^{-1} s^{-1}
8.	$O^*(s) + O^*(s) \rightarrow O_2 + 2(s)$	$k_{O8}[O^*(s)]^2$	$\sqrt{\frac{A_v}{B}} F_{O,2D} * 10^{-3} * \exp\frac{-15000}{T}$	m^2 mol^{-1} s^{-1}
9.	$O(s) + O(s) \rightarrow O_2 + 2(s)$	$k_{O9}[O(s)]^2$	$\sqrt{\frac{A_v}{B}} F_{O,2D} * 5 * 10^{-5} \exp\frac{-15000}{T}$	m^2 mol^{-1} s^{-1}
10.	$N + (s) \rightarrow N(s)$	$k_{N1}[N][(s)]$	$\frac{F_N}{B} \exp\frac{-2500}{T}$	m^3 mol^{-1} s^{-1}

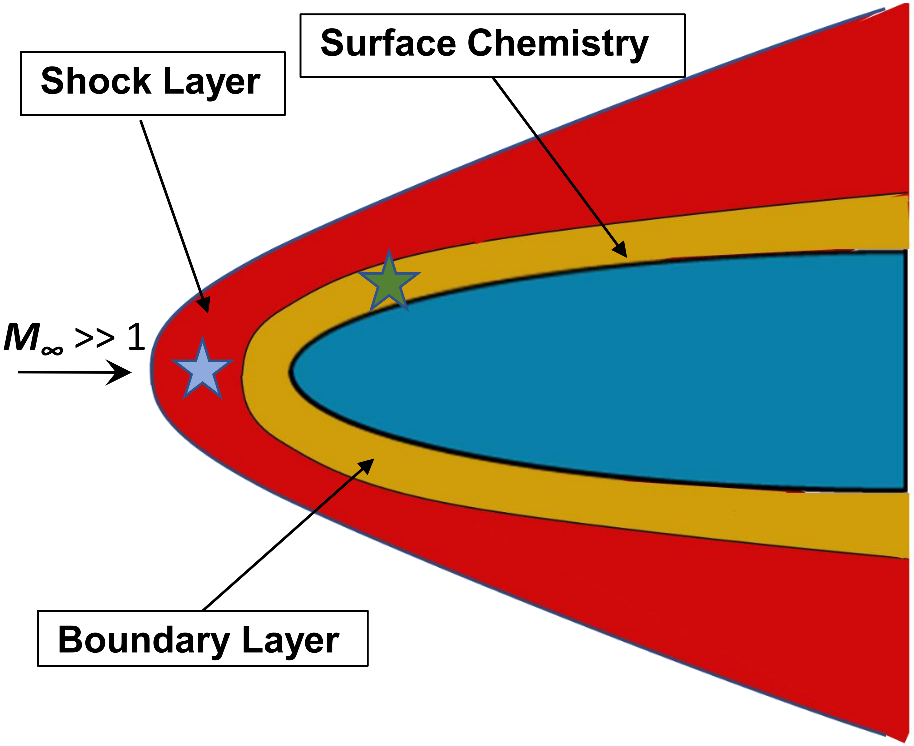
10.	$N + (s) \rightarrow N(s)$	$k_{N1}[N][(s)]$	$\frac{F_N}{B} \exp\frac{-2500}{T}$
11.	$N(s) \rightarrow N + (s)$	$k_{N2}[N(s)]$	$\frac{2\pi m_N k_b^2 T^2}{A_v B h^3} \exp\frac{-73971}{T}$
12.	$N + N(s) + C(b) \rightarrow CN + N + (s)$	$k_{N3}[N][N(s)]$	$\frac{F_N}{B} * 1.5 * \exp\frac{-7000}{T}$
13.	$N + N(s) \rightarrow N_2 + (s)$	$k_{N4}[N][N(s)]$	$\frac{F_N}{B} * 0.5 * \exp\frac{-2000}{T}$
14.	$N(s) + N(s) \rightarrow N_2 + 2(s)$	$k_{N5}[N(s)]^2$	$\sqrt{\frac{A_v}{B}} F_{N,2D} * 0.1 * \exp\frac{-21000}{T}$
15.	$N(s) + C(b) \rightarrow CN + (s)$	$k_{N6}[N(s)]$	$10^8 \exp\frac{-20676}{T}$
16.	$O_2 + 2(s) \rightarrow 2O(s)$	$k_{ox1}[O_2][(s)]^2$	$\frac{F_{O_2}}{B^2} \exp\frac{-8000}{T}$
17.	$O_2 + O(s) + C(b) \rightarrow CO + O_2 + (s)$	$k_{ox2}[O_2][O(s)]$	$\frac{F_{O_2}}{B} * 100 * \exp\frac{-4000}{T}$
18.	$O_2 + O(s) + C(b) \rightarrow CO_2 + O + (s)$	$k_{ox3}[O_2][O(s)]$	$\frac{F_{O_2}}{B} \exp\frac{-500}{T}$
19.	$O_2 + 2(s) \rightarrow 2O^*(s)$	$k_{ox4}[O_2][(s)]^2$	$\frac{F_{O_2}}{B^2} \exp\frac{-8000}{T}$
20.	$O_2 + O^*(s) + C(b) \rightarrow CO + O_2 + (s)$	$k_{ox5}[O_2][O^*(s)]$	$\frac{F_{O_2}}{B} * 1000 * \exp\frac{-4000}{T}$

* Kinetics are based on Minton et al. molecular beam data

How Can we Inform Ablation Modeling?

Notable Quotes on Persistent Modeling Gaps (Candler et al. 2017)

- "The study … show[s] that **standard ablation modeling approaches very likely overestimate carbon oxidation rates and are highly inaccurate** regarding the chemical species that evolve from the surface"
- "The **modeling of gas–surface interactions at conditions relevant to reentry flows is still rather ad hoc** and is largely based on empirical data to develop phenomenological models"
- "**Detailed measurements of ablation products under well-controlled conditions are [still] required** to identify and correct specific deficiencies in these models"



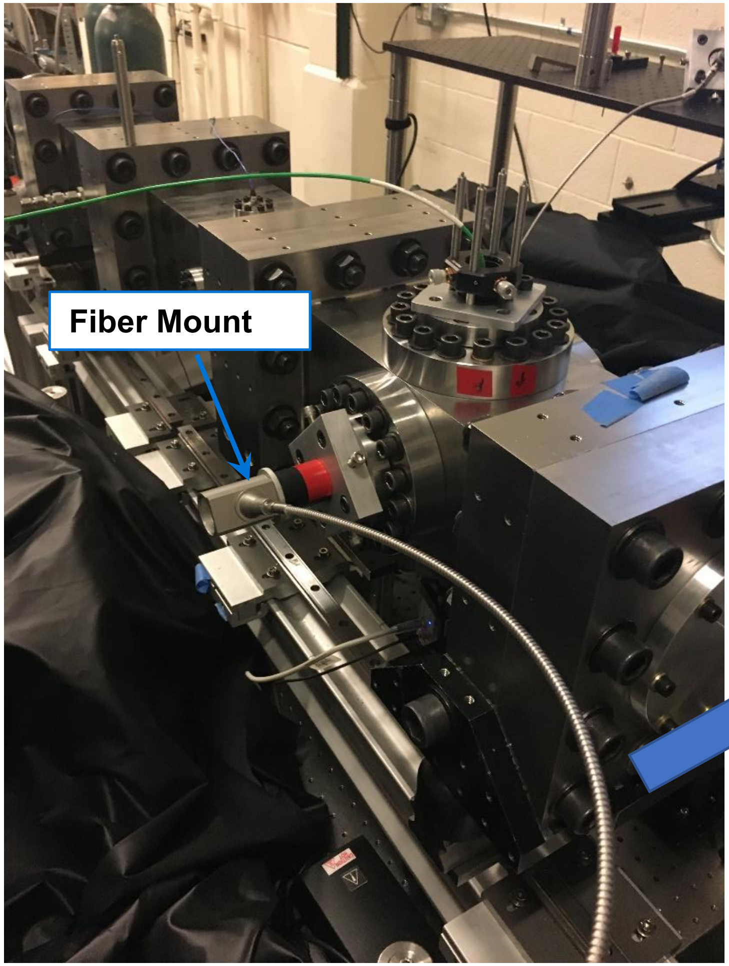
Where we Fit in

- We can make ***quantitative measurements of thermochemistry in the shock layer.***
  - Measure of dissociation and formation of the atomic oxygen responsible for surface oxidation reactions
- We also plan to ***measure species concentration and temperature of ablation products within the boundary layer.***

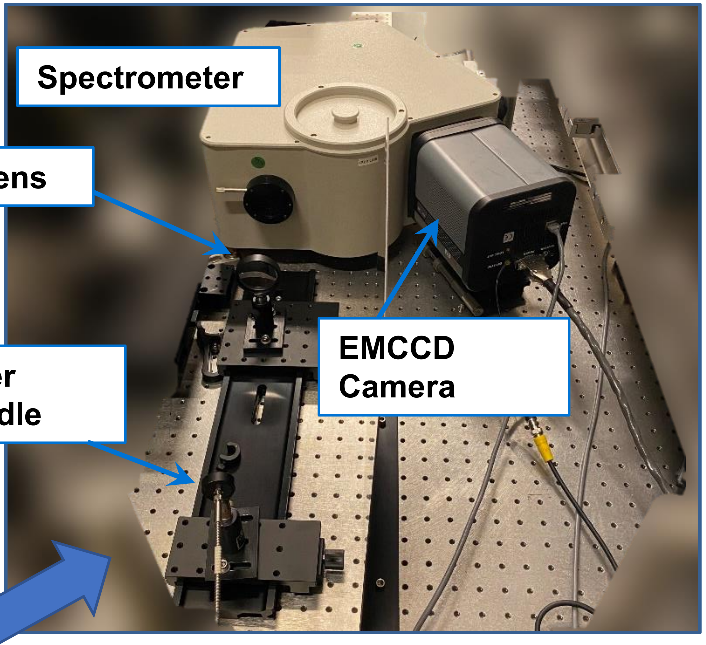
Emission spectroscopy, laser absorption spectroscopy and Raman scattering diagnostics will be utilized to address modeling gaps.

High-Speed Optical Emission Spectroscopy in the HST

Light Collection in the Test Section



High-Resolution Spectrometer



- Highly sensitive, low-noise, electron multiplied CCD (EMCCD) detector
- Max frame rate = 400 kHz, Spectral resolution ≈ 0.1 nm

High-speed emission spectroscopy measures formation of species most critical to hypersonic air chemistry and subsequent surface chemistry.

Emission Spectroscopy Following a **Mach 19 Shock**

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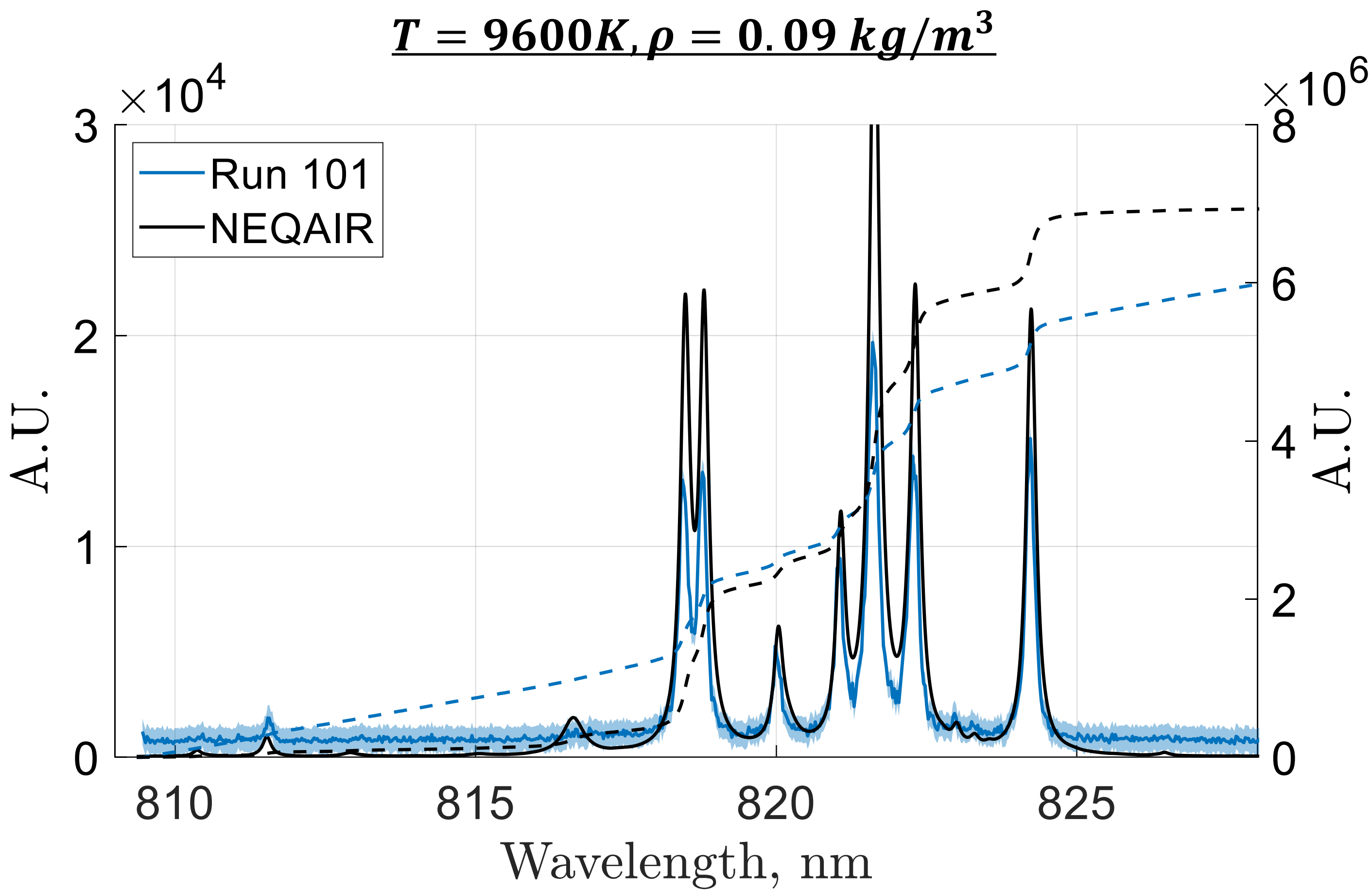
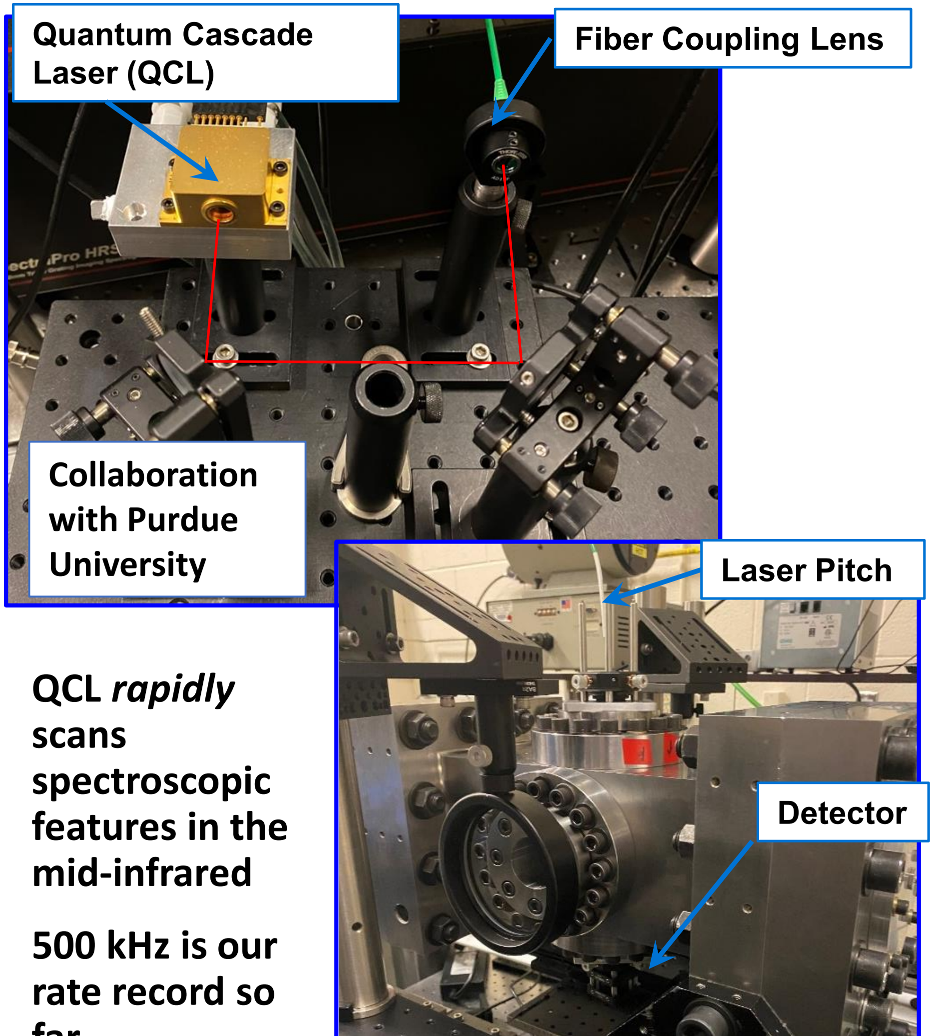


Detecting O and N is a step in the right direction, but we really need more quantitative measures of gas chemistry.

- Measurements are compared to NASA's NEQAIR code, which is used for heat shield design
- Relative emission so far. Plans for absolute (calibrated) data
- Measurements at 100 kHz
- **Lines are atomic nitrogen and atomic oxygen (N and O)**
- **Future work will focus on atomic O concentration measurements**

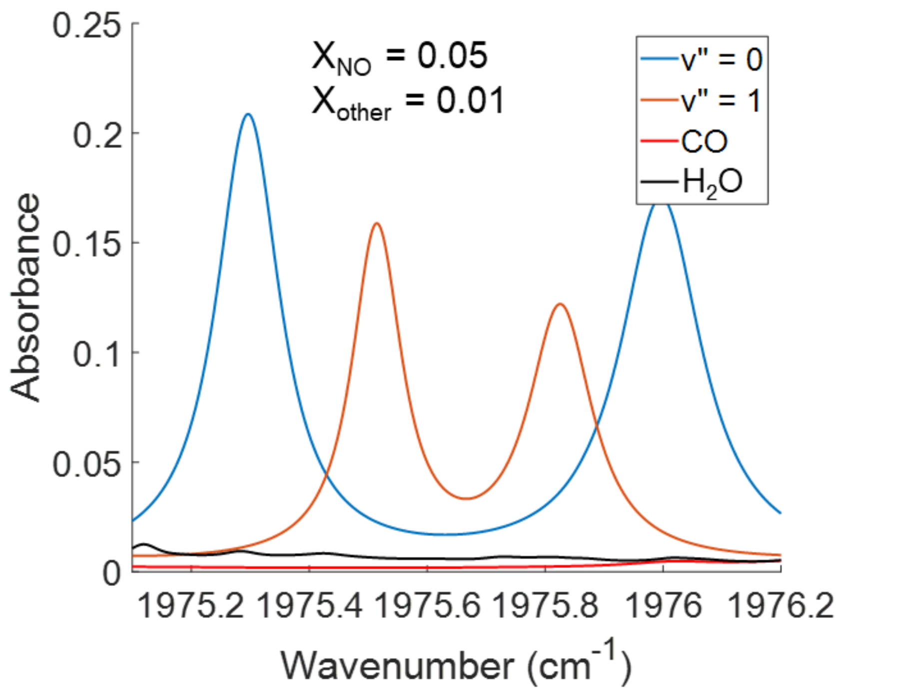
Laser Absorption Spectroscopy in the HST

Fast-Scanning Laser used in HST



- QCL *rapidly* scans spectroscopic features in the mid-infrared
- 500 kHz is our rate record so far…

Modeled Absorption at T = 4000 K



- Here we target nitric oxide (NO)
- Temperature and species concentration is determined by fitting measured spectra to modeled absorption features.

LAS provides fast & accurate measures of chemistry behind shock waves.

Thermochemistry in the HST (Nitric Oxide Example)

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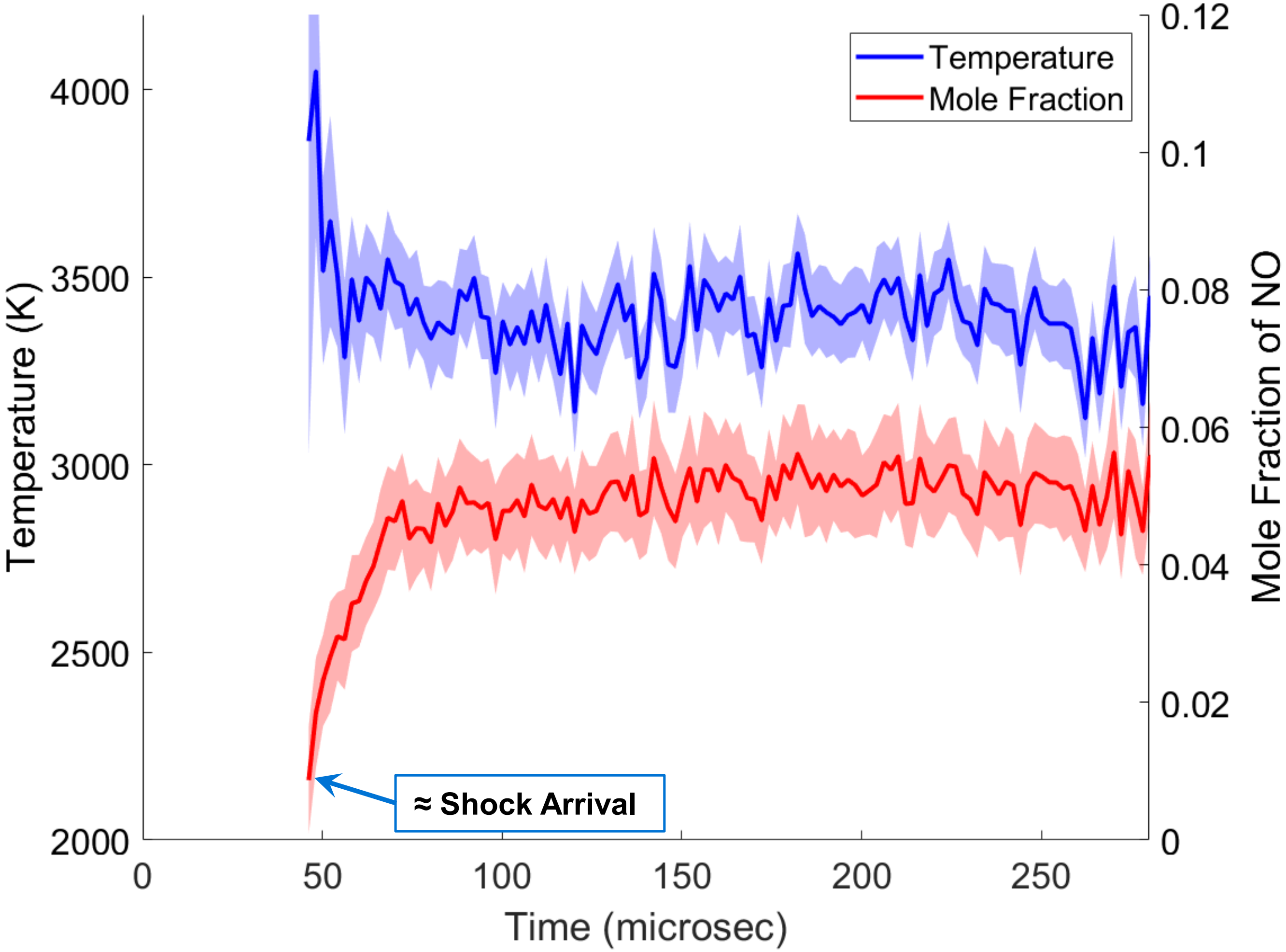
500-kHz Measurements of NO Vibrational Temperature and Concentration

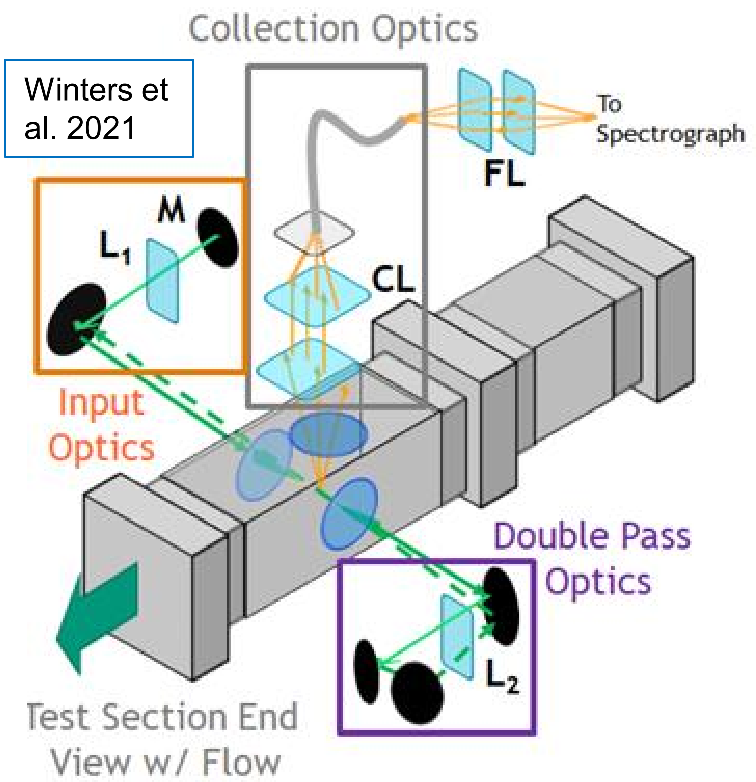


- Temperature cools as NO forms during this endothermic reaction
- Nitric oxide thermochemistry behind hypersonic shock waves is an ongoing area of research
- **Data like these inform chemistry models for air behind strong shock waves**

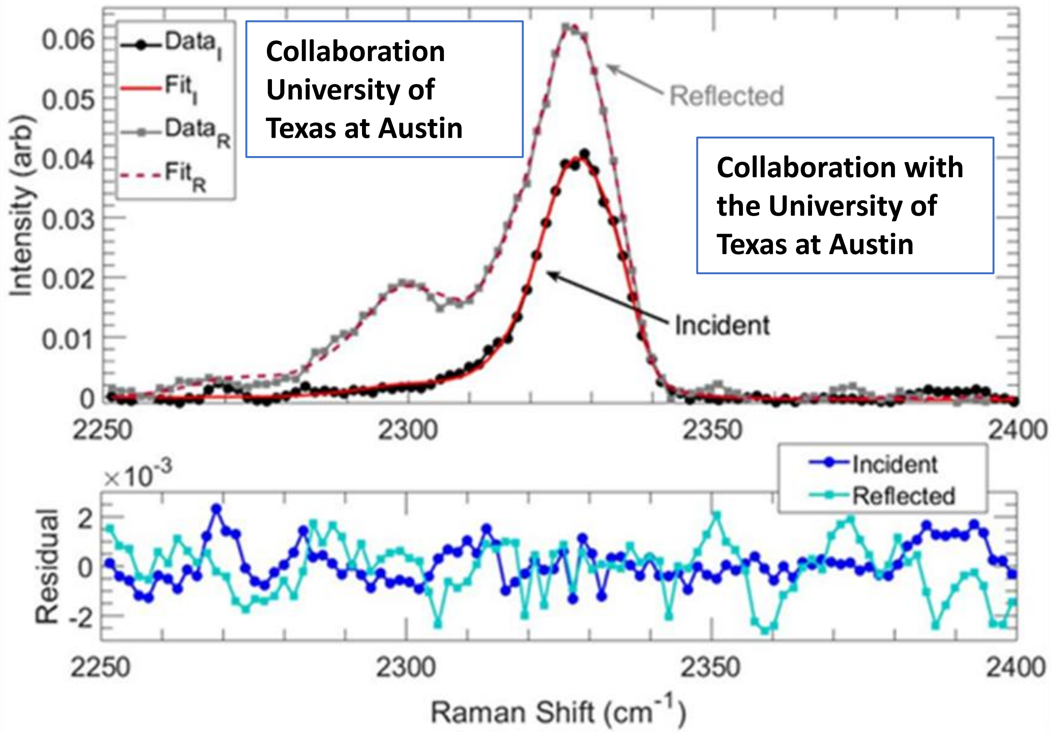
Our TPS project will also focus on carbon ablation products (i.e., CO) to quantify surface chemistry reactions

Raman Scattering Methods for N_2 Measurements in HST

Raman-Scattering Configuration in HST



Measured and Modeled Vibrational Raman Spectra



- We make high-speed, laser-based Raman scattering measurement using a pulse-burst laser.
- **Fits of measured Raman spectra provide the vibrational temperature of homonuclear molecular species**

Raman-based measurements gives us access to other important molecules like O_2 and N_2

Example Vibrational Raman Spectroscopy Measurements in HST

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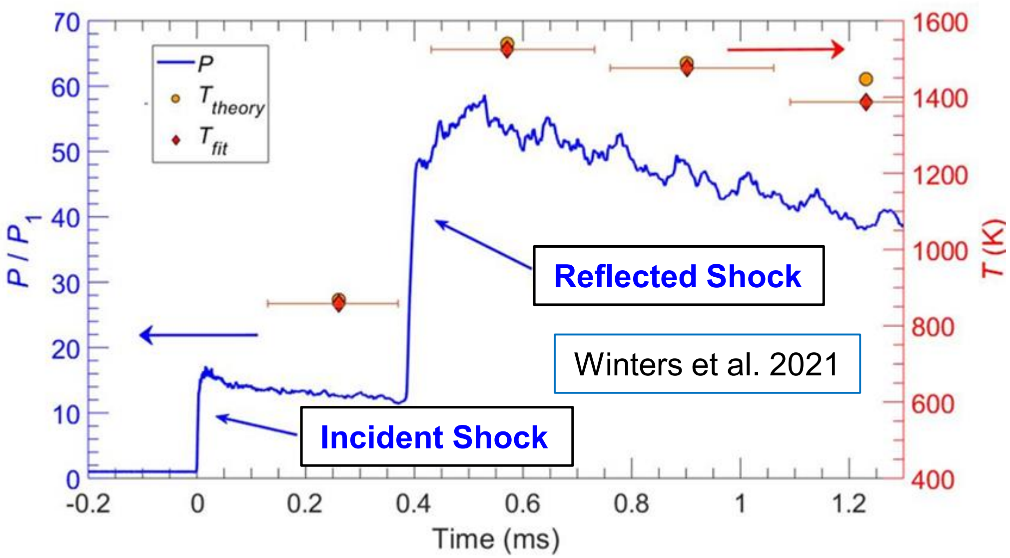
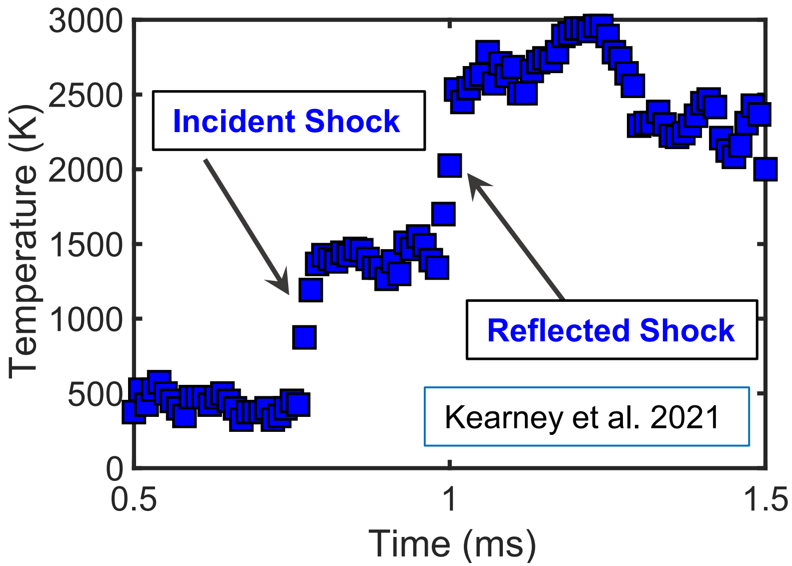
3-kHz Raman Thermometry Measurements Behind Incident and Reflected Shocks



- **Vibrational Raman scattering thermometry provides a very accurate measure of molecular vibrational temperatures.**
- Challenge here is that Raman scattering is very weak and therefore can be overwhelmed by optical emission.

100-kHz Coherent Anti-Stokes Raman Scattering (CARS) Thermometry

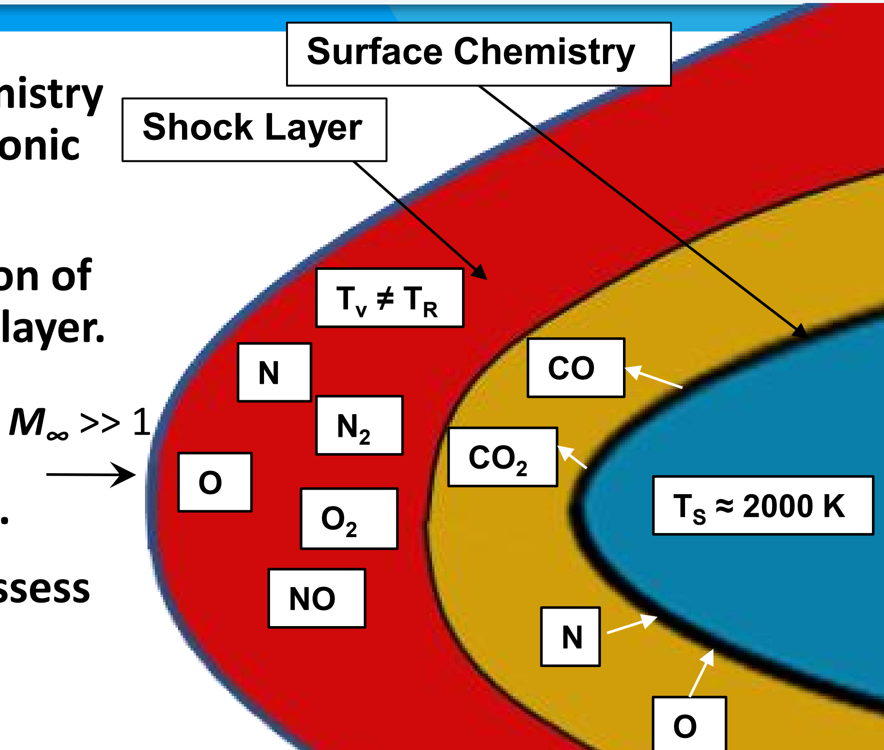


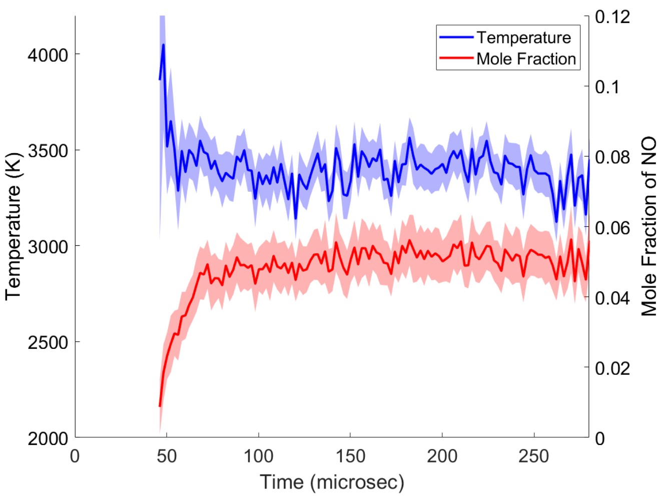
- CARS provides a coherent signal, which is much stronger than Raman scattering.
- **CARS thermometry offers potential to go to high-repetition-rates while overcoming optical emission. Challenge right now is measurement noise, but we have a fix.**

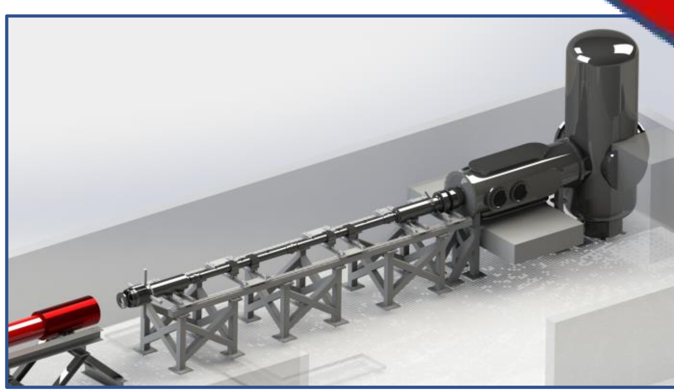
Vibrational relaxation of N_2, O_2 is important across shocks. Additionally, desorption of atomic N from reactive surfaces can lead to vibrationally excited N_2 within the flow.

Summary

- **We will replicate the air-carbon ablation chemistry found in flight with high-temperature, hypersonic flow and an electrically preheated surface**
- **Measurement diagnostics will capture diffusion of oxidation products like CO into the boundary layer.**
- **We will measure air thermochemistry and species formation behind strong shock waves as this is critical to surface interactions.**
- **This experimental campaign will be used to assess existing air-carbon ablation models**







Acknowledgments / Questions

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Do you have any questions?