Shock Interactions in Nonequilibrium Hypersonic Flows

Andy Swantek and Joanna M Austin
Department of Aerospace Engineering
University of Illinois at Urbana-Champaign

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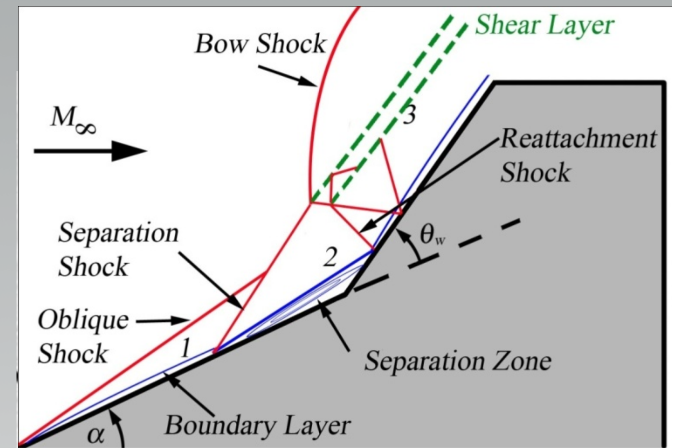
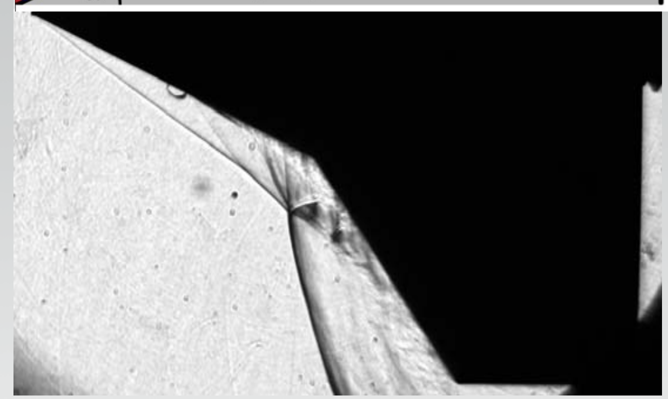
Experiments with "Tunable" Freestream

- Double cone/wedge flows are a sensitive model problem for thermochemical modeling validation.
- Significant work both experimentally and computationally has been performed (Olejniczak *et al.* (1999); Wright *et al.* (2000); Nompelis *et al* (2003, 2005, 2010)).
- *State-of-the-art* simulations and experiments show poor agreement in high enthalpy (≥ 5MJ/kg) air flows, in spite of good agreement at lower enthalpies and in N_2
- Outstanding questions: freestream characterization, flow steadiness. thermochemistry.





A novel method of gas acceleration that minimizes free stream dissociation while producing a broad range of hypervelocity flows. Turn on/off the thermochemistry:

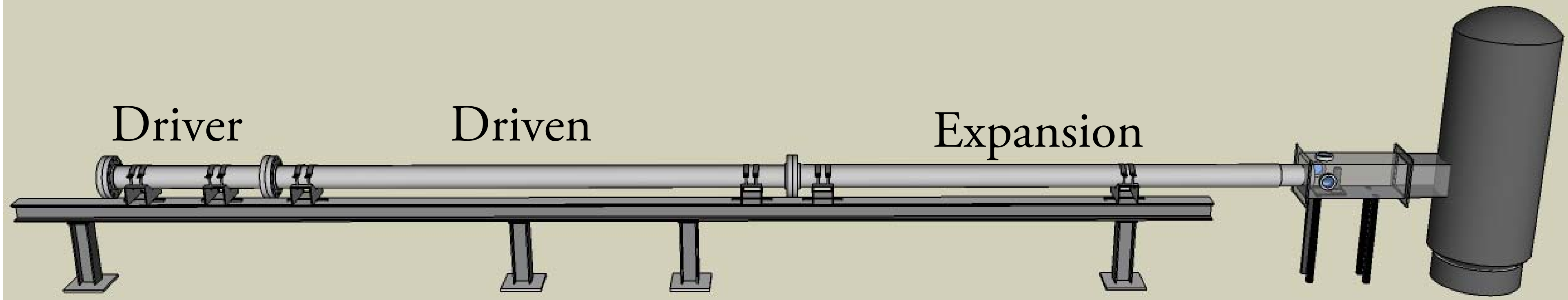
1) **N2 to air while maintaining Mach and Ho**
2) **Low enthalpy to high.**

Quantify the response of viscous and inviscid flow features

Hypervelocity Expansion Tube (HET)

- 152 mm ID, 9.14m length impulse facility
- Mach Numbers from 3-7.5
- Stagnation enthalpies from 2-9 MJ/kg
- Test times from 100 μs to 500 μs

Dufrene, Sharma, Austin 2007



- Diagnostic capabilities
  - Pressure Measurements
  - **Schlieren** (single frame & **high speed)**
  - **Heat transfer measurements**
    - Coaxial thermocouple
    - Platinum thin film gauges
  - **Emission spectroscopy**
  - Pressure Sensitive Paint

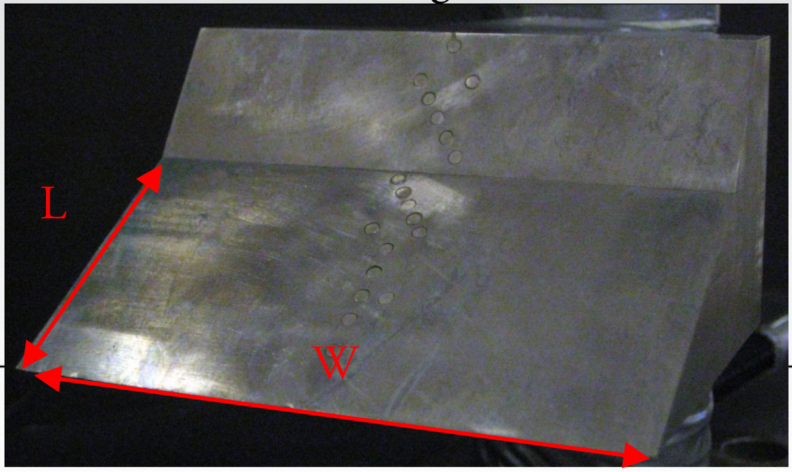
Test Conditions and Models

- Air can be replaced with N_2 and yields nearly the same freestream conditions.
- Two different model geometries are used.

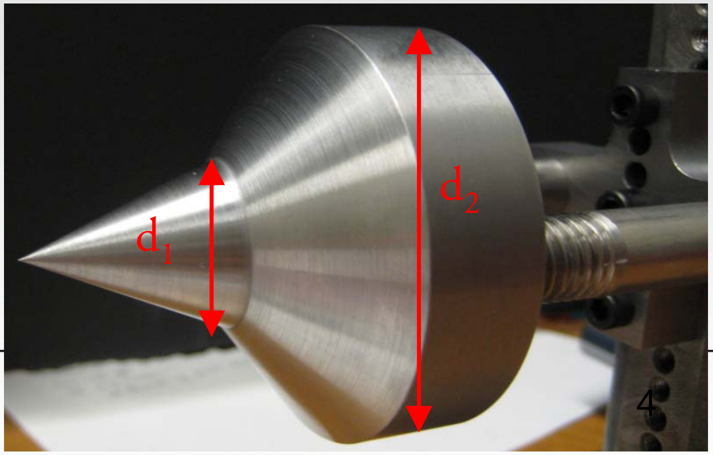
Run Condition	M	h_0 MJ/kg	T, K	P, kPa	ρ, kg/m^3	u, km/s	Re/m *10^{-6}
M7_8	7.14	**8.0**	710	0.78	0.0038	3.81	**0.44**
M5_4	5.12	**4.2**	676	8.2	0.042	2.67	**3.47**
M4_3.6	3.95	**3.6**	862	19	0.077	2.33	**4.73**
M7_2.2	7.11	**2.1**	191	0.39	0.0071	1.97	**1.10**

- 25°-55° cone
  - Widely studied
  - Second angle allows for standoff sho
- 30°-55° wedge
  - Scale model of Davis and Sturtevan wedge
  - 2D configuration allows for exceptional visualization

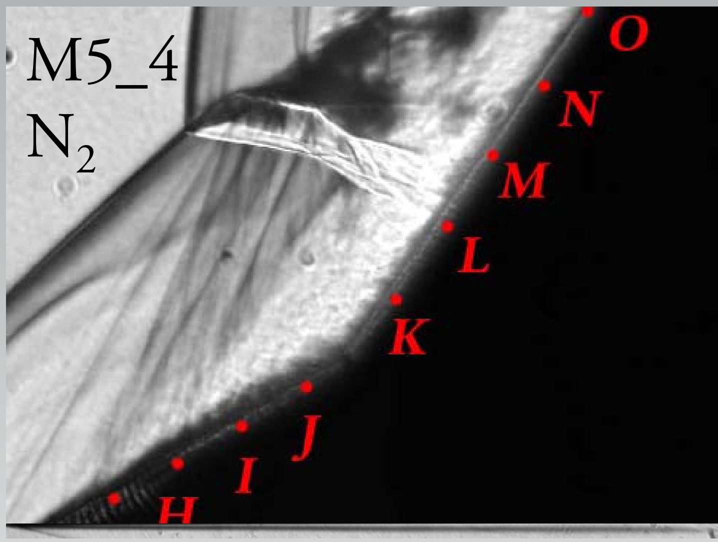
30-55 Double Wedge L=2”, b=4”

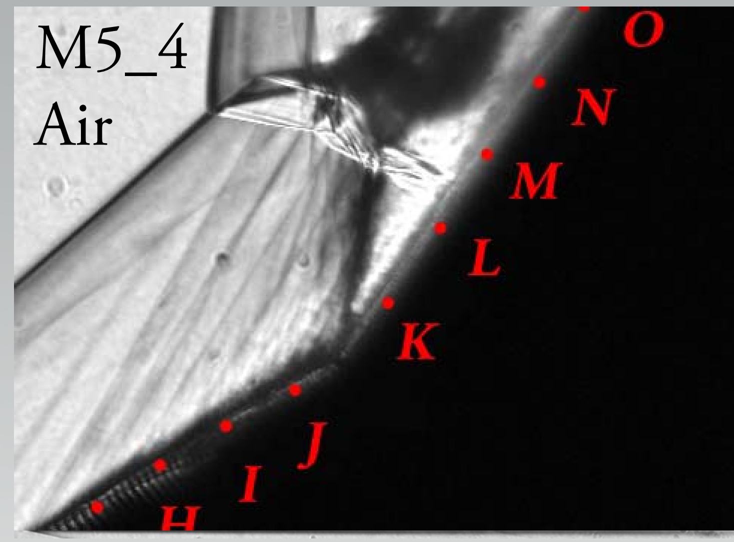


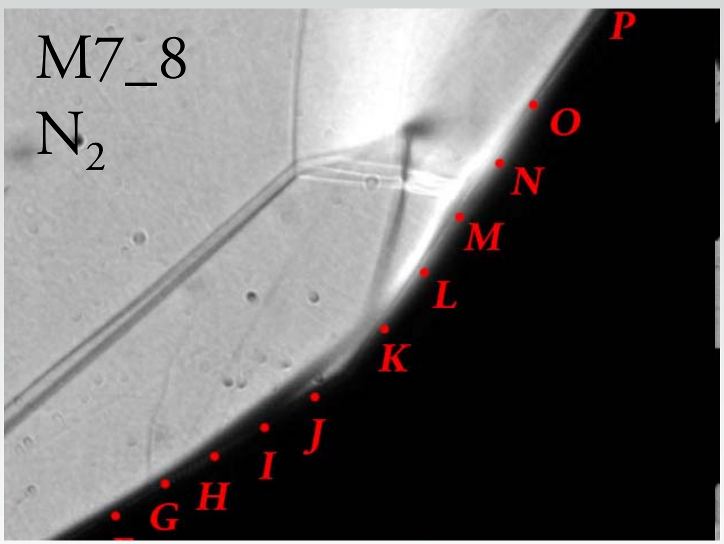
25-55 Double Cone d_1=0.984”, d_2=2.5”

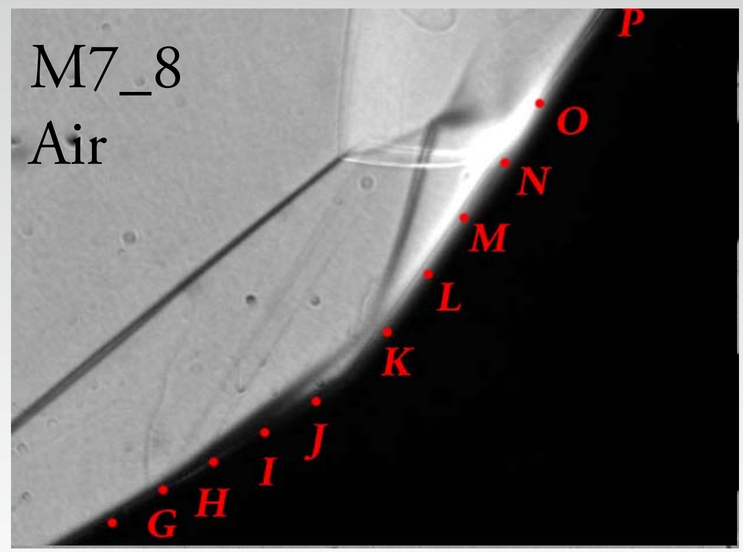


Air/N_2 Comparison





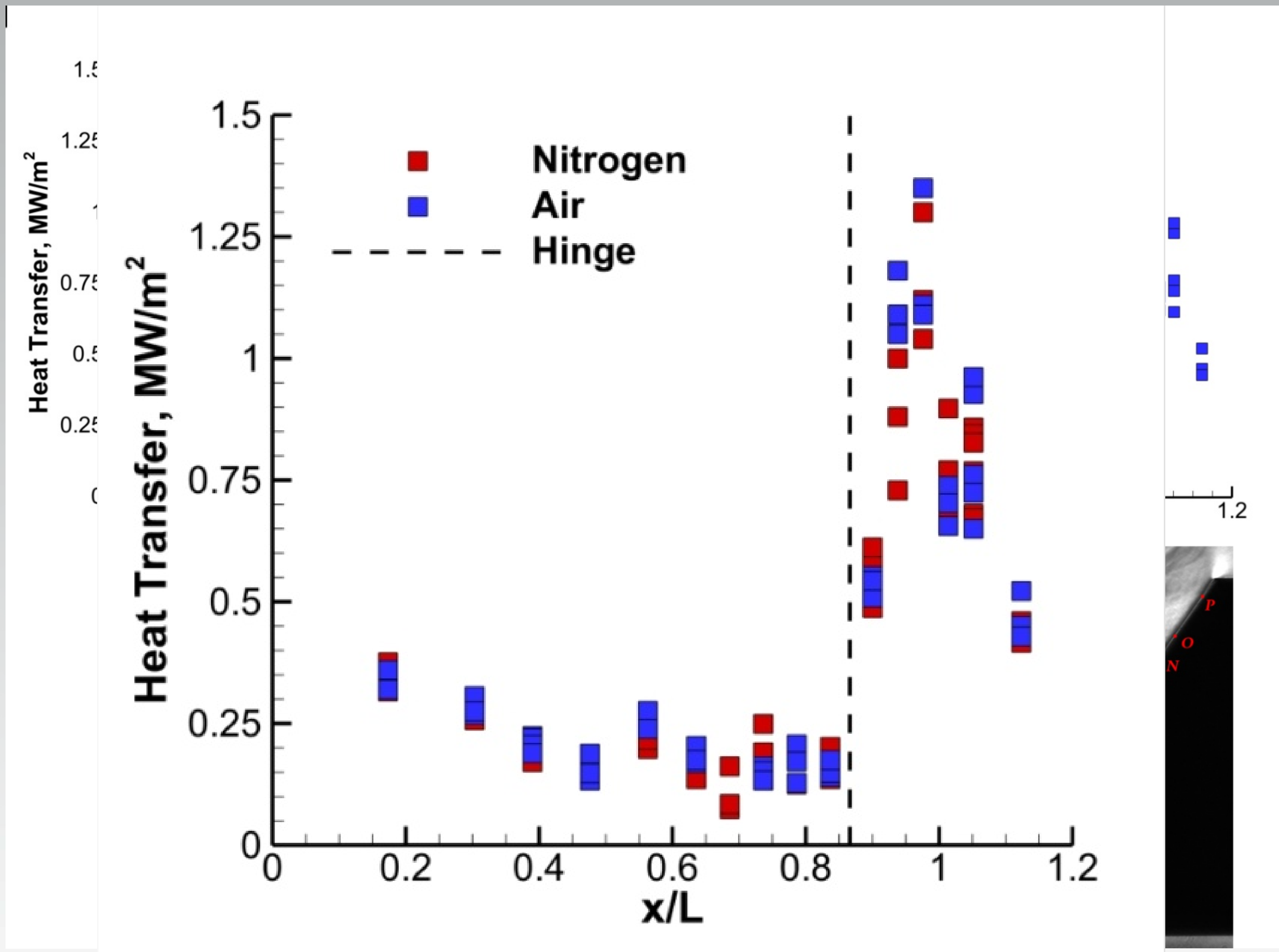




Mean Surface Heat Transfer – 2MJ/kg

Mach 7

(M7_2)



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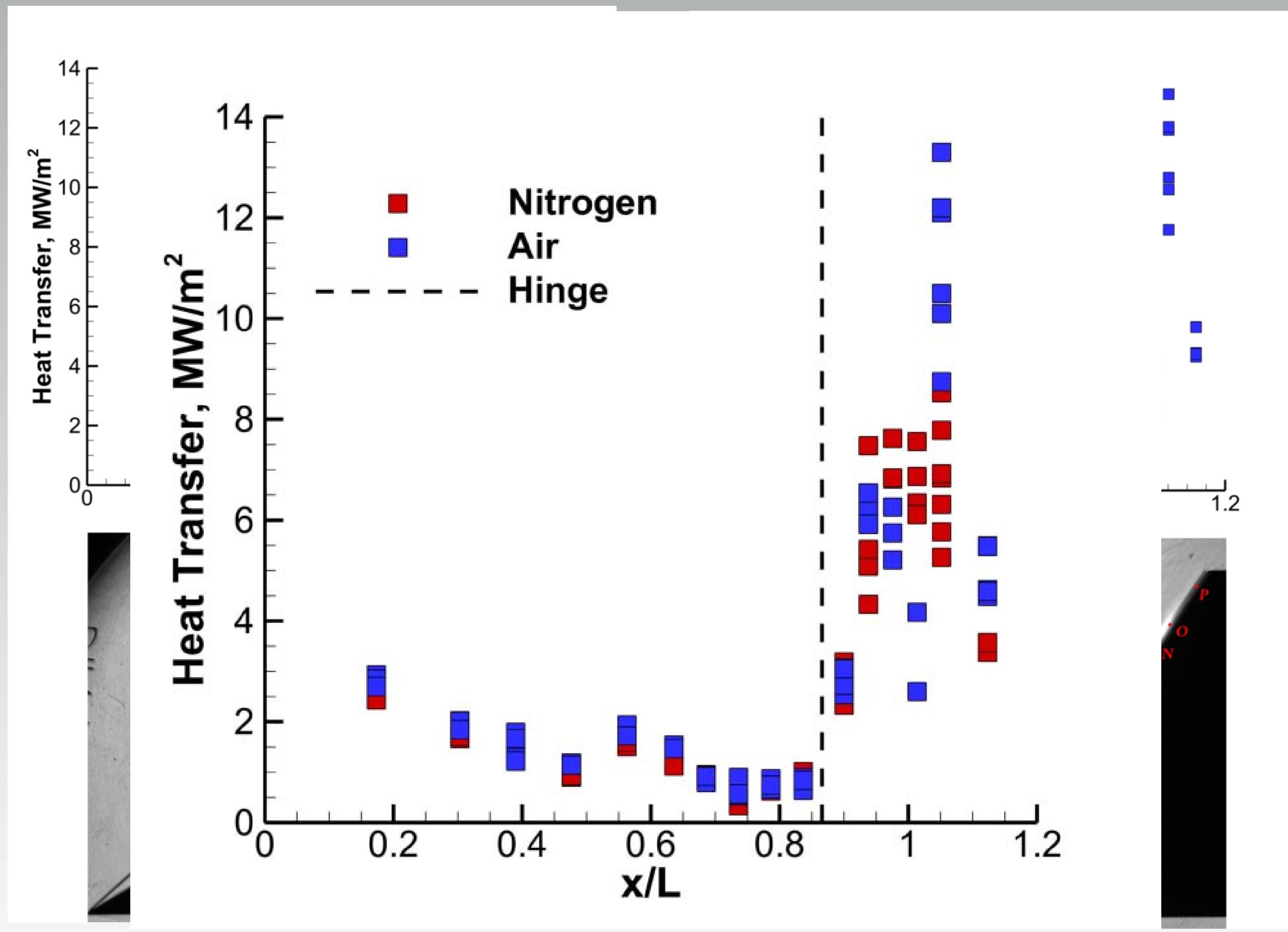
Mean Surface Heat Transfer – 8MJ/kg

Mach 7

(M7_8)



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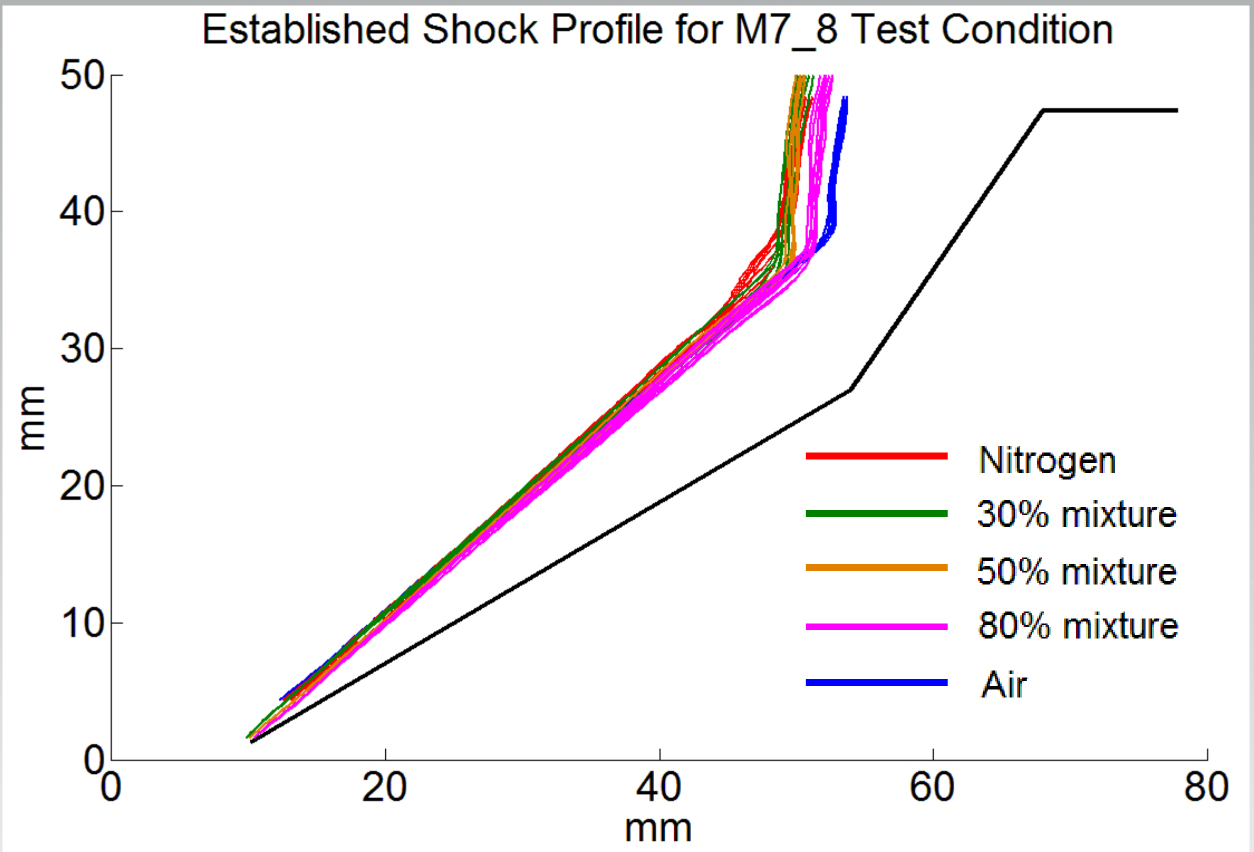
Boundary Tracing – Double Wedge

Composition Sweep
M7_8

Free stream composition is varied from pure nitrogen to atmospheric air.

Percentages indicate the freestream oxygen percentage compared to atmospheric air. Compositions below.



Equilibrium

Mixture	Freestream N_2	Freestream O_2	Post Shock N_2	Post Shock N	Post Shock O_2	Post Shock O	Post Shock NO	T, K
Nitrogen	1.000	0.000	9.330E-1	6.697E-2	-	-	-	5178
30%	0.926	0.074	8.404E-1	2.329E-2	3.250E-4	1.286E-1	7.343E-3	4754
50%	0.883	0.117	7.821E-1	8.755E-3	1.978E-3	1.924E-1	1.473E-2	4425
80%	0.825	0.175	7.057E-1	2.025E-3	1.474E-2	2.480E-1	2.949E-2	3990
Air	0.790	0.210	6.659E-1	1.082E-3	3.152E-2	2.639E-1	3.751E-2	3902

Dissociation Fraction

Mixture	f_{N_2}	f_{O_2}
Nitrogen	3.46	-
30%	1.79	99.5
50%	1.48	98.1
80%	2.18	90.4
Air	2.82	82.7

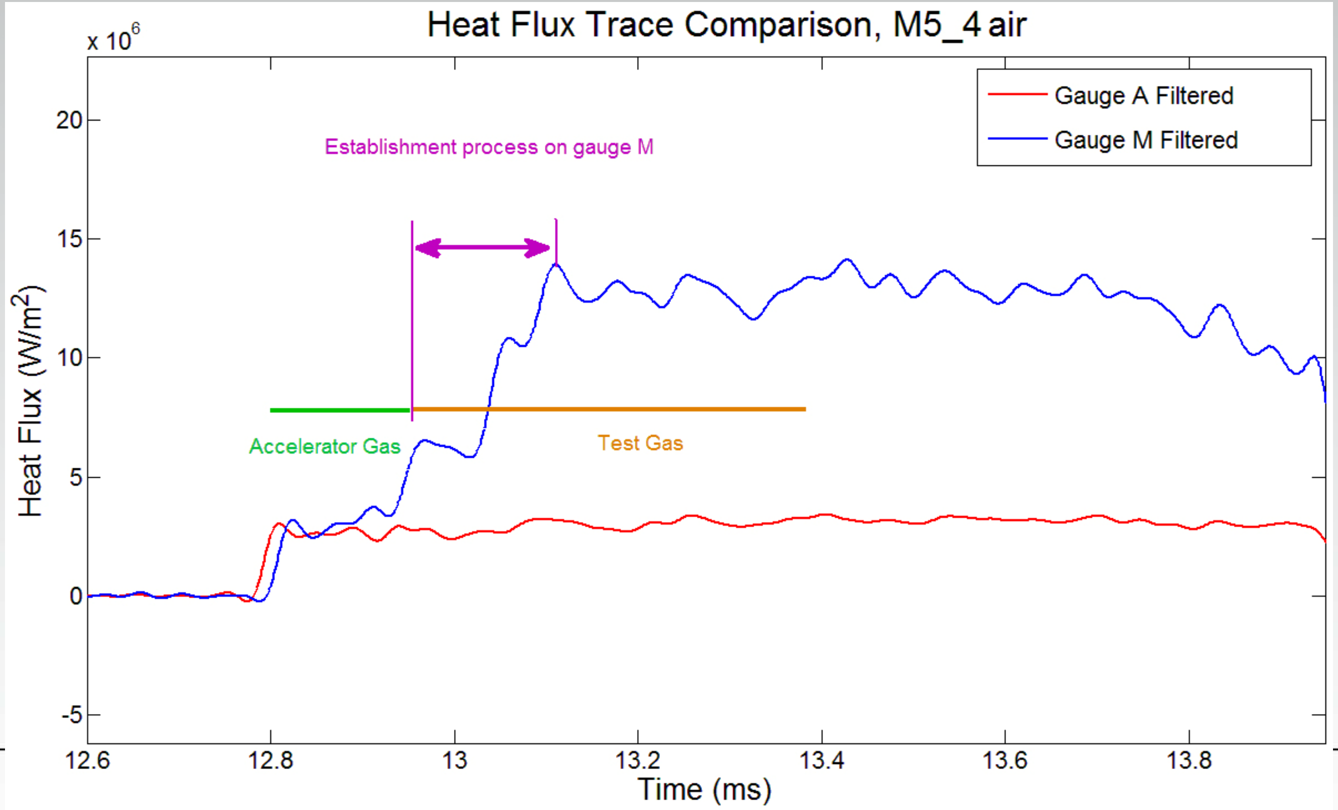
- Heat transfer & single-shot schlieren data for eight test cases
- Observable differences between N2 and Air heat transfer and shock configurations

- Flow field establishment and possible unsteadiness
- Combine flow visualization with direct measurements of chemical species and temperatures

Time-dependence: establishment & possible unsteadiness

Comparison of triple point/ shock configuration, heat transfer, and laminar flat plate boundary layer establishment times.

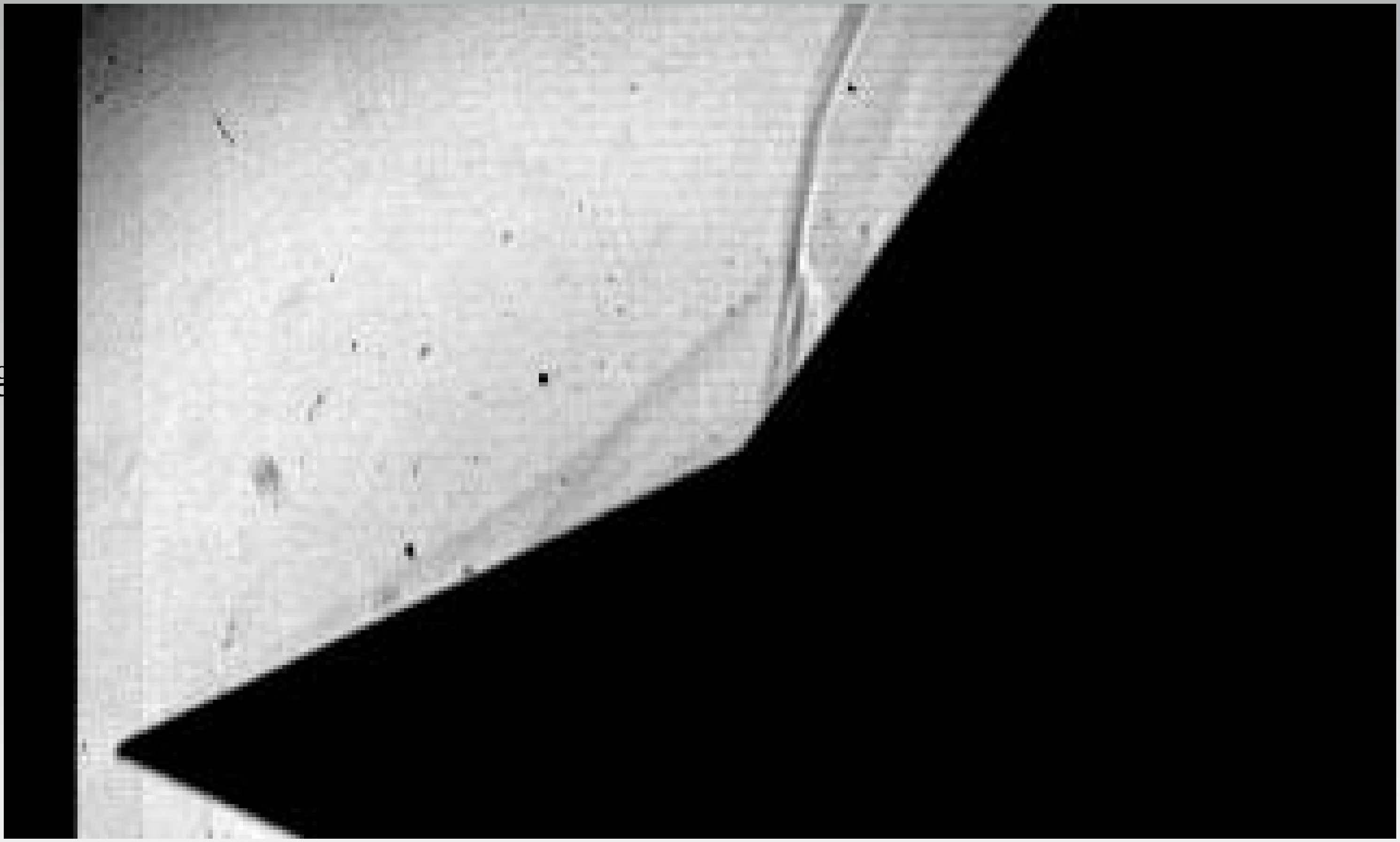
Times are scaled by the test conditions "flow time." Flow time is the time it takes for a freestream particle to traverse the model's surface. $t_{flow} = (L_1+L_2)/U_\infty$ for the wedge model



High Speed Imaging – Double Wedge

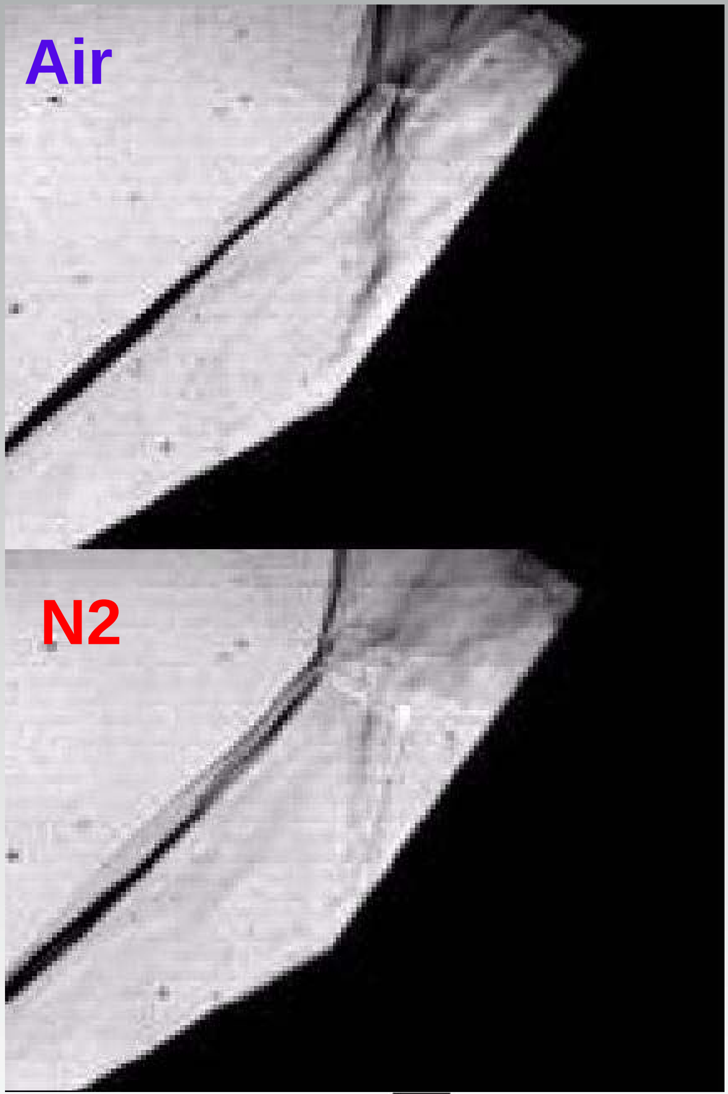
Double Wedge
M5_4, air
100,000 fps
7 fps playback
1μs exposure

(accelerator + test g



High Speed Imaging – Double Wedge

Double Wedge
M5_4
Top: Air
Bottom: N_2
100,000 fps
7 fps playback
1μs exposure
350μs test time



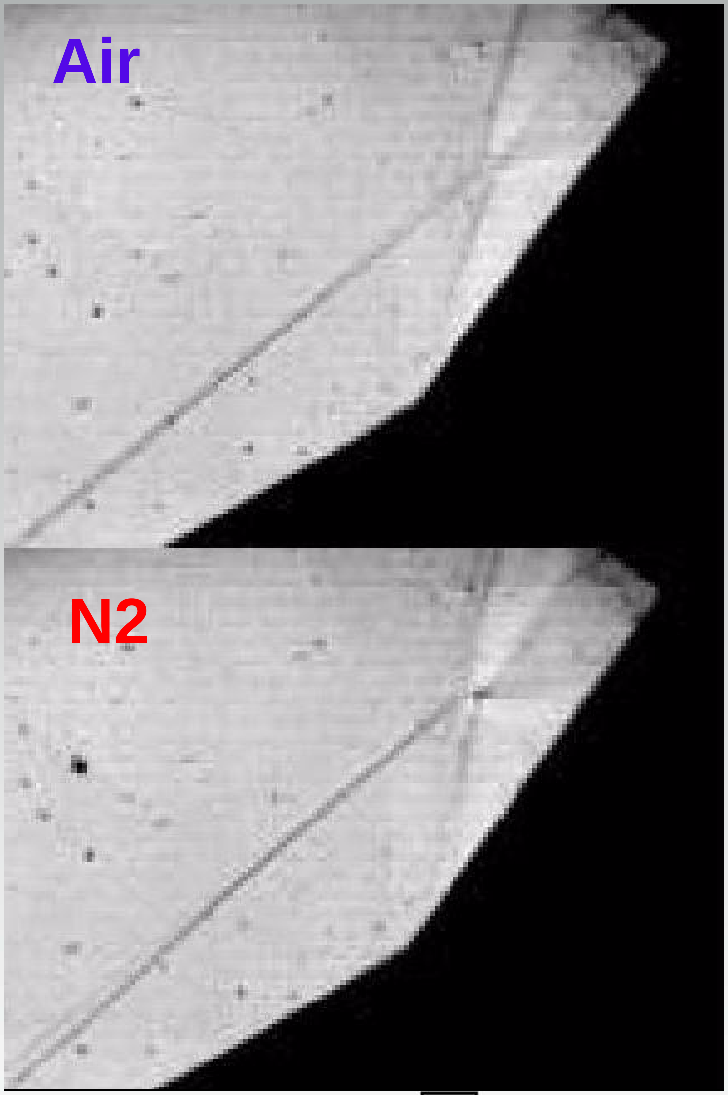
Notice the oblique shock in the corner of the model.

It breaks down in N_2 at 90 μs, while this doesn't occur until 250 μs in air.

The break down occurs over approximately 30 μs. This is an example of an unsteady flow feature.

High Speed Imaging – Double Wedge

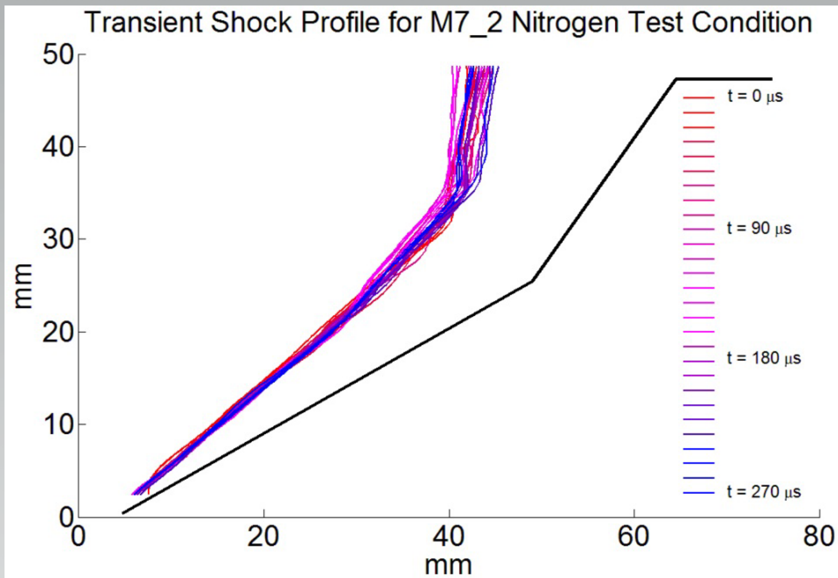
Double Wedge
M7_8
Top: Air
Bottom: N_2
100,000 fps
7 fps playback
1µs exposure
200 µs test time

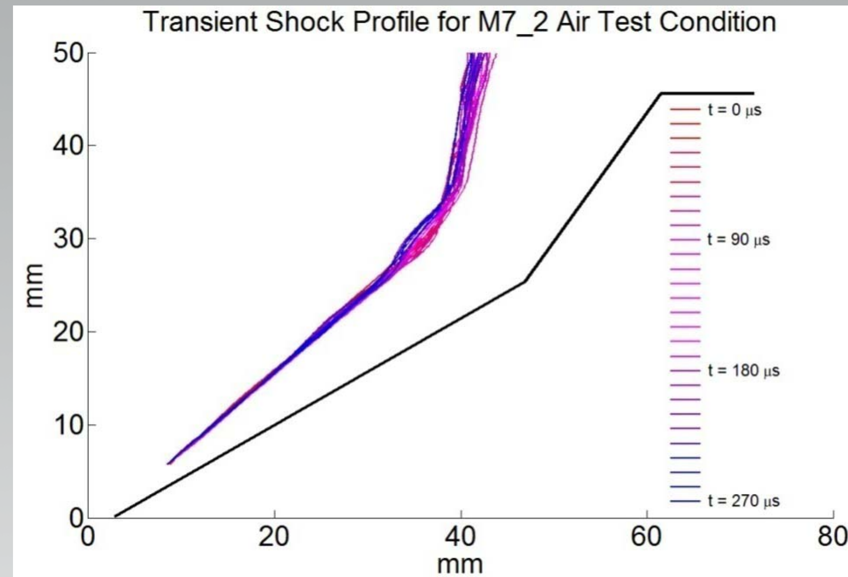


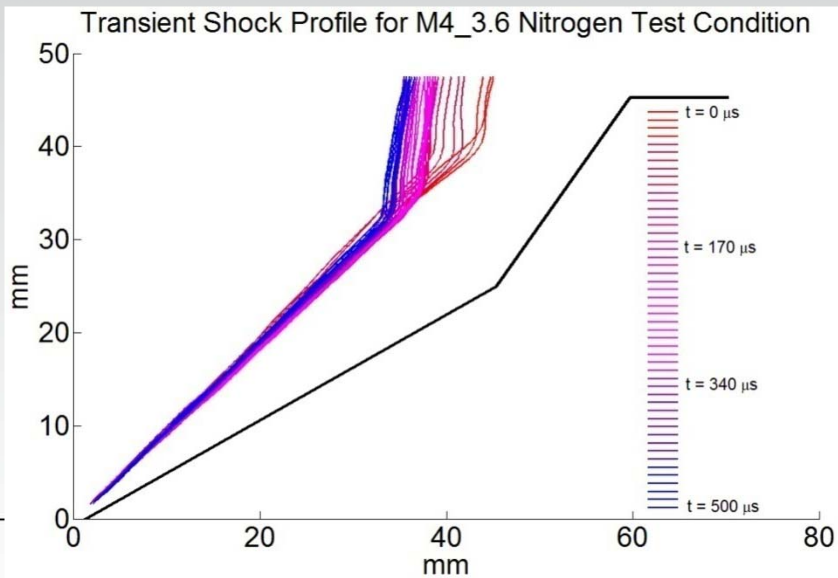
Nitrogen establishes faster than air.

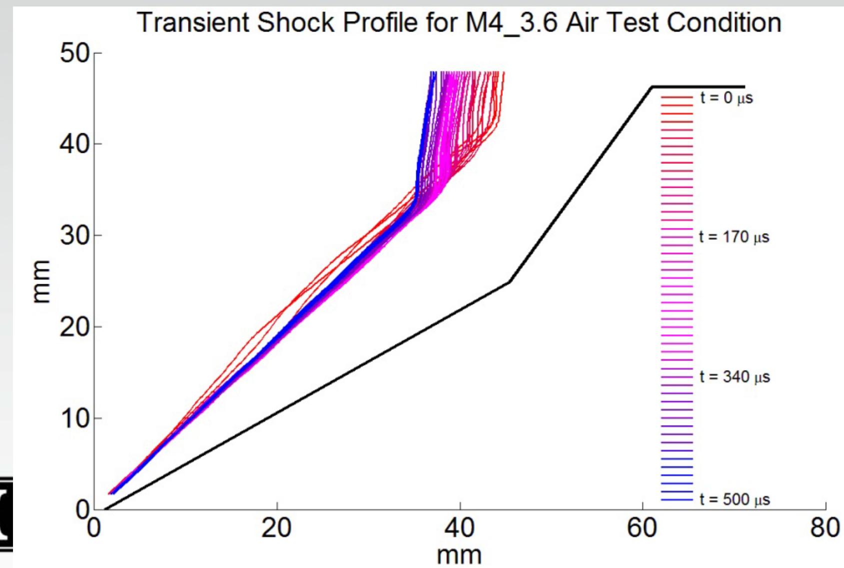
Additionally, the final shock configuration is different.

Boundary Tracing – Double Wedge

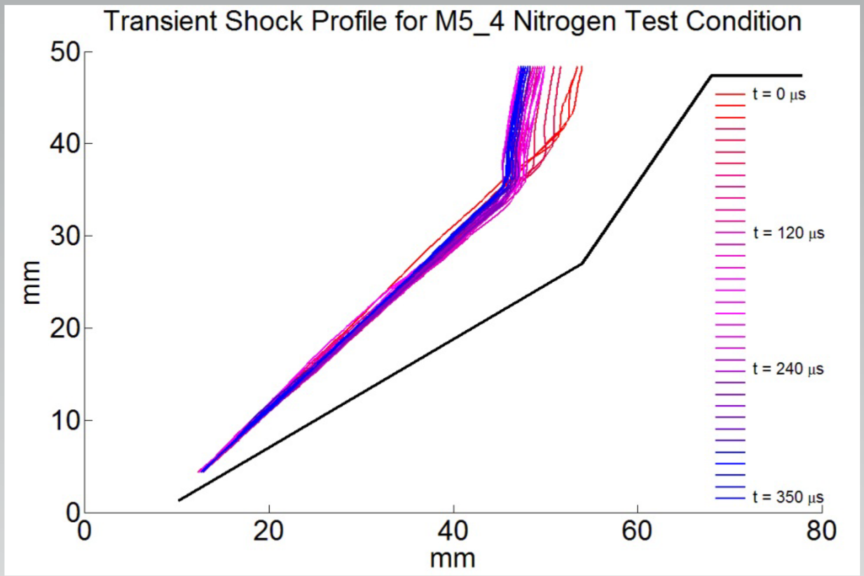


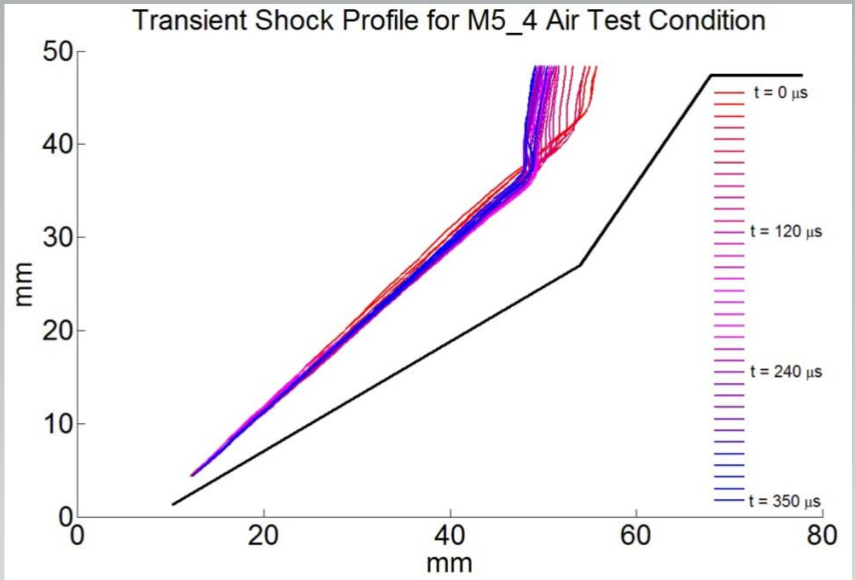


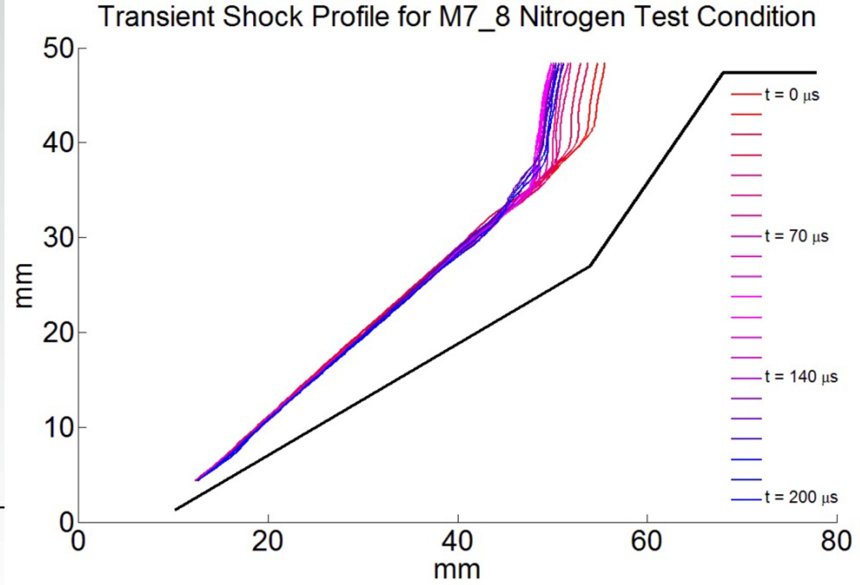


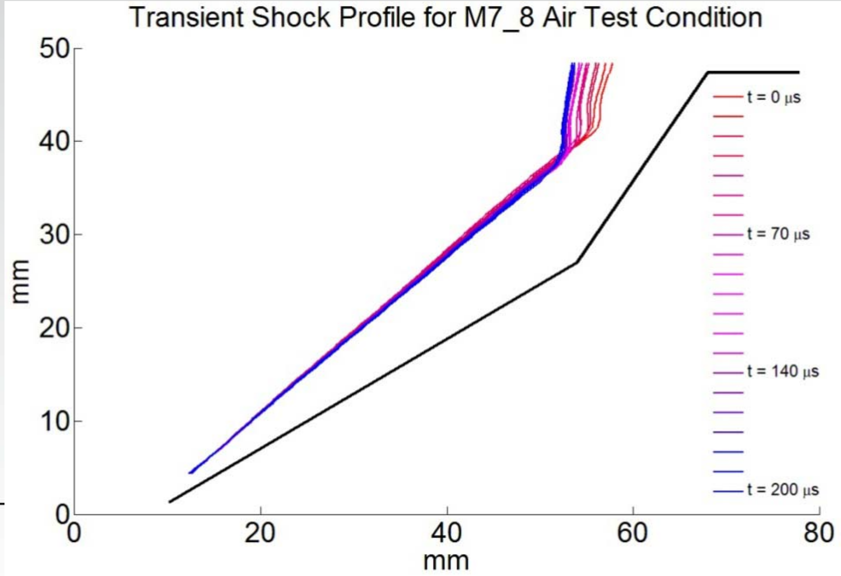


Boundary Tracing – Double Wedge



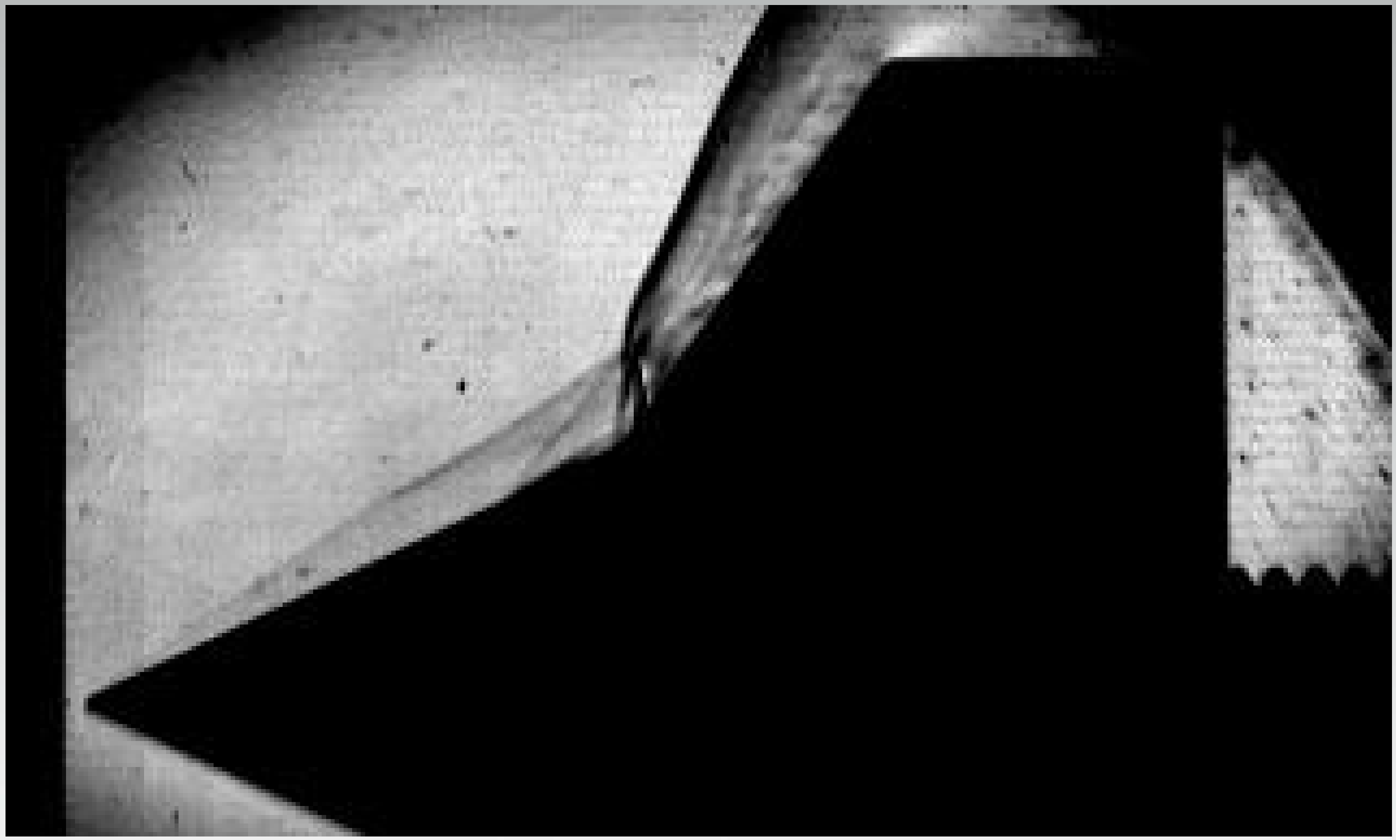






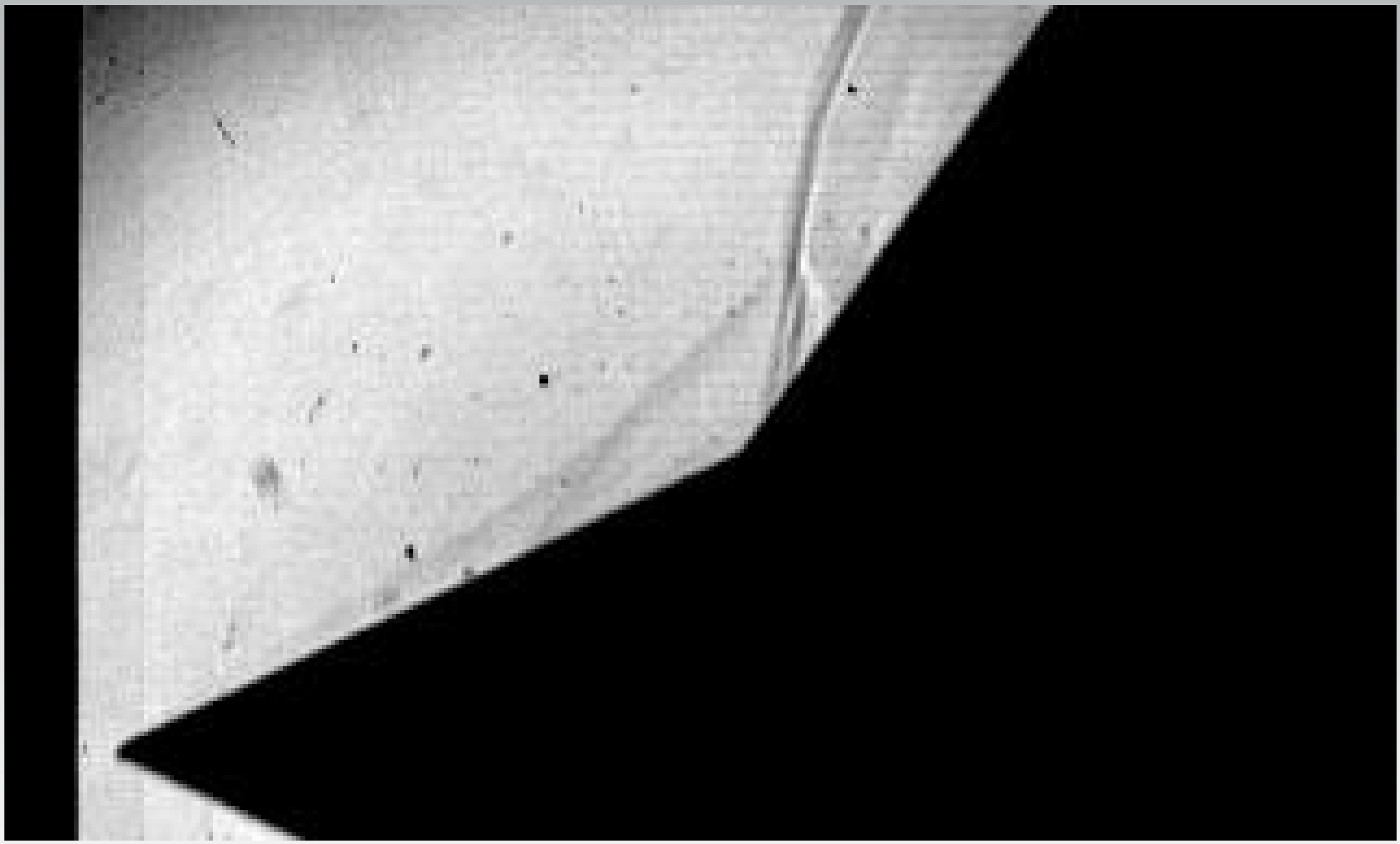
High Speed Imaging – Double Cone

Double Cone
M4_3, Air
100,000 fps
7 fps playback
1μs exposure



High Speed Imaging – Double Cone

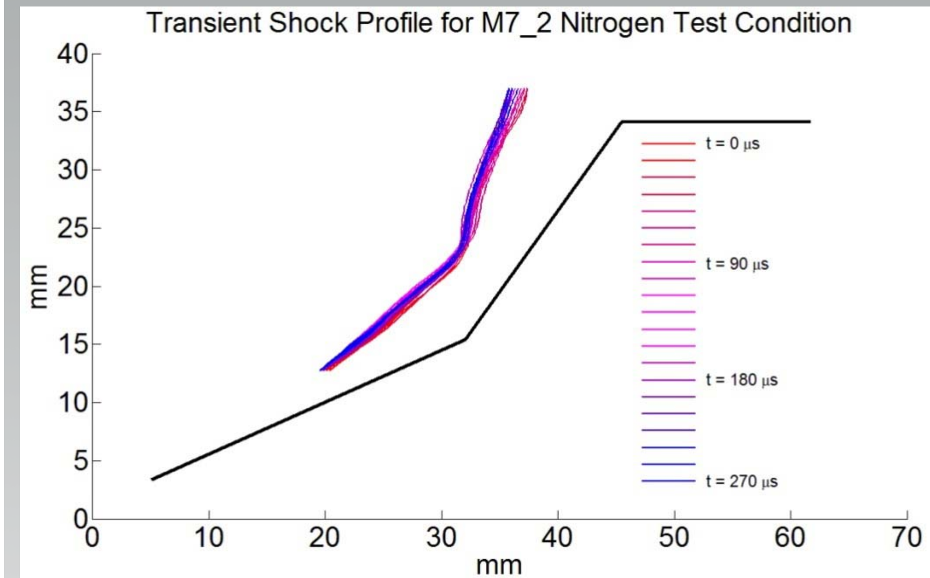
Double Cone
M5_4, Air
100,000 fps
7 fps playback
1μs exposure

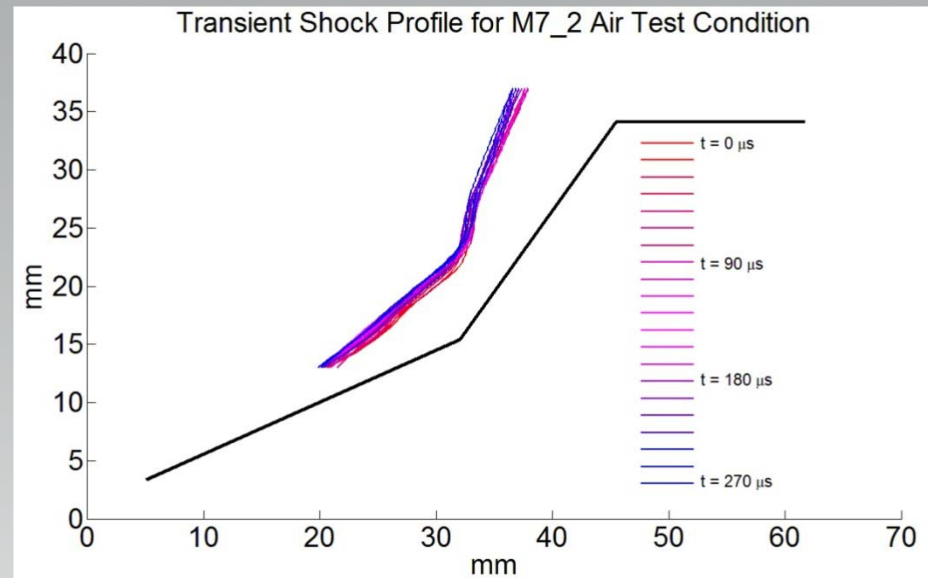


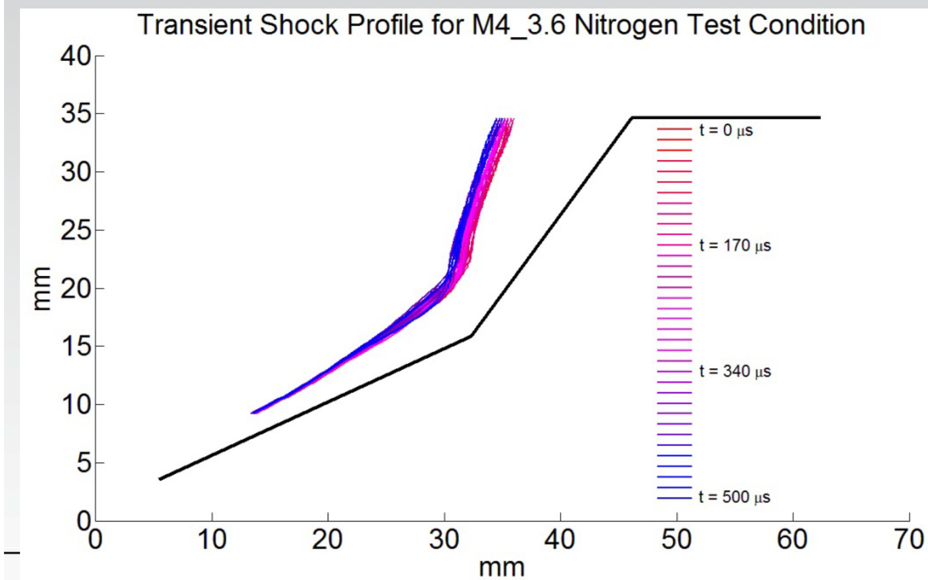
High Speed Imaging – Double Cone

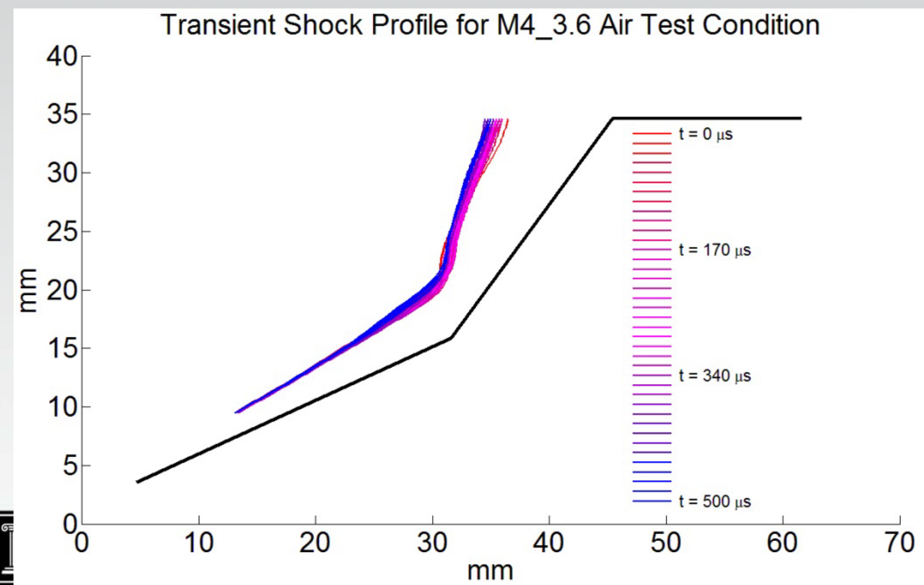
Double Cone
M7_8, Air
100,000 fps
7 fps playback
10μs exposure

Boundary Tracing – Double Cone

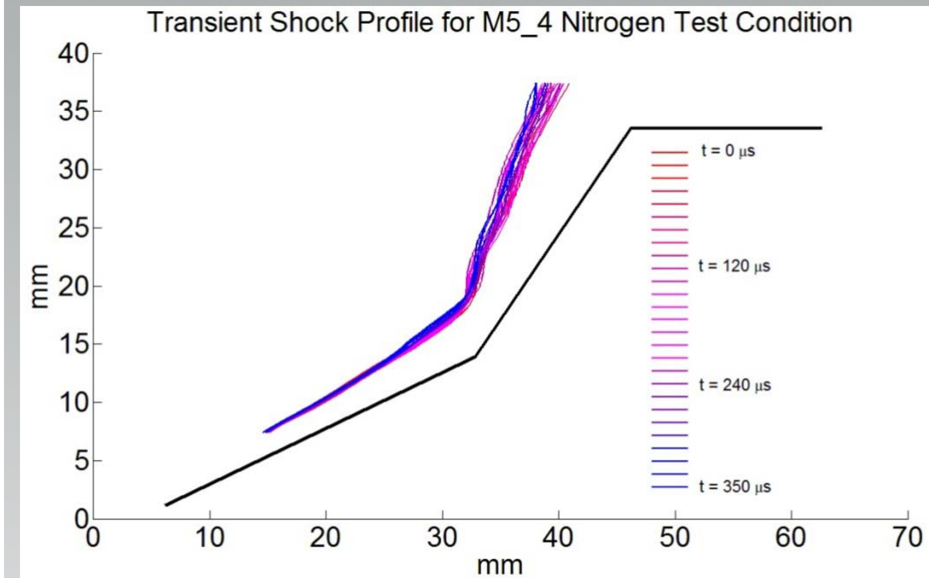


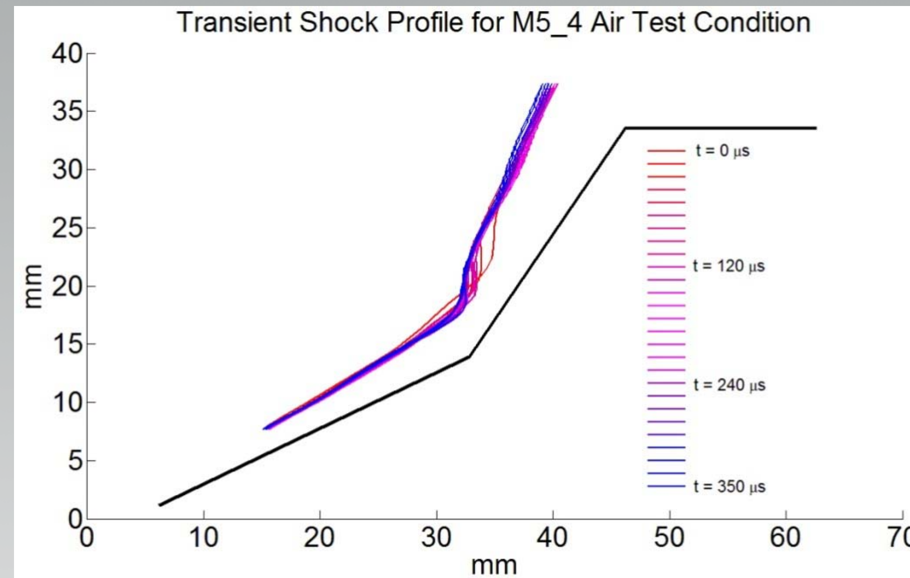


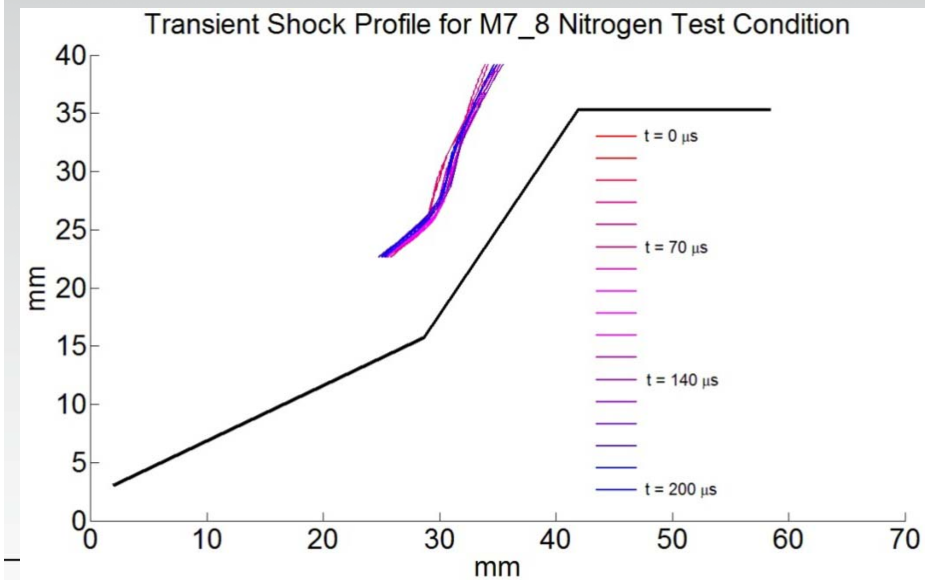


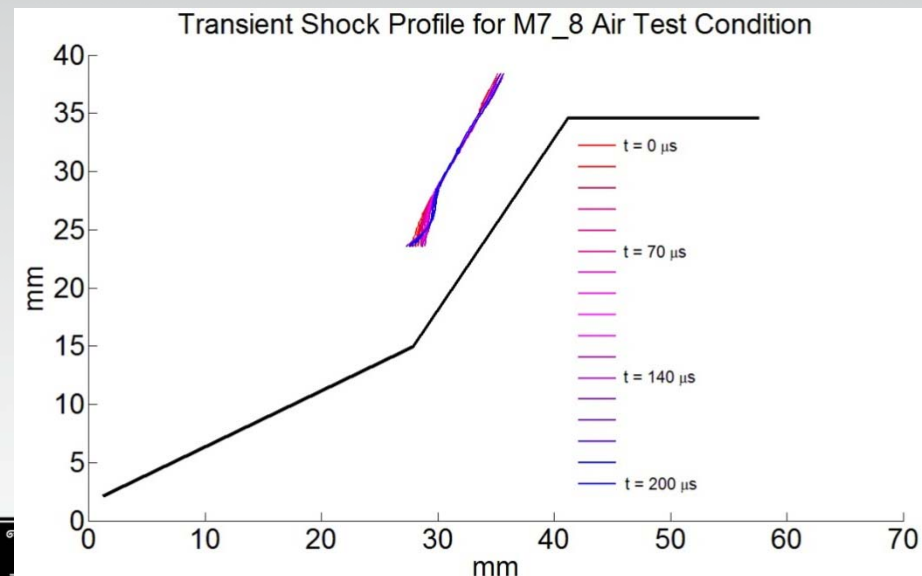


Boundary Tracing – Double Cone





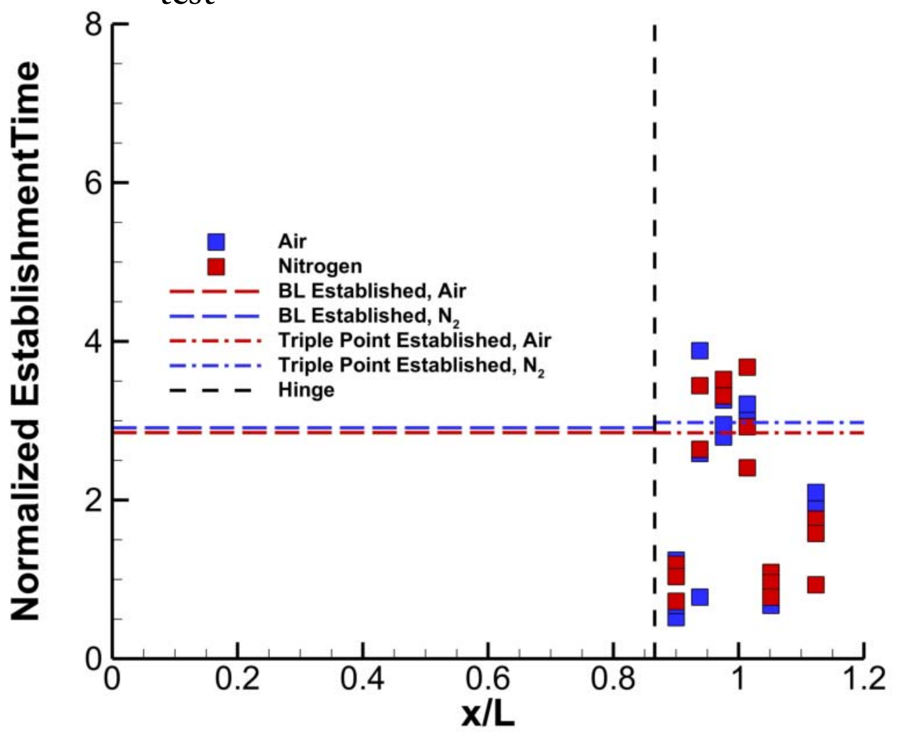




Wedge Establishment Times

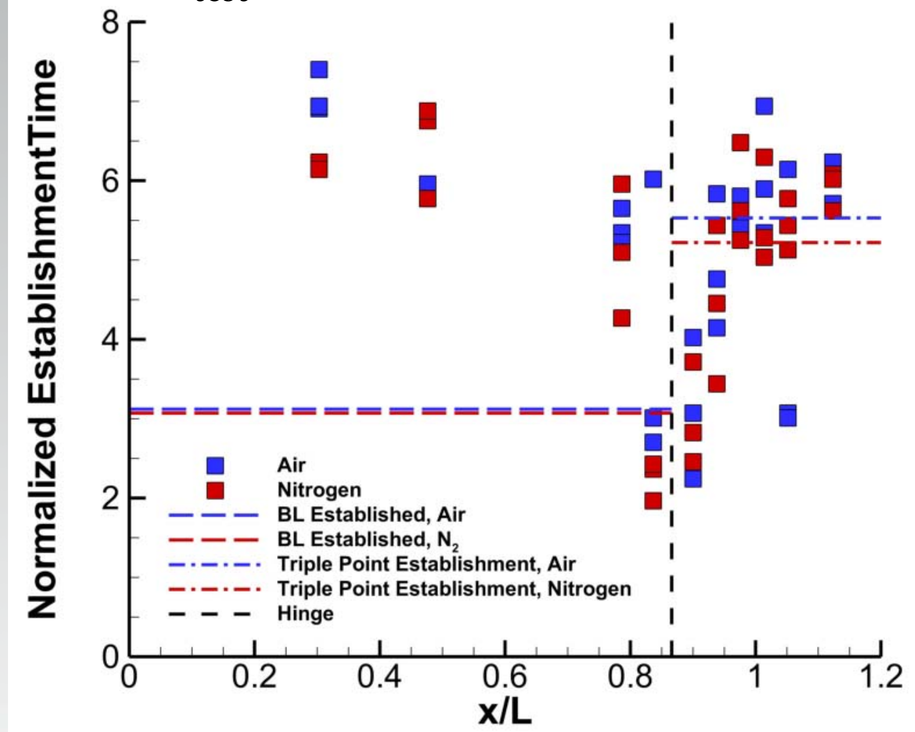
M7_2

t_{test}=7.0



M4_3

t_{test}=15.4

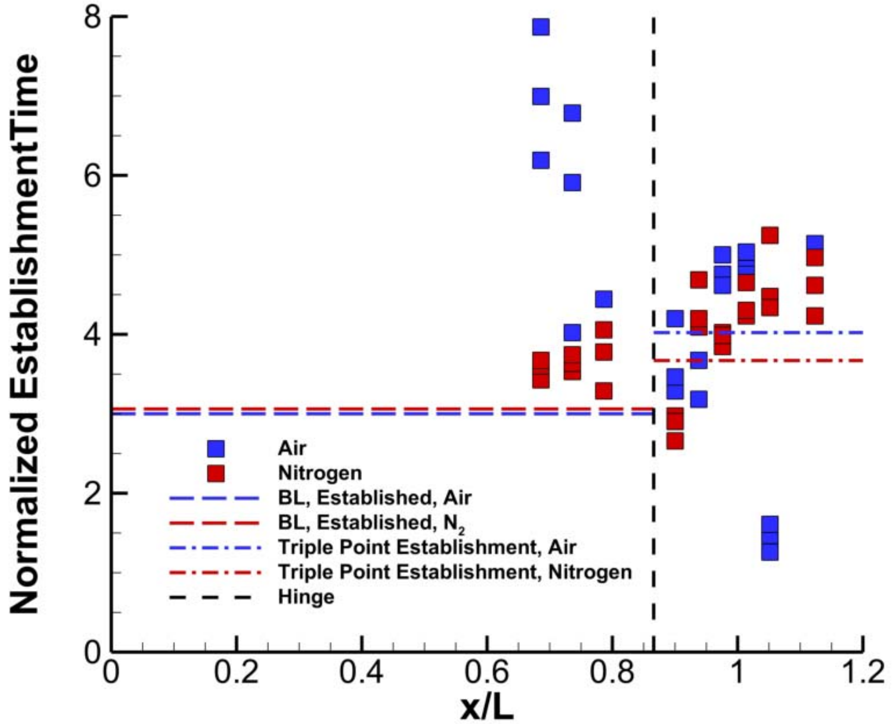


Boundary layer prediction from Gupta (1972): $t=3.3*L/U_\infty$

Wedge Establishment Times

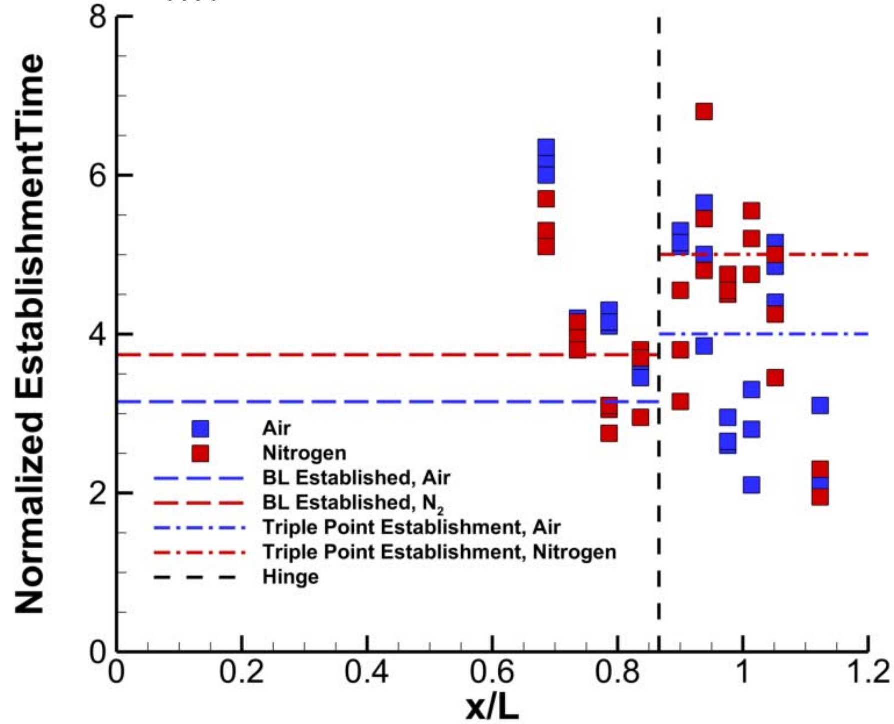
M5_4

t_{test}=12.2



M7_8

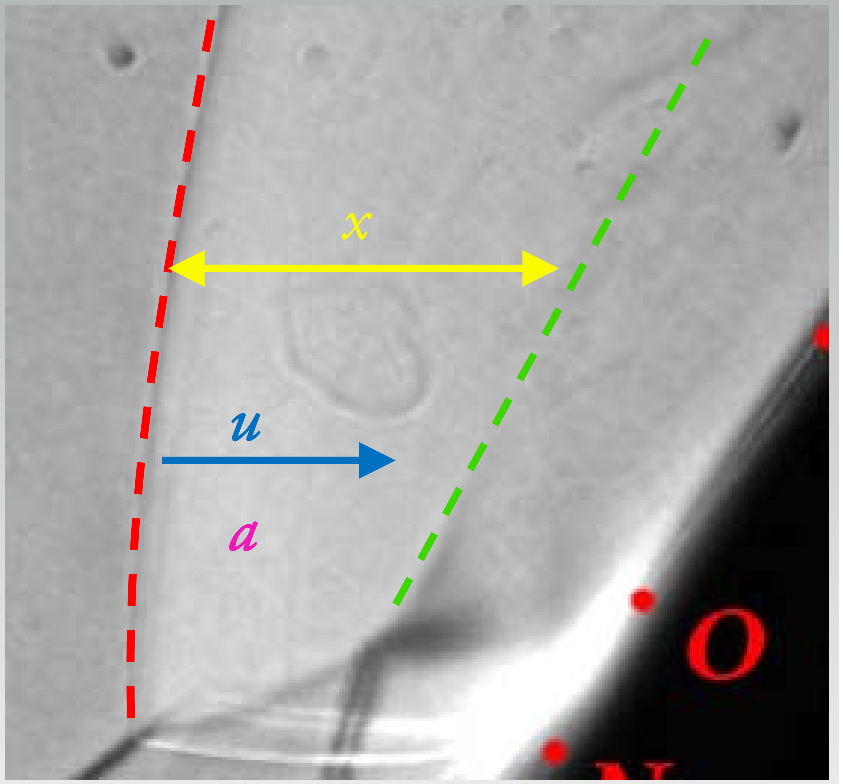
t_{test}=11.0



Boundary layer prediction from Gupta (1972): $t=3.3*L/U_\infty$

Shock Tracking Acoustic Predictions

- Order of magnitude estimation of the time it takes for an acoustic wave (sound speed *a*) to travel from the bow shock to the shear layer and back (a distance of *x*) with post shock velocity *u*.
  - *x* is an average distance
  - *u* is the average of fr. and eq. velocities
  - *a* is the average of fr. and eq. sound speeds
- Downstream traversal time, t_d, is $x/(a+u)$.
- Upstream traversal time, t_u, is $x/(a-u)$.
- Predicted frequency, *f*, is $1/(t_d+t_u)$.
- Reminders: order of magnitude predictions, these are only a single source of shock oscillation.



Shock Tracking FFT Results

Double Wedge

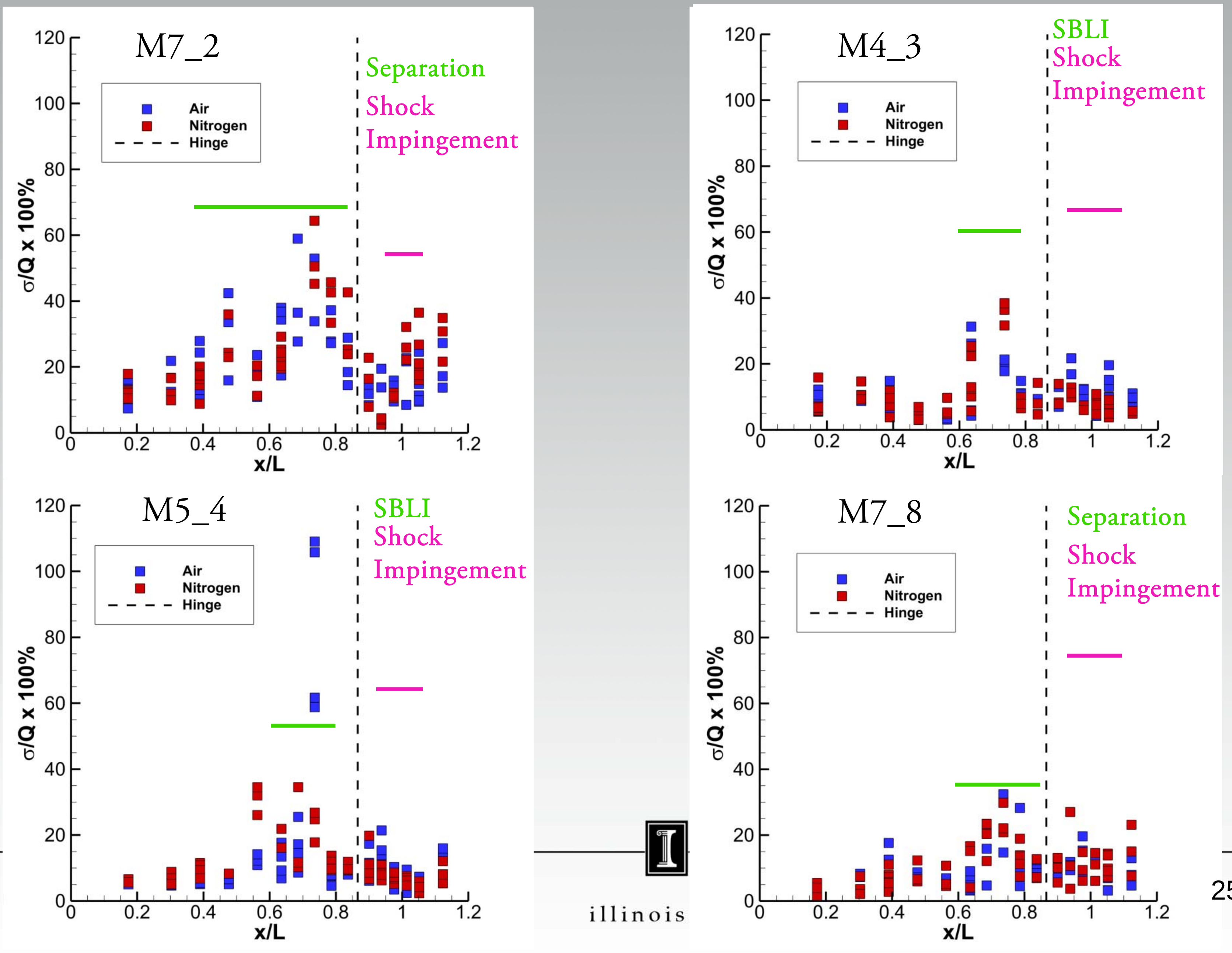
Test Condition	N_2, Experiment			Prediction	Air, Experiment			Prediction
M7_2	9.38	18.8	25.0	4.21	25.0	43.8	-	4.01
M4_3.6	4.69	7.81	10.9	9.46	4.69	7.81	10.9	7.95
M5_4	6.25	25.0	40.6	6.19	6.25	25.0	40.6	6.29
M7_8	12.5	37.8	-	7.22	12.5	37.8	-	7.52

Double Cone

Test Condition	N_2, Experiment			Prediction	Air, Experiment			Prediction
M7_2	12.5	21.9	31.3	95.0	12.5	21.9	31.3	103
M4_3.6	6.25	10.9	15.6	63.7	6.25	10.9	15.6	86.8
M5_4	7.03	14.1	18.8	140	7.03	14.1	18.8	167
M7_8	12.5	21.9	28.1	199	12.5	28.1	-	226

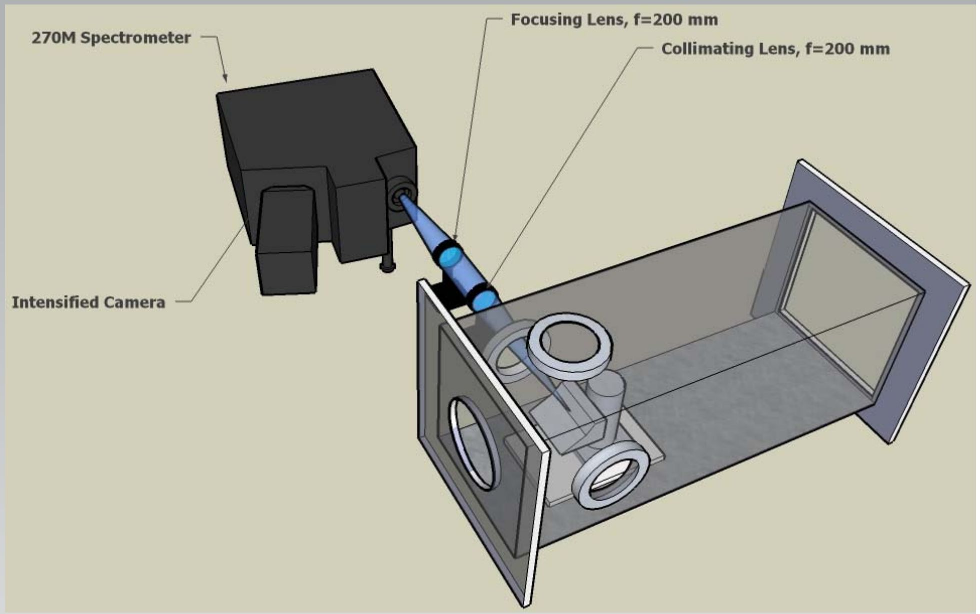
Nyquist frequency of 50 kHz.

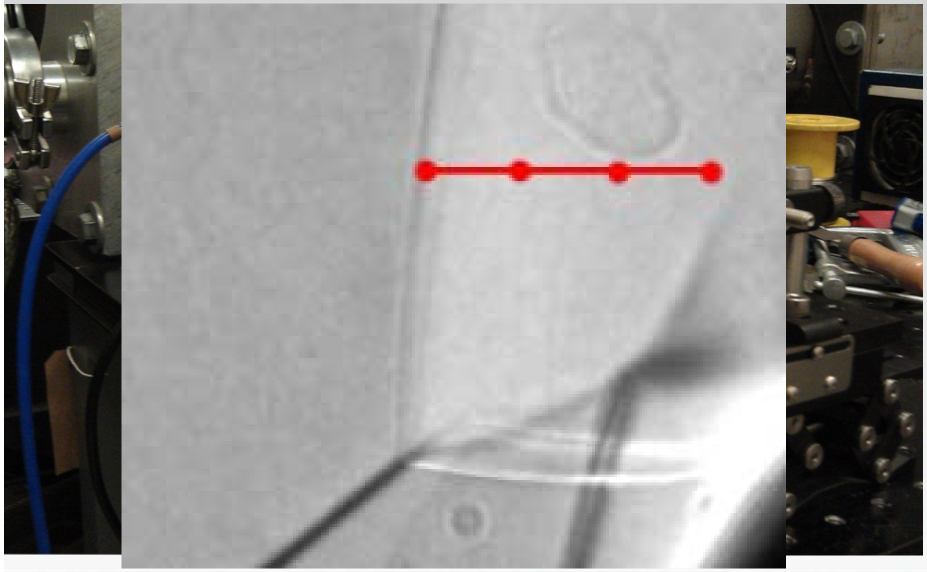
Surface Heat Transfer - Fluctuations



Experimental Setup

- NO Emission Spectroscopy.
  - NO A-X band in the UV (220-355nm) is interrogated.
  - *f*/4 270M SPEX spectrometer: 43 μm slit, 1200 g/mm grating, 1.56 A resolution
  - PI-Max 512 ICCD camera
  - 110 μs exposure time in highest enthalpy condition on the double wedge
- Calibration
  - Fe Hollow cathode for wavelength
  - Hamamatsu UV-VIS Deuterium lamp for intensity.





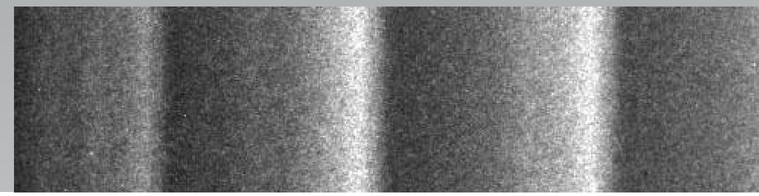
- Guide plate fabricated via wire EDM for spatial alignment of the optics
  - Four holes at 2 mm spacing are drilled 6.1 mm above the nominal triple point location
- Optic fiber is used to transmit light.
  - Non-negligible losses through the fiber, therefore calibration of the fiber is performed

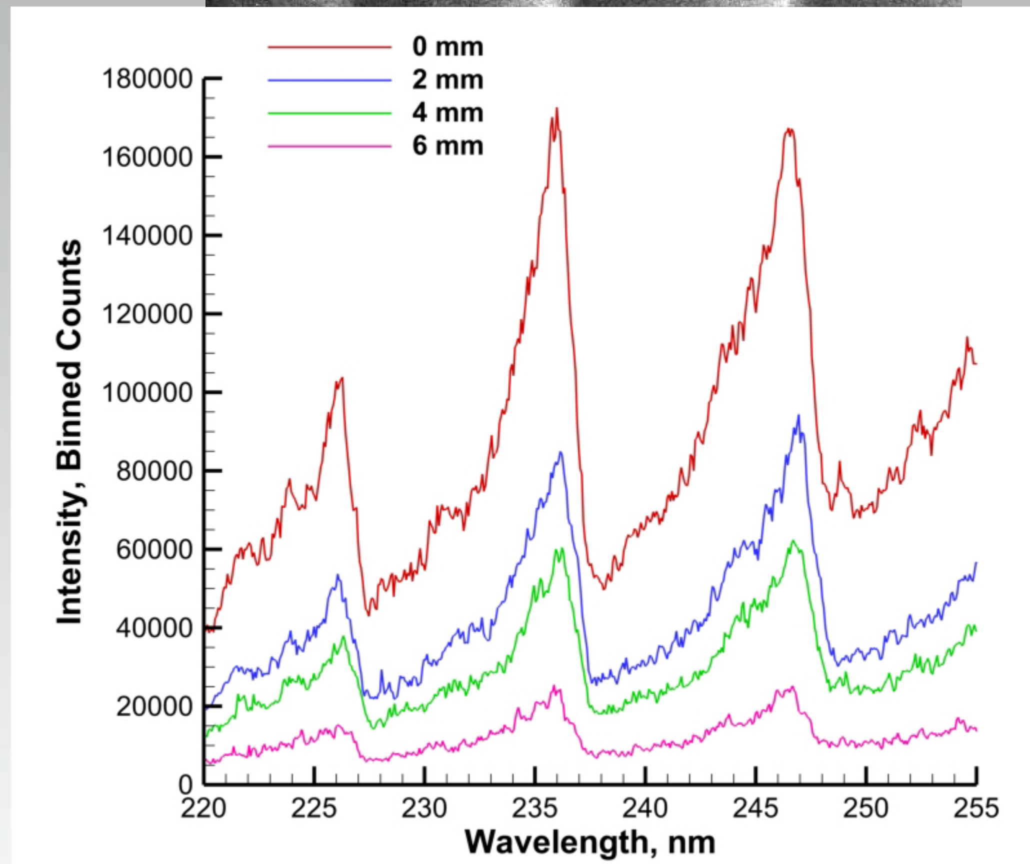
Interrogation

- M7_8 test condition
- 4 spatial locations, at 2mm increments, 6.1 mm above the triple point.

- NO γ band (A-X transition, $^2\Sigma^+ \rightarrow {}^2\Pi_{1/2,3/2}$)
- Wavelength range of 220-255 nm (near UV)

- Current experiments are based on Sharma's (2010)





Uncalibrated data shown.

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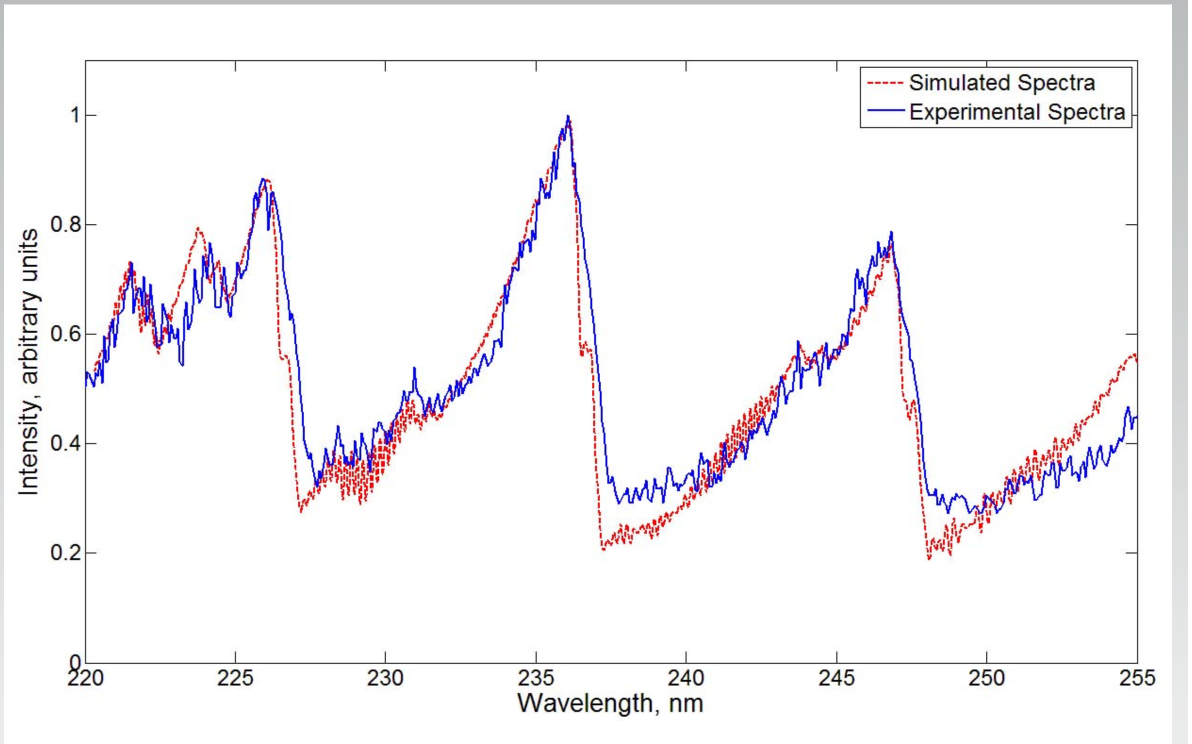
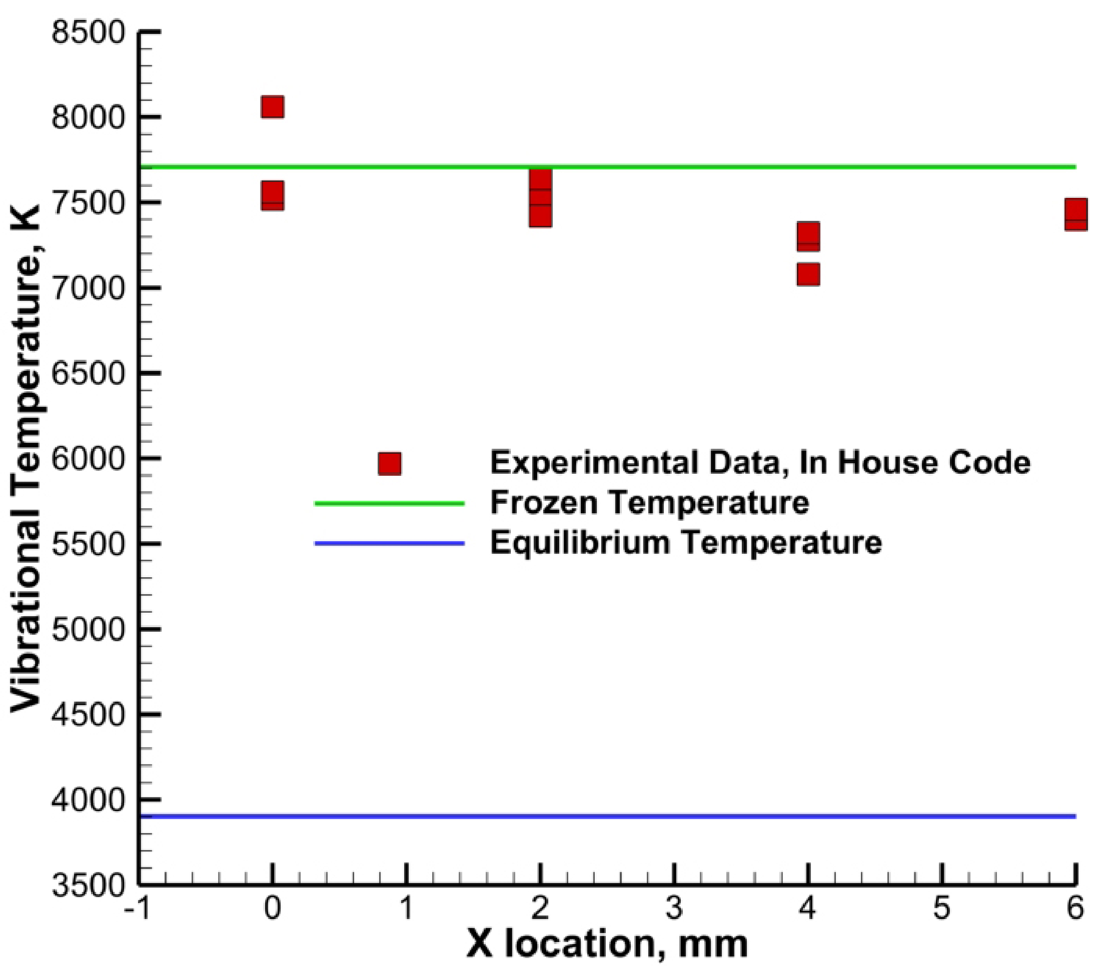
Experimental & simulated spectra

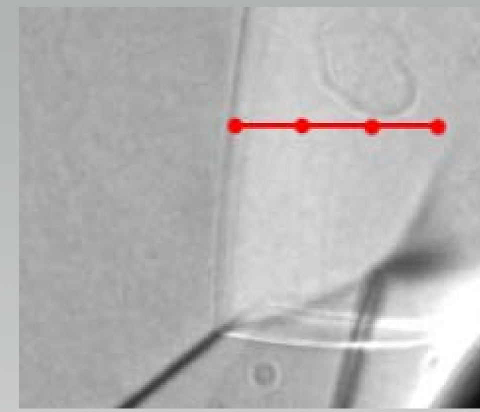
- Two codes are used for temperature fitting.
  - LIFBASE
    - 5 vib. levels
    - 80 rot. levels
  - In house code
    - 20 vib. levels
    - 250 rot. levels
- Simulation wavelengths interpolated to match experimental data.
- Residuals calculated at each wavelength and minimized to obtain vibrational temperature fit.



Shot 1197, 4mm position, in house simulation, T=7280K

Post-shock temperature profile





Location, mm	NO Temperature, K LIFBASE		In House Code	
	T	σ	T	σ
0	8573	370	7713	301
2	8300	110	7527	110
4	7968	133	7227	129
6	8360	28	7647	42

Mean temperatures, T, and standard deviations, σ

Chemical kinetics simulation estimates the relaxation region at 37mm.

Conclusions

- Heat transfer data is acquired over the double wedge model for flow enthalpies of 2-8 MJ/kg
- Minimal differences are observed in the laminar flat plate portion of the first wedge
- In the two highest Reynolds number cases, a departure from laminar behavior is seen, in agreement with visualization
- On the aft wedge considerable differences are noticed with varying freestream O_2 content at higher enthalpies
  - Near peak heating location, air generally exhibits larger heating values in agreement with previous research
- Standard deviations show that the fluctuations, when normalized, are largest near areas dominated by viscous effects.

Conclusions

- High speed image series over the double wedge and double cone models.
  - Shock profiles are extracted; frequencies compared with acoustic predictions.
- Establishment times using triple point location and heat transfer are made.
  - Aft wedge heat transfer establishment agrees with triple point establishment.
  - Increased time required near regions of shock/boundary layer interaction and separation zone.
  - Times (2-8) are in agreement with historical experimental times (5.5-11), and disagree with simulations (100-200).
    - Establishing shocks move upstream
- Differences are directly observed between nitrogen and air.
  - Establishment times, shock behavior, heat transfer.
  - Investigation of intermediate mixtures.
- NO emission spectra in the ultraviolet (220-255 nm) have been collected and temperatures fit.
- Reasonable agreement with frozen temperature and then relaxation.
- Comparisons with simulations from D. Levin's group
  - Collaborations with AFRL (E. Josyula et al.)
  - Contributions to NATO RTO AVT 205 working group

Challenges

Technical Challenges

- Installation and operation of Cordin camera
- Short test times
- Light source needs improvement
- Spatial resolution of spectroscopic measurements
- Low gas density at higher Mach numbers (good for simulations)

Broader Challenges

- Generalization of results requires excellent facility characterization, spatial and temporally resolved data
  combine experimental and numerical tools
  comparative studies

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