Experimental Studies of Shock Wave Boundary Layer Interaction in Laminar and Turbulent Hypervelocity Flows to Evaluate Models of Air Chemistry and Turbulence

AFOSR/NASA Review

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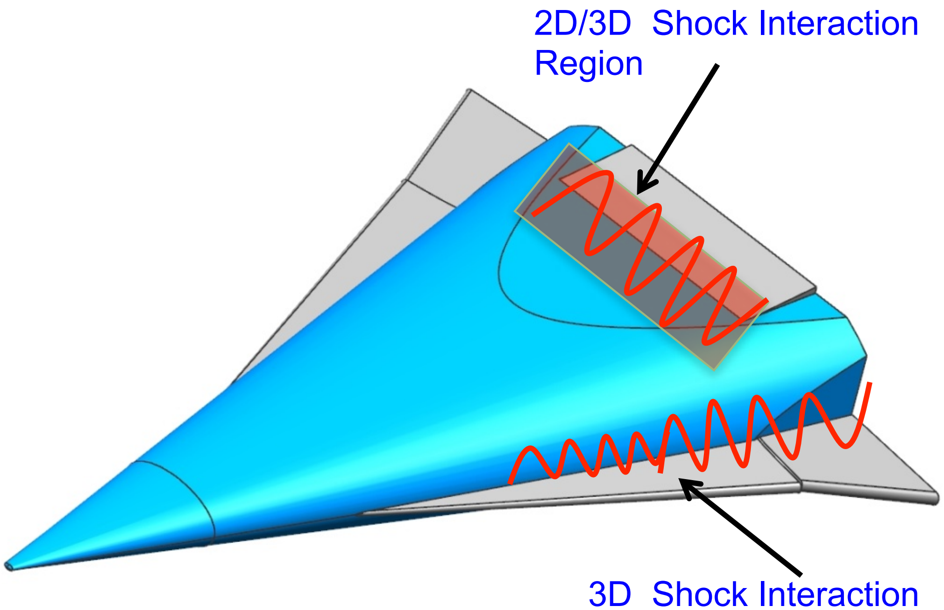
Outline of Presentation

- Experimental Test Cases from Earlier and Current Studies and Comparison with RANS Solutions to Examine Modeling of Turbulence in RANS and DES/LES Solutions for Regions of SWTurbulentBLI at Mach numbers from 4 to 8 at flight Total Enthalpies and Reynolds numbers.(New Test Cases to be Presented at January 2013 AIAA Meeting)

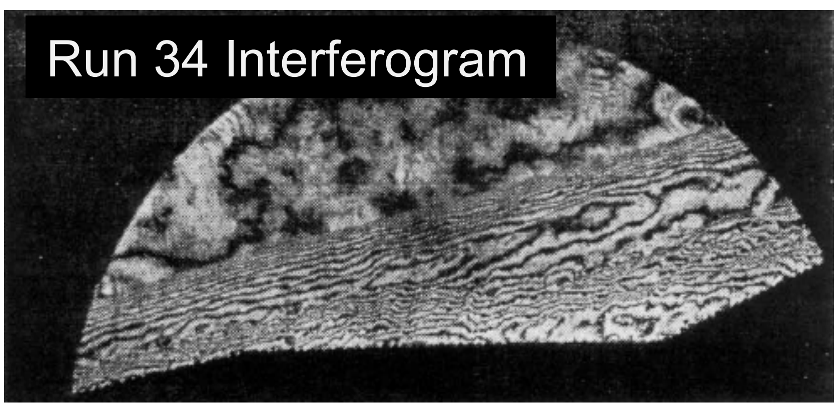
- Measurements , Model Configurations and Test Conditions from Experimental Studies of SWLaminarBLI Conducted in LENS I and XX Tunnels at Total Enthalpies from 5Mj/kg to 18Mj/kg. to Evaluate the Models of Air Chemistry and Flow/Surface Interaction Employed in Navier-Stokes Computations. .(New Test Cases to be Presented at January 2013 AIAA Meeting)

Shock Wave Transitional/Turbulent Boundary Layer Interactions on Control Surface Heating and Performance to Slender Hypervelocity Vehicles (Example HTV-2)



Key Issues for Vehicle Design

- Heating and control characteristics of transitional/turbulent interactions
- Modeling turbulence in transitional/ turbulent unsteady 3D interaction regions
- Gross unsteadiness of transitional interaction regions



Separated shock interaction region over Control Surface at Mach 11

Sub-Grid Scaling for LES Model

$$\partial_t \bar{\rho} + \partial_j\left(\bar{\rho}\tilde{u}_j\right) = 0$$

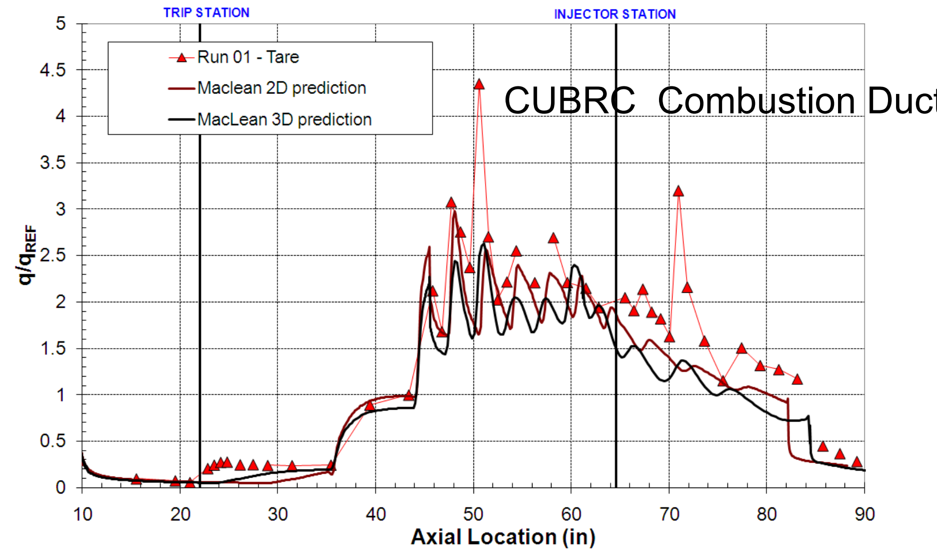
$$\partial_t\left(\bar{\rho}\tilde{u}_i\right) + \partial_j\left(\bar{\rho}\tilde{u}_i\tilde{u}_j\right) + \partial_i\left(\bar{p}\right) - \partial_j\left(\hat{\sigma}_{ij}\right) = -\partial_j\left(\bar{\rho}\tau_{ij}\right)$$

$$\partial_t\left(\hat{e}\right) + \partial_j\left(\left(\hat{e} + \bar{p}\right)\tilde{u}_j\right) - \partial_j\left(\hat{\sigma}_{ij}\tilde{u}_j\right) + \partial_j\left(\hat{q}_j\right) = -\tilde{u}_i\partial_j\left(\bar{\rho}\tau_{ij}\right) - \partial_j\left(\overline{pu_j} - \bar{p}\tilde{u}_j\right)/(\gamma - 1) - \left(\overline{p\partial_j u_j} - \bar{p}\partial_j\tilde{u}_j\right) + \left(\overline{\sigma_{ij}\partial_j u_i} - \bar{\sigma}_{ij}\partial_j\tilde{u}_i\right)$$

Requires sub-grid wall layer model and filter

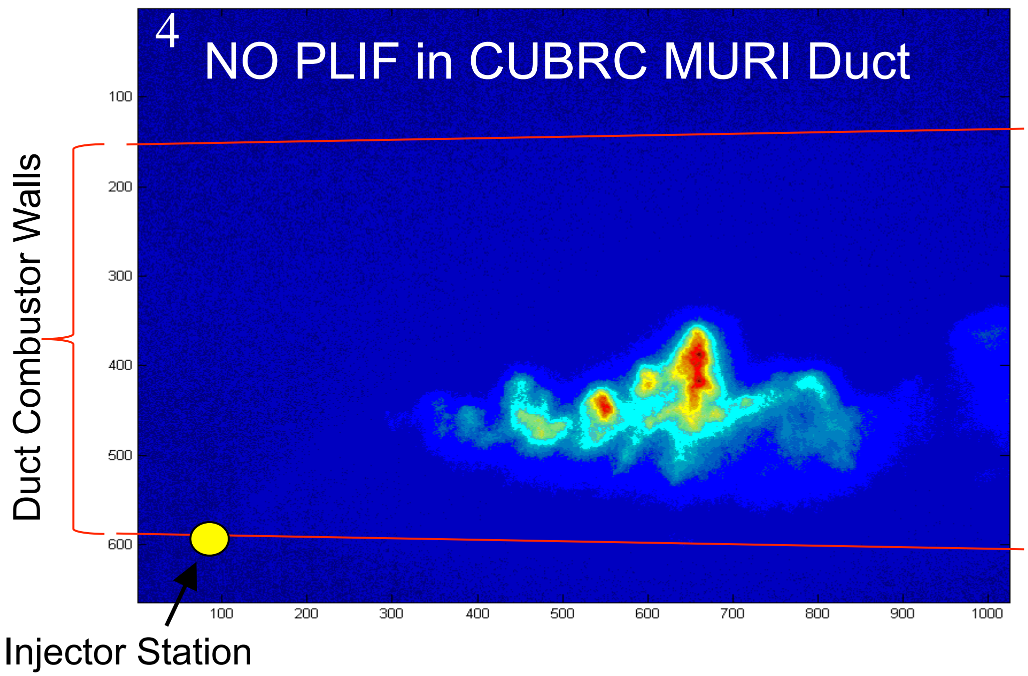
Shock Wave /Turbulent Boundary Layer Interactions in Inlet and Combustor Sections of Mach 4 to 7 Scramjet Engines –A Major Factor in Engine Operability and Performance (Example- X51)

Full-Scale X-51 in LENS II

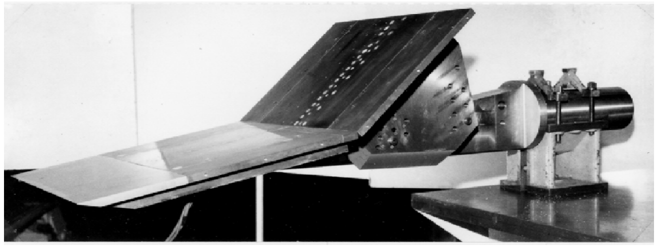


Heat Transfer Data from Combustion Duct Inlet and Combustor Compared to Computational Results

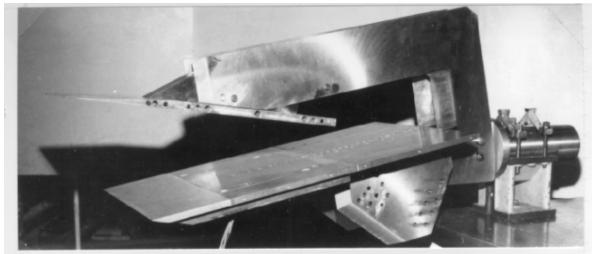
CUBRC MURI Combustion Duct



Model Configurations Employed in Earlier CUBRC Studies of SWTBLI

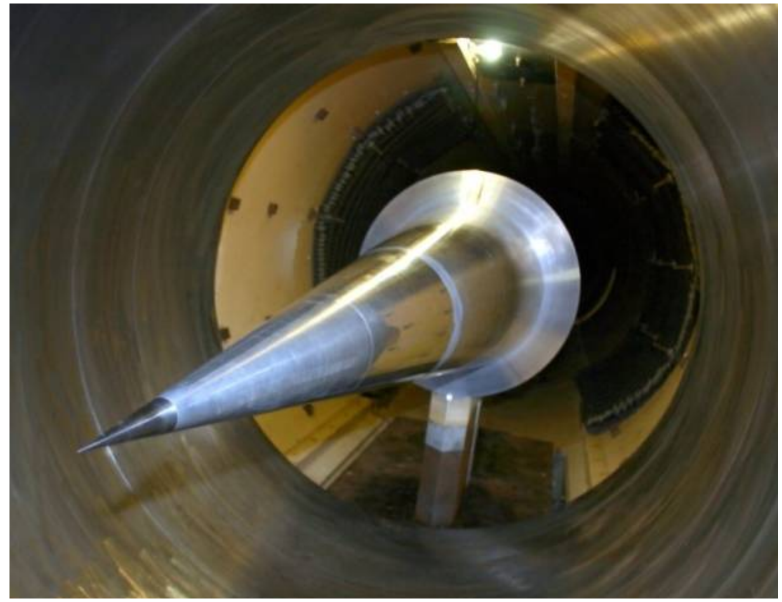


Flat Plate / Wedge



Flat Plate / Shock Generator

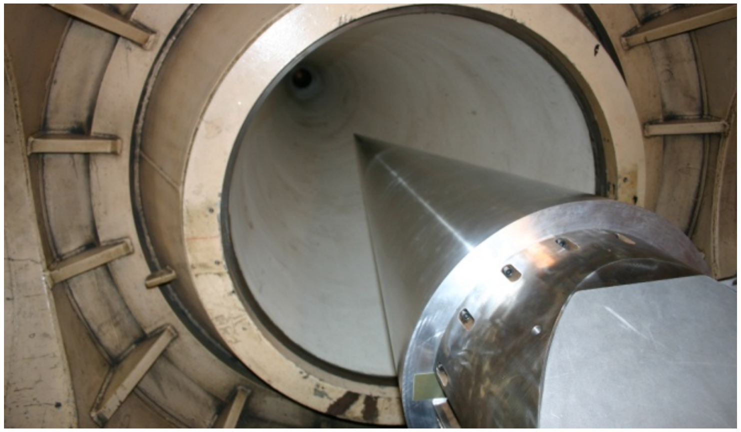
Large Cone/Flare Model



7° Cone-Flare

7° HiFIRE Cone

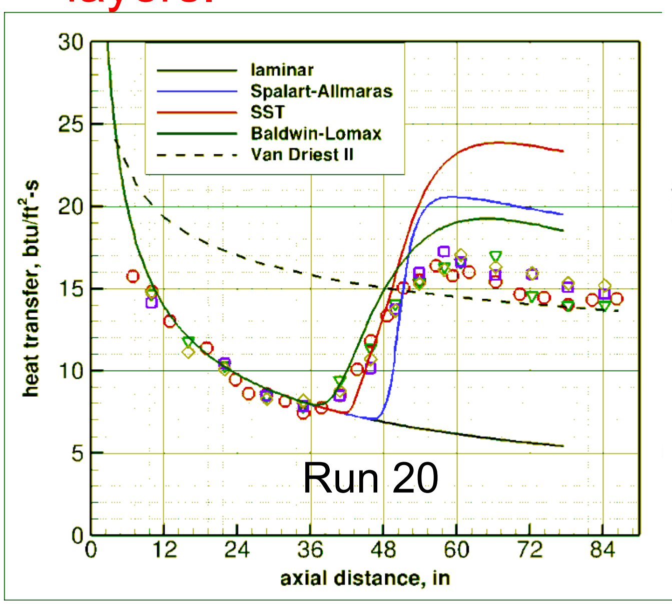
Serious Questions on the Accuracy of Turbulence Models in Prediction of Heating in Transitional and Turbulent hypervelocity Flow ° Cone M=10 Flight Enthalpy Measurements s

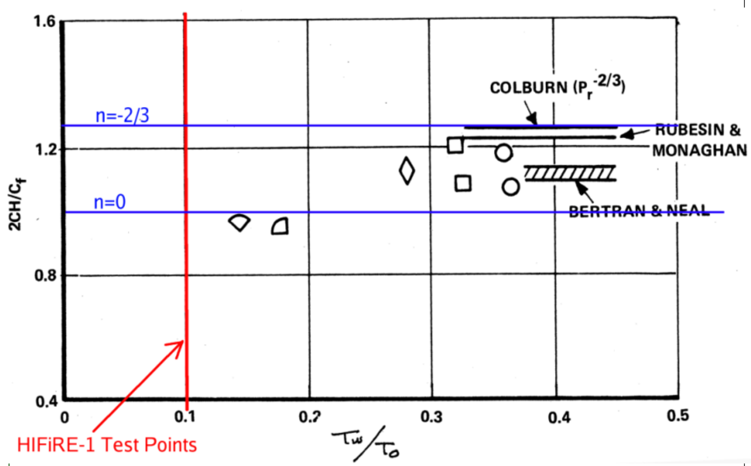


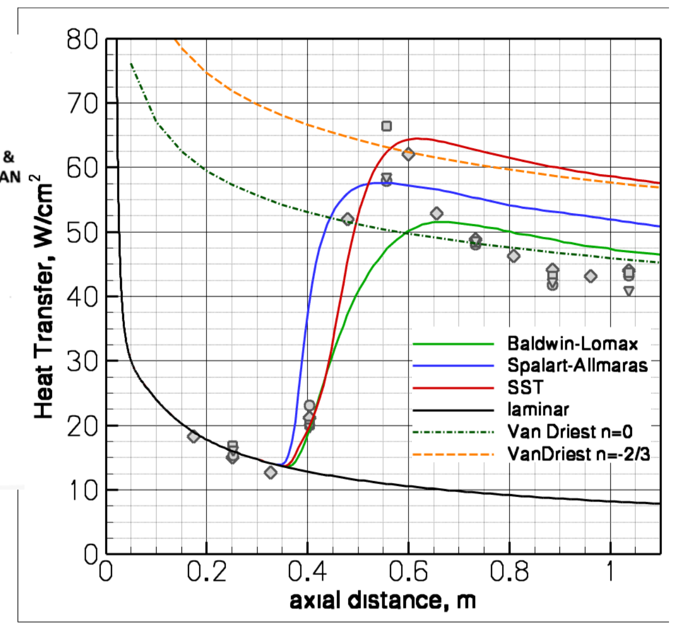
Run	Mach	U_∞ (m/s)	ρ_∞ (kg/m³)	T_∞ (K)	Nose radius (mm)
19	10	2845	.012	205	2.5
20	10	2850	.012	205	Sharp

8-ft, 7 cone installed in LENS I for studies at Mach 10 Flight conditions studies

Questions remain in modeling constant pressure high enthalpy turbulent boundary layers.

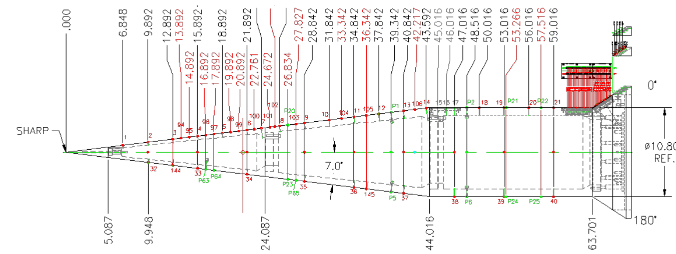




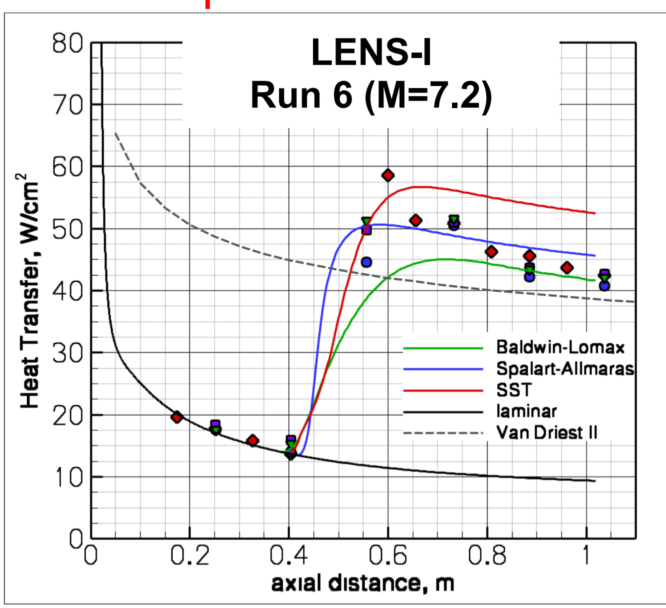


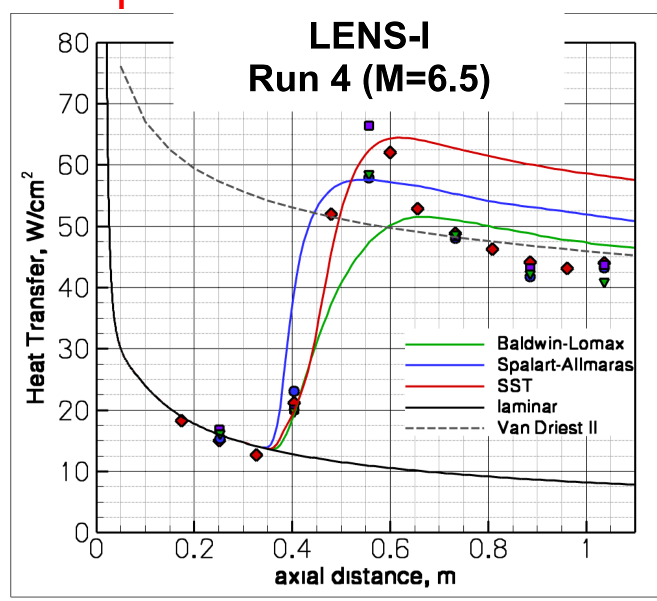
Heat Transfer Measurements in Transitional and Turbulent Flows Over HIFiRE 7° Cone at Duplicated Mach 6.5 and 7.2 Flight Conditions

Run	Mach	U_∞ (m/s)	ρ_∞ (kg/m^3)	T_∞ (K)	Nose radius (mm)
4	6.5	1925	0.125	213	2.5
5	7.2	2185	0.070	232	2.5
6	7.2	2185	0.071	231	5.0
8	6.5	1930	0.126	214	5.0

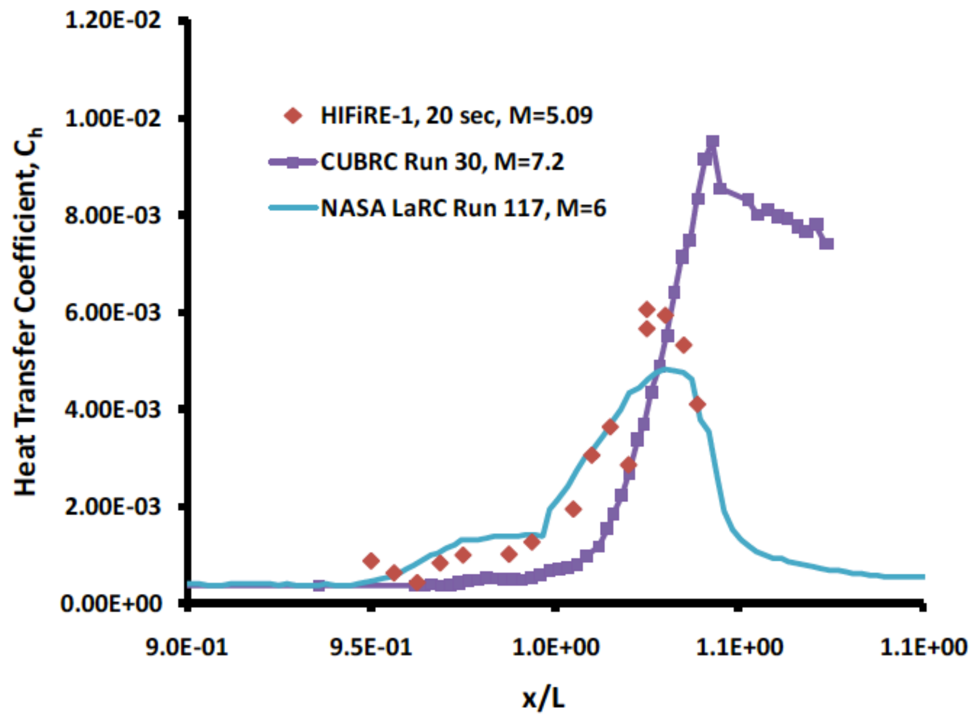


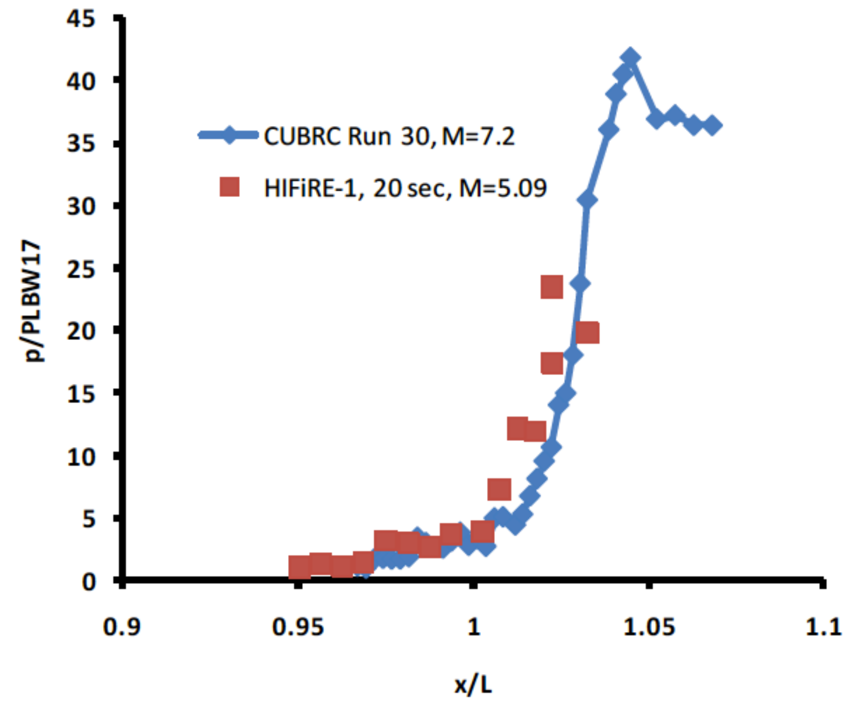
There remain questions on modeling turbulent flow upstream of interaction regions.





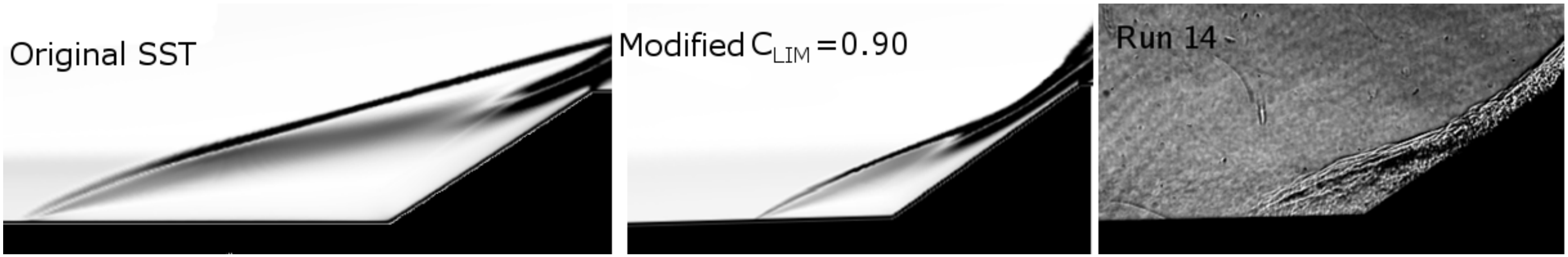
Kimmel's Comparisons Between CUBRC and NASA Measurements with Flight Data-

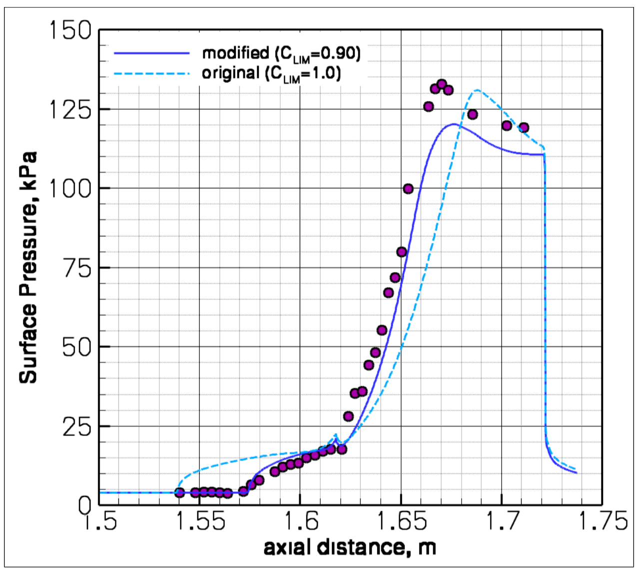


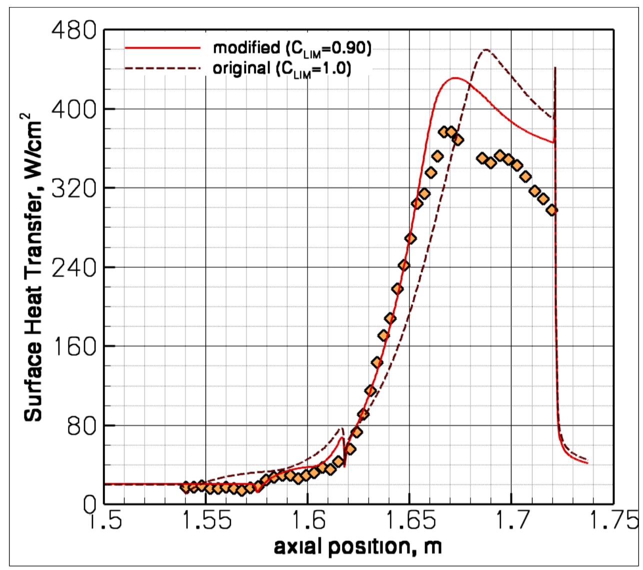


Strong Mach Number Effects Make These Comparisons of Questionable Value—Measurements are Required at duplicated Flight Conditions Flight

Hi-Fire Flare Heating Prediction with Wilcox Modified Reynolds Stress Limiter, C_{LIM}=0.90

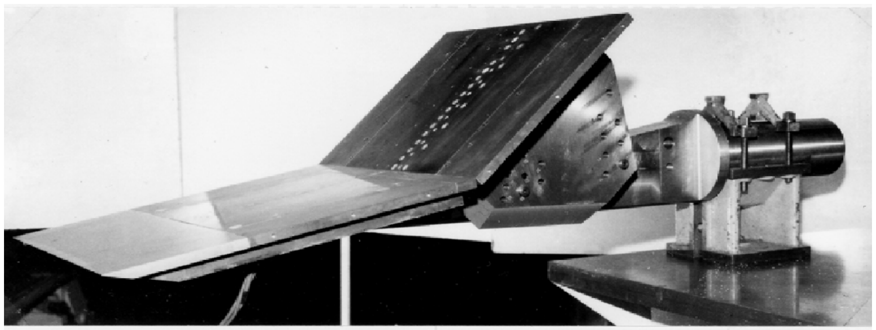


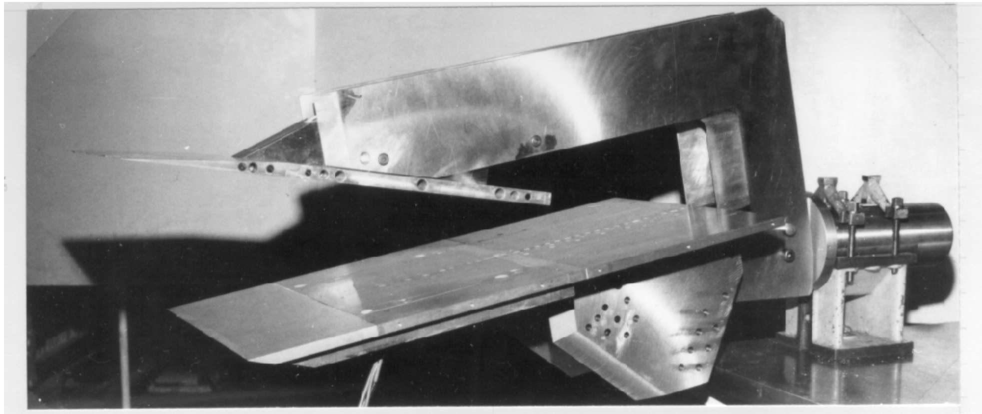


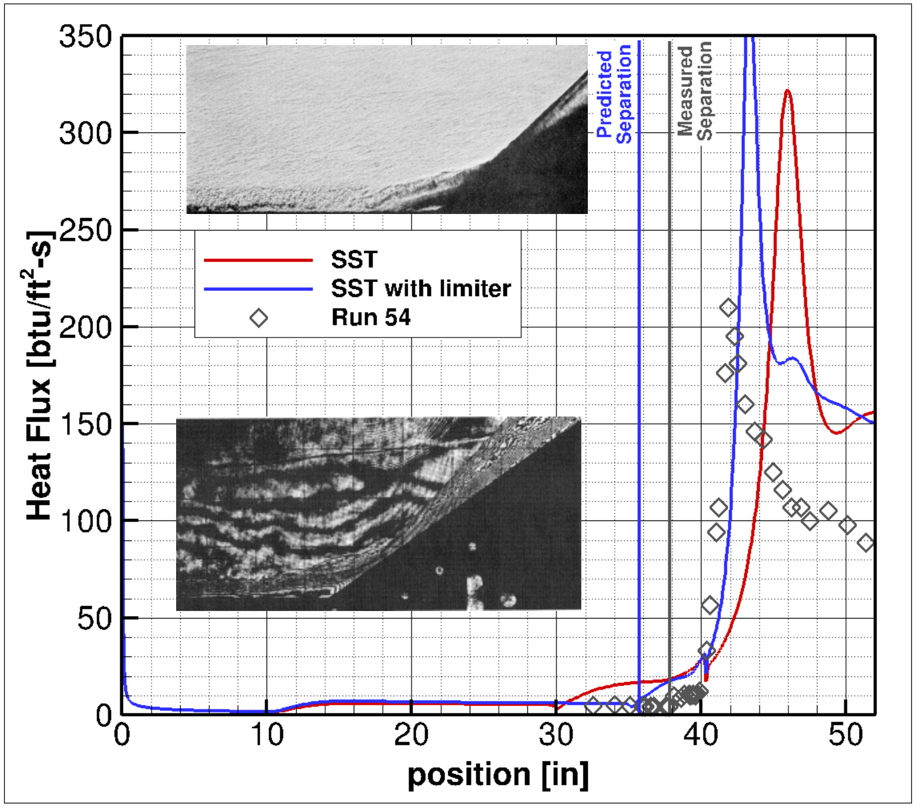


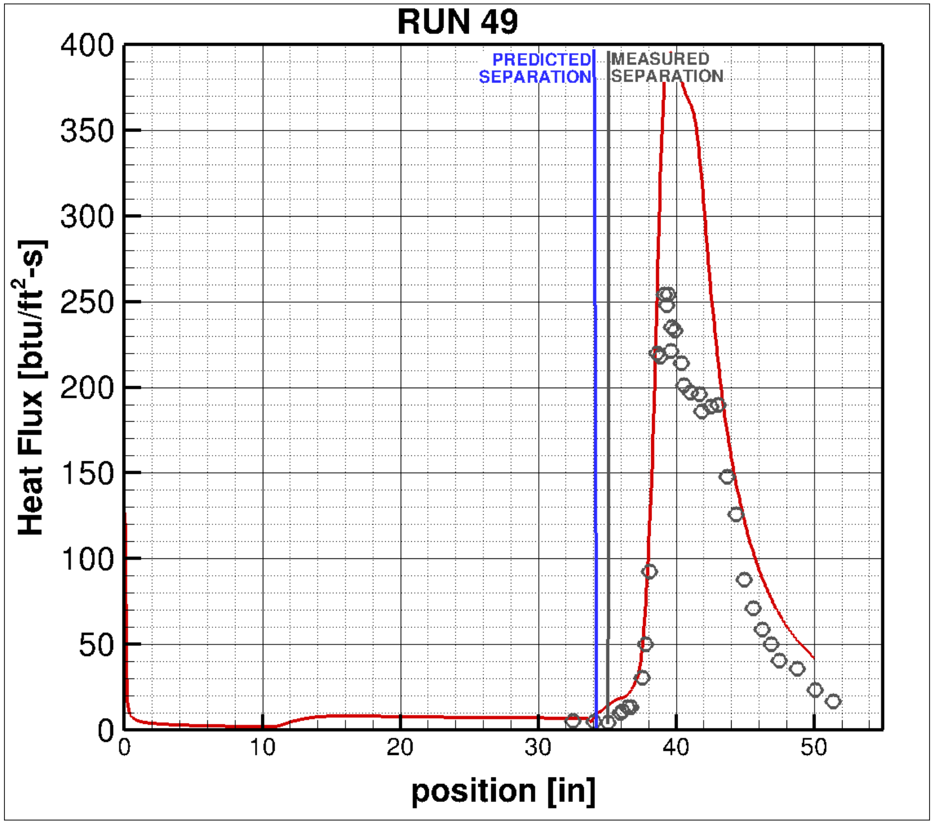
- Adjusting stress limiter coefficient on SST model provides qualitative agreement with surface measurements.

Comparison Between DPLR Predictions with modified SST turbulence Model I for Mach 8 – 11 Wedge-Induced and Shock- Induced Separated Flow –Not to Good Agrement



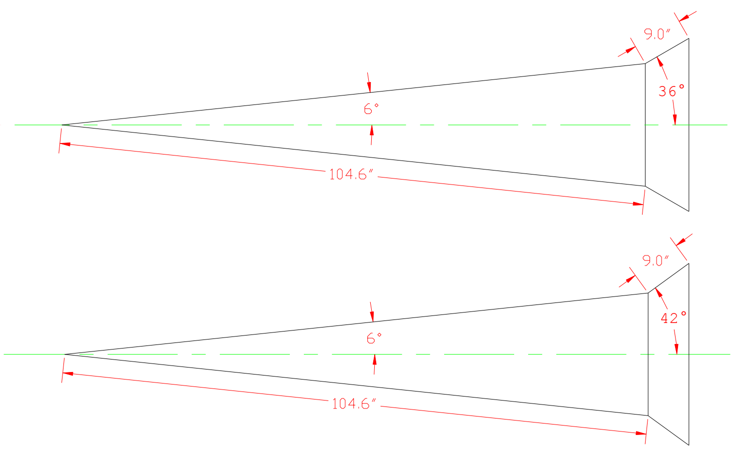


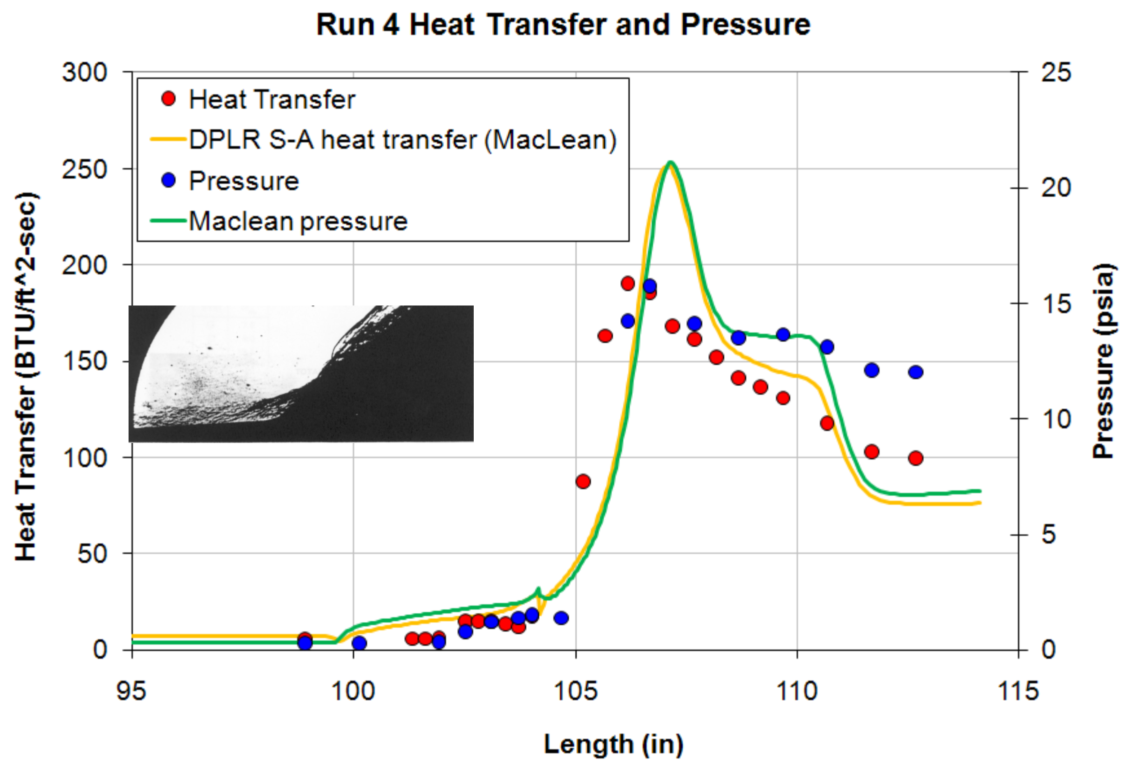




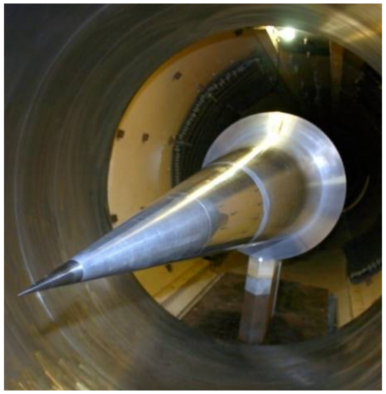
Heat Transfer and Pressure Measurements in SWTBLI on Original Large 6 degree Cone 42 Degree Flare at M=11,13 Again not good agreement at Duplicated Flight Conditions and Vehicle Size

Test Condition	M_∞	Re/ft	T_∞, K	Flare angle
4	11	4E6	65	42°
6	13	4E6	65	42°
7	13	4E6	65	36°
8	11	4E6	65	36°

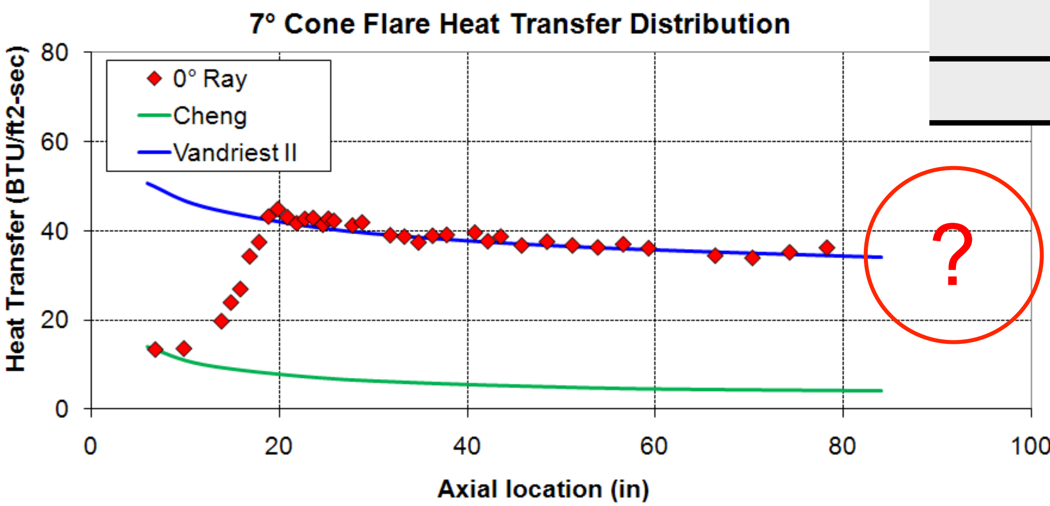


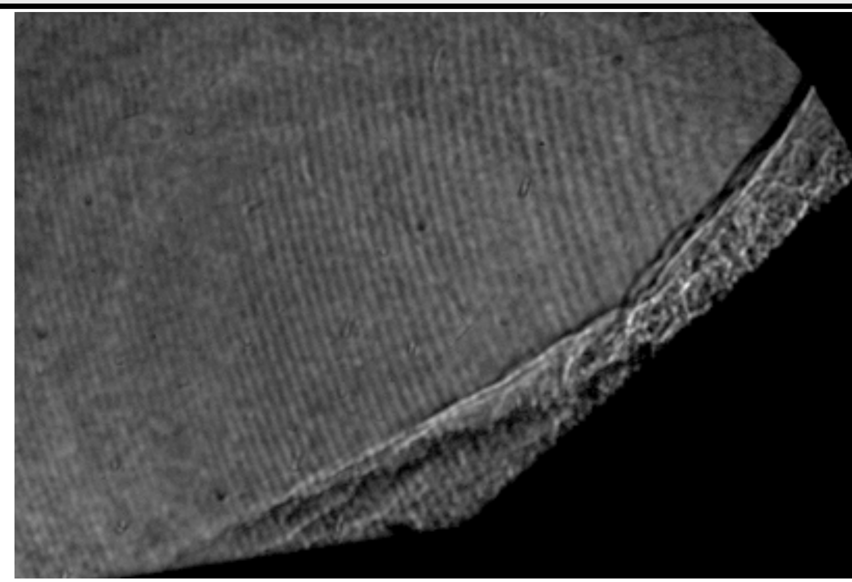


NEW Measurements in SWTBLI over New Large Cone-Flare Model at Mach 5, 6, 7 and 8 at Cold Flow and Matched Flight Enthalpy for "Blind" Code-Evaluation Test Cases.



Test Condition	M_∞	Re/ft	T_∞, R	Turning angle
1	5	7.5E7	100	37°
2	5	1.0E7	400	37°
3	6	3.2E7	100	37°
4	6	4.0E6	427	37°
5	7	1.5E7	100	37°
6	7	2.0E6	416	37°
7	8	8E6	100	37°
8	8	0.9E6	420	37°



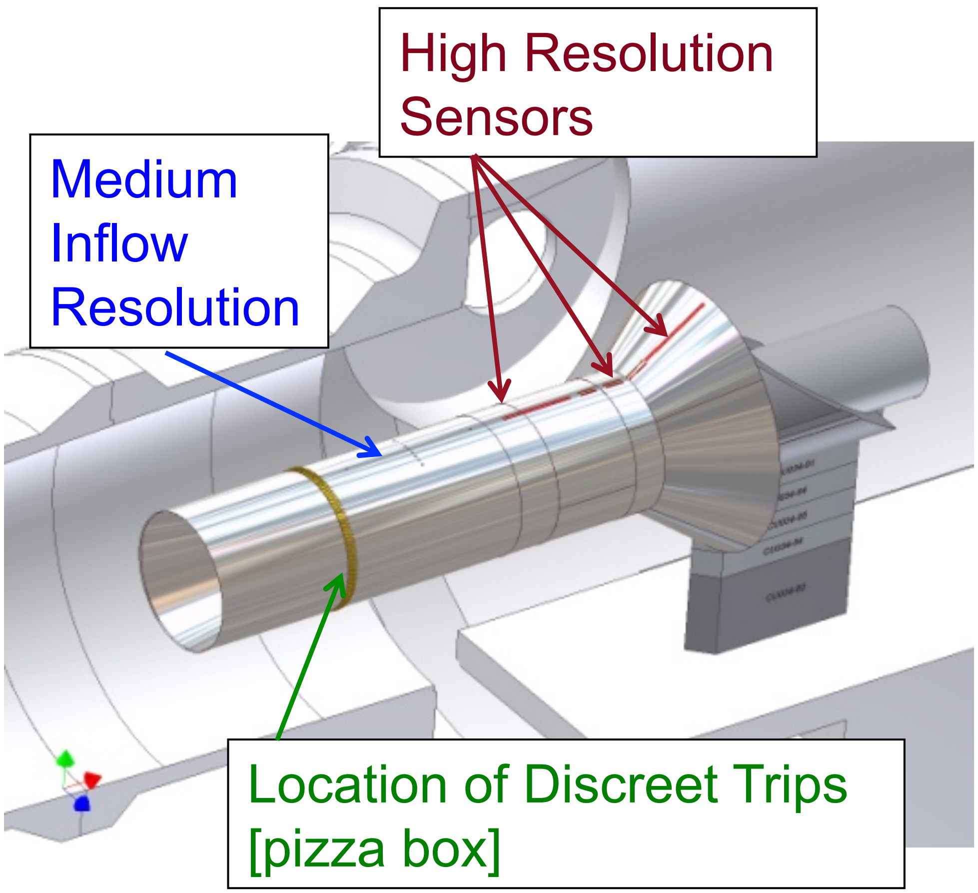


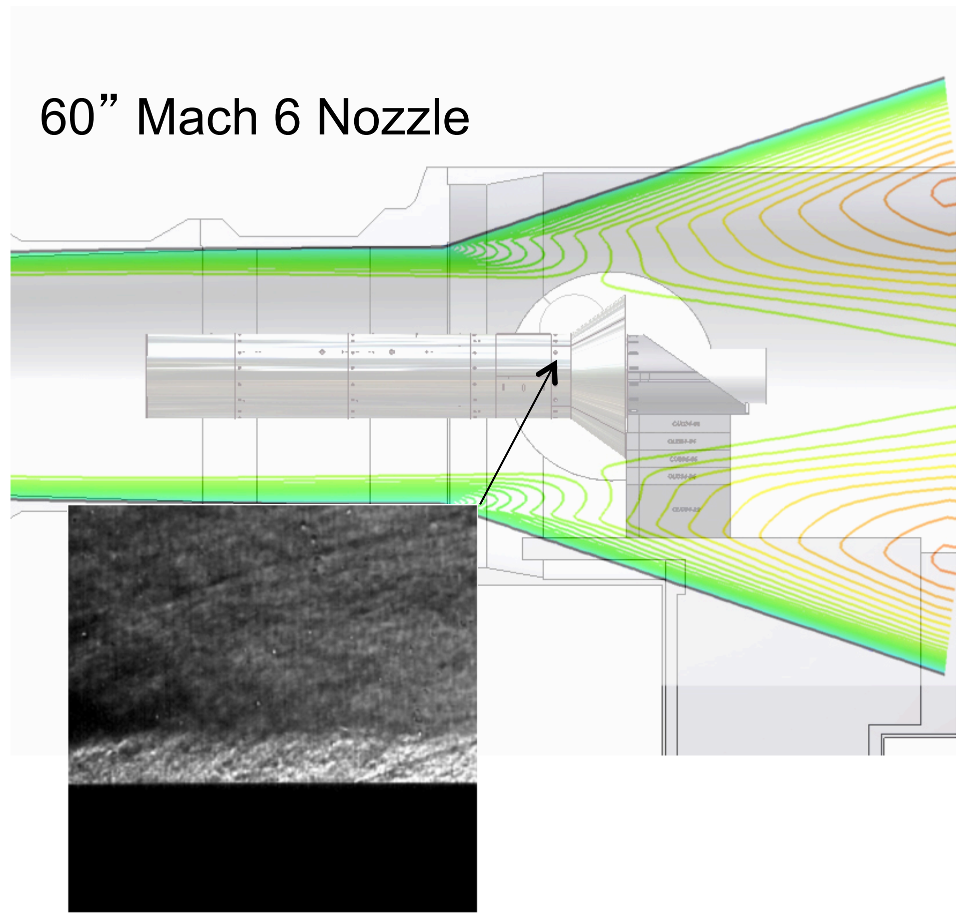
Transitional Flow (not the test case) over Cone/Flare Junction

NEW Measurements of SWTBI on Large Hollow Cylinder-Flare in High Reynolds Number and Tripped Turbulent Flows at Mach 5, 6, 7 and 8 at Cold Flow and Matched Flight Enthalpy for "Blind" Code-Evaluation Test Cases.

Test Condition	M_∞	Re/ft	T_∞, R	Turning angle
1	5	7.5E7	100	37°
2	5	1.0E7	400	37°
3	6	3.2E7	100	37°
4	6	4.0E6	427	37°

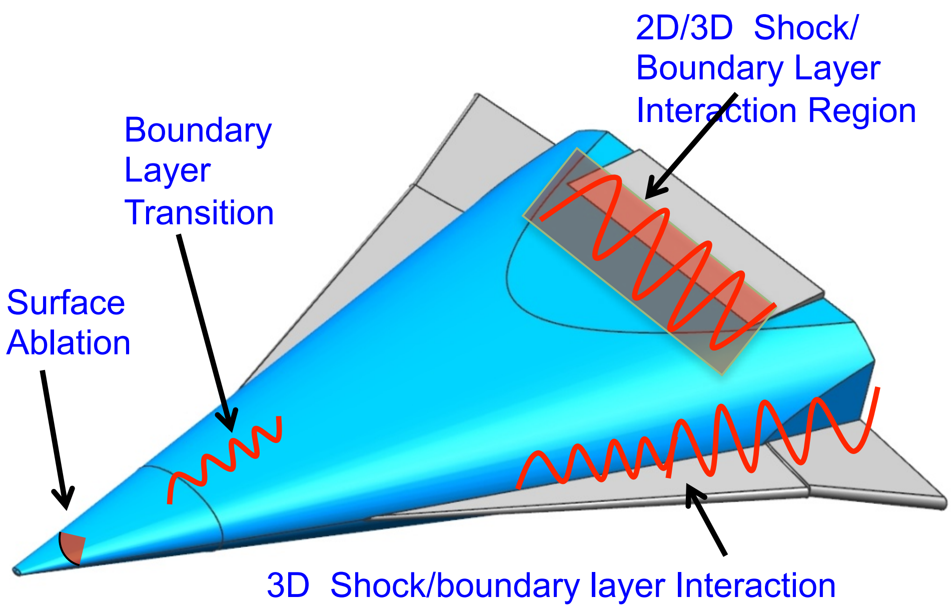
Test Condition	M_∞	Re/ft	T_∞, R	Turning angle
5	7	1.5E7	100	37°
6	7	2.0E6	416	37°
7	8	8E6	100	37°
8	8	0.9E6	420	37°





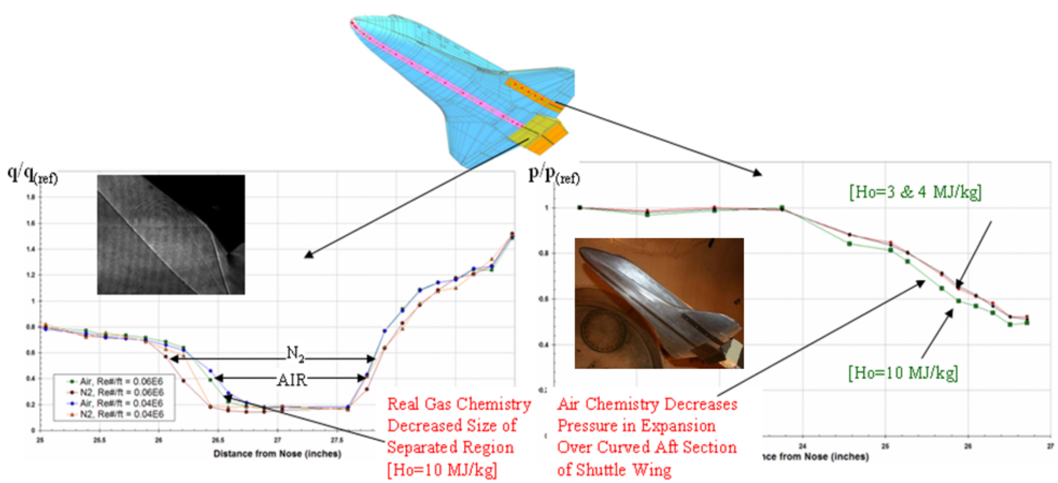
Turbulent Boundary Layer Upstream of Interaction

Non-Equilibrium Air and Ablation Chemistry on Shock Layer Properties and Regions of Shock Wave /Laminar Boundary Layer Interaction (SWLBI)



Key Issues for Vehicle Design

- Flow Chemistry Effects Associated with Ablation
- Boundary Layer Transition Delay and Reduced Drag (Game Changing)
- Control Surface Performance
- EM propagation through plasma
- DNS models incorporating flow chemistry require resources which might be available in 20 years



Not accounting for real gas effects almost caused the demise of the Shuttle Orbiter on its first flight.

One of the Empirical Models of Vibration/ Dissociation Coupling of a Cut-off Harmonic Oscillator

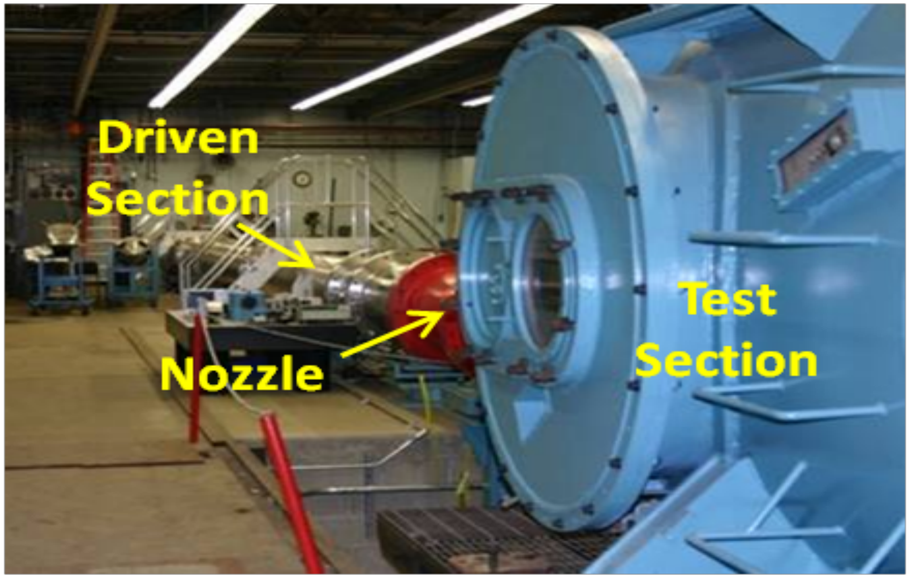
$$k_{f,m}(T,T_V,U) = \left[\frac{Q(T)Q(T_F)}{Q(T_V)Q(-U)}\right]\left[C_m T^{\eta} e^{-\beta/T}\right]$$

$$with\ Q(x) = \frac{1-e^{-\beta/x}}{1-e^{-\theta_V/x}}$$

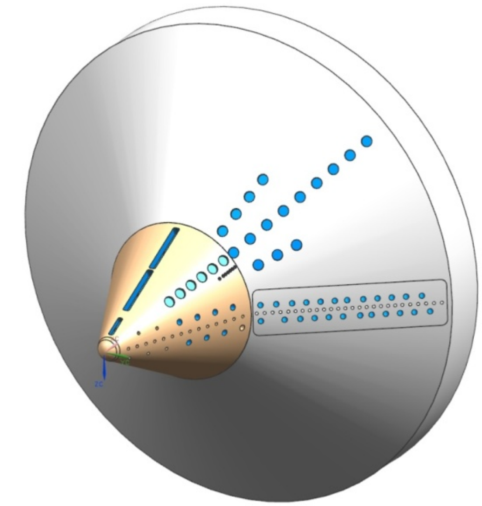
$$with\ T_F = \frac{1}{1/T_V - 1/T - 1/U}$$

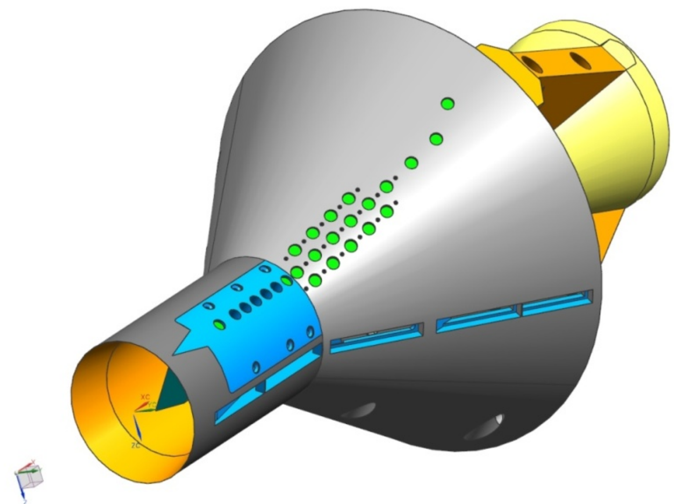
Models within Models

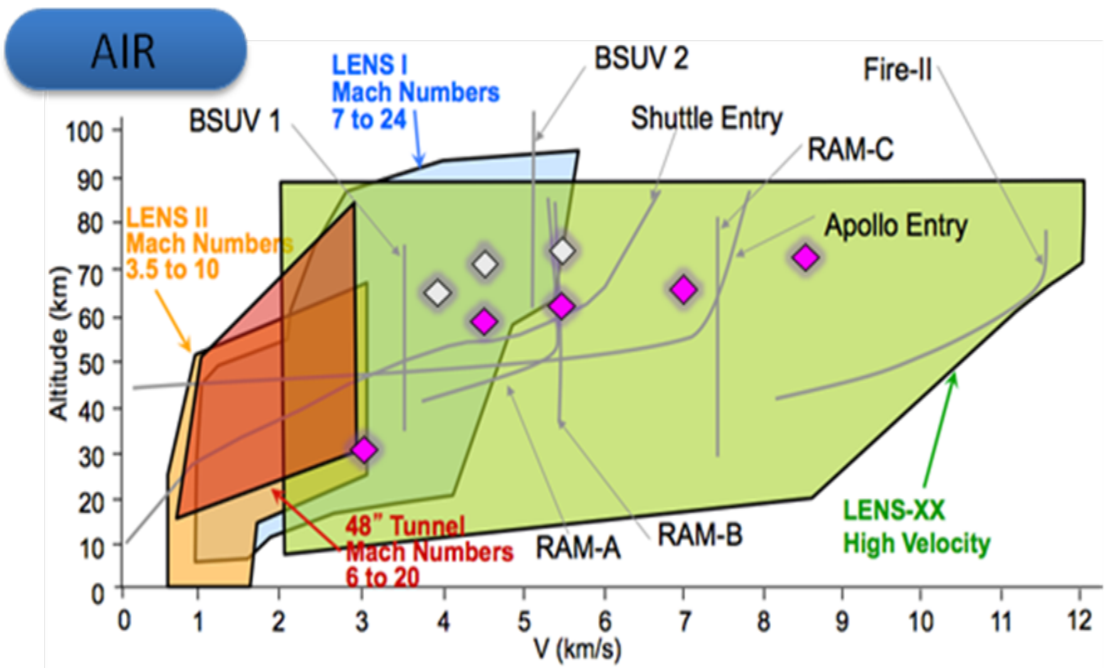
Test Points at Total Enthalpies of 10 to 25 MJ/kg where Studies with the new Hollow Cylinder Flare and Double Cone Models being Conducted in LENS XX



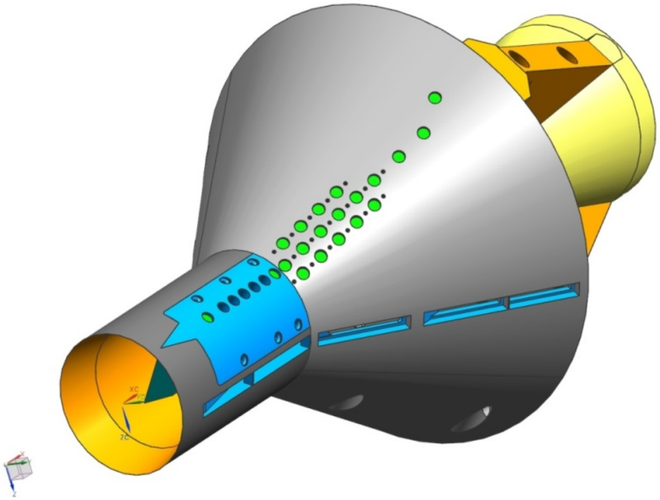
New Models for Upcoming Studies In LENS-XX in N_2 and Air
[10 MJ/kg – 25 MJ/kg]

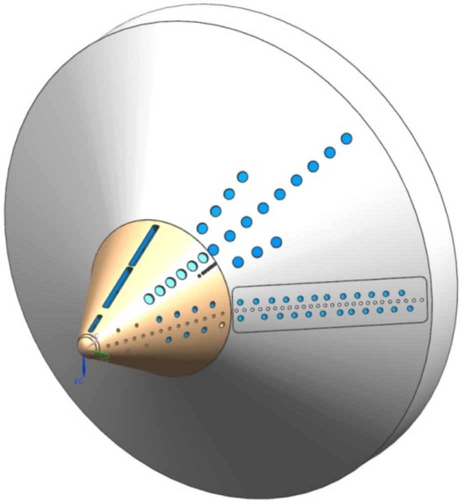






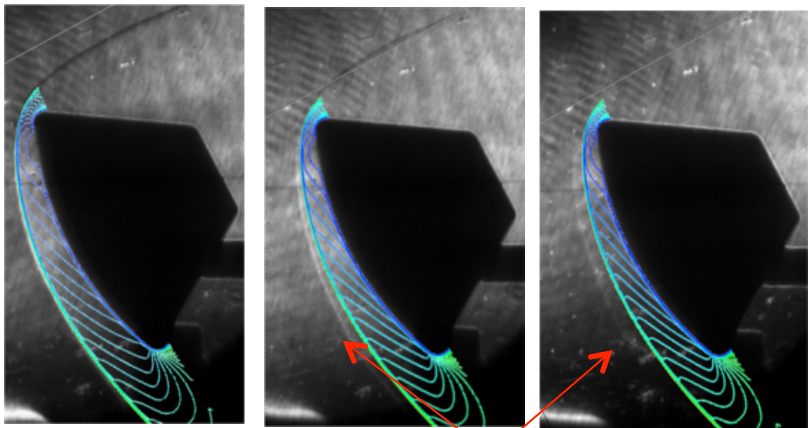
Old and New Hollow Cylinder/Flare and Double Cone Models being Employed in Studies of Real Gas Effects on Laminar Regions of Shockwave/Boundary Layer Interaction



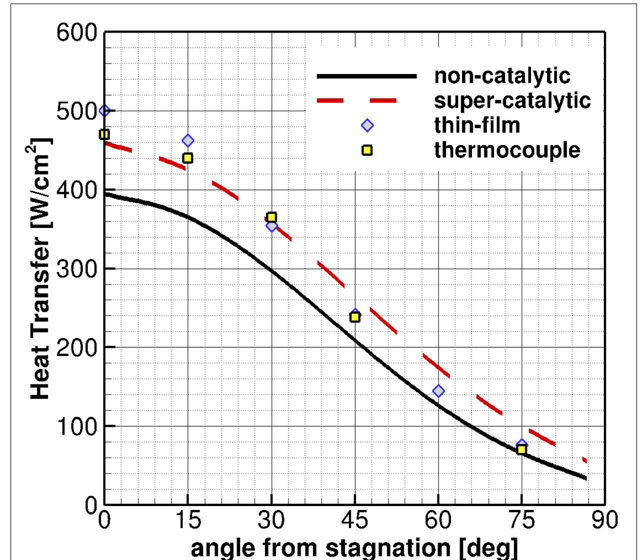


Research Activities leading uDesigned to Develop Accurate Prediction Flow Chemistry in Hypervelocity Flows

5 MJ/kg 10 MJ/kg 14 MJ/kg

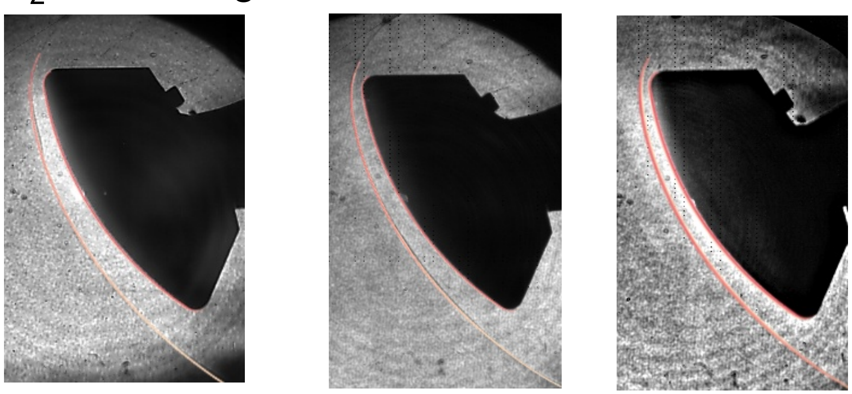


Significant Error in Shock Stand-off distance Resulting from Gas Chemistry Model in High Enthalpy Flows in LENS II

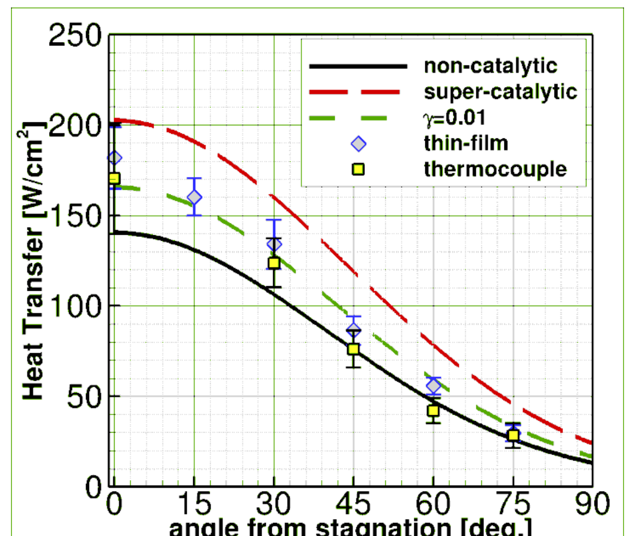


LENS-I Air @ 14,000 ft/sec

N_2 - 17 MJ/kg Air - 17 MJ/kg Air - 25 MJ/kg

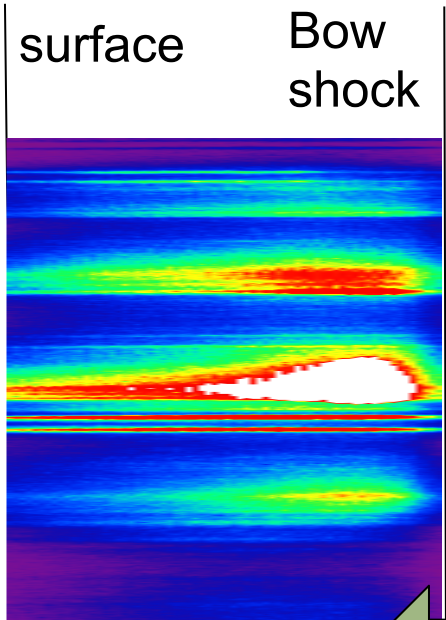


Shock Stand-off in LENS-XX Closer to Predicted Values

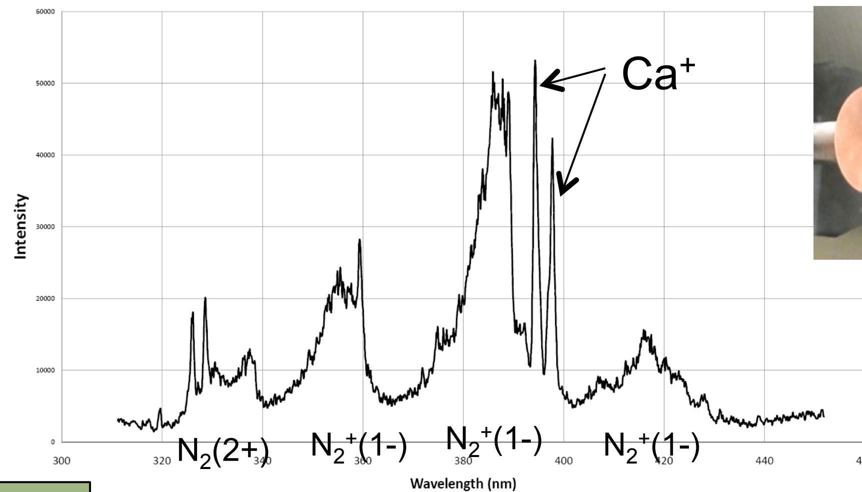


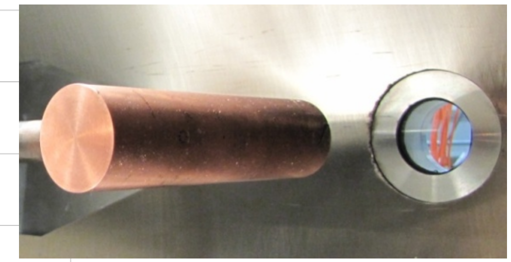
LENS-XX Air @ 14,000 ft/sec

Spectroscopic Emission Measurements in Shock Layer of Cylinder at 4-7 km/sec

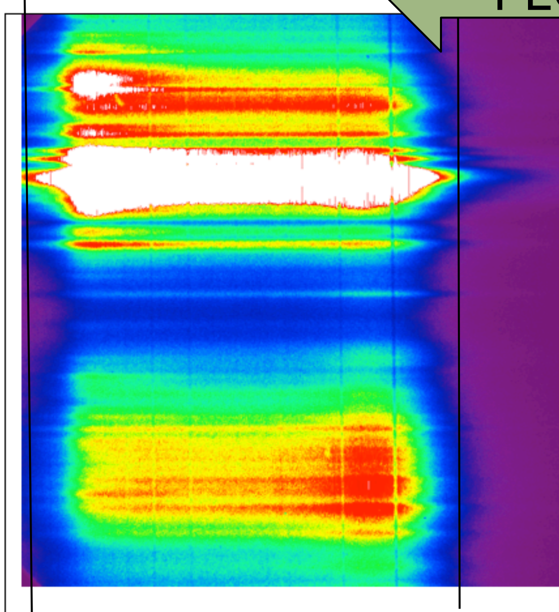


U ~ 7 km/s

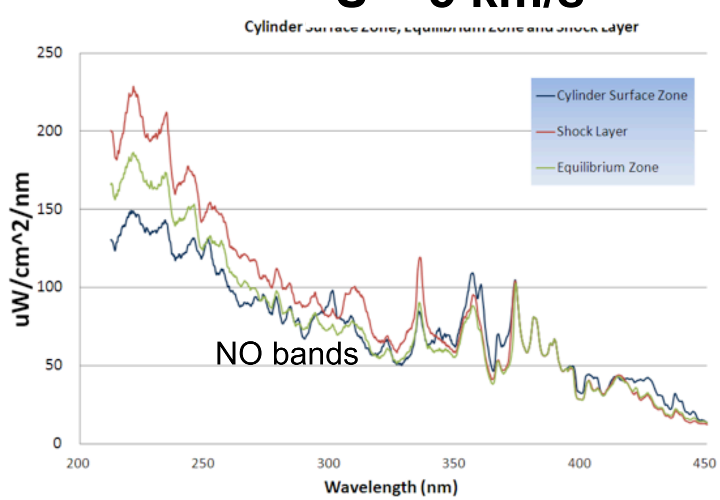


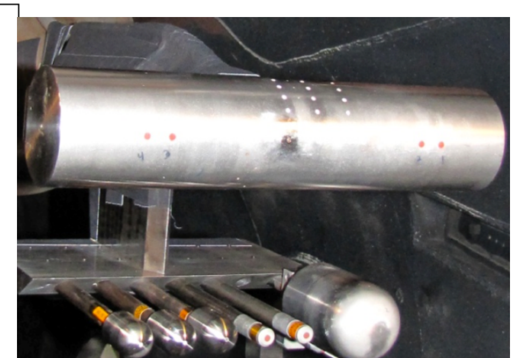


FLOW

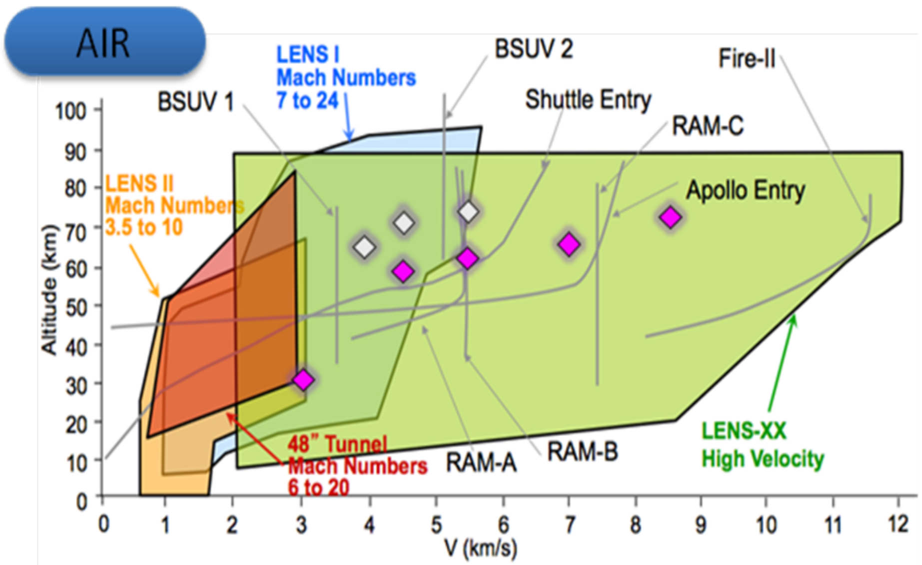


U ~ 5 km/s

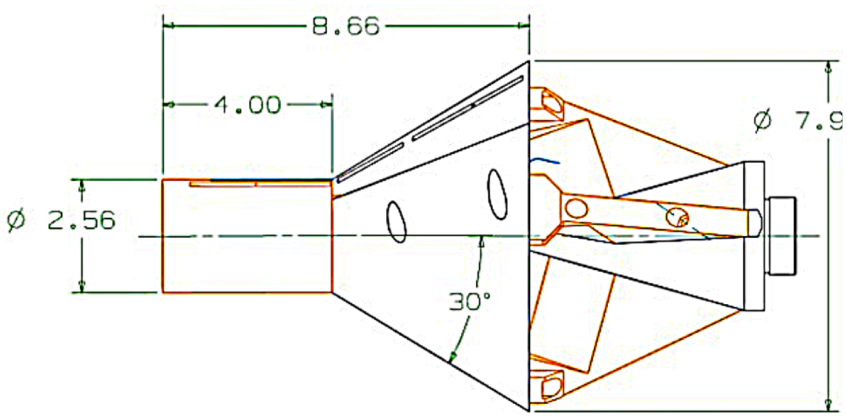




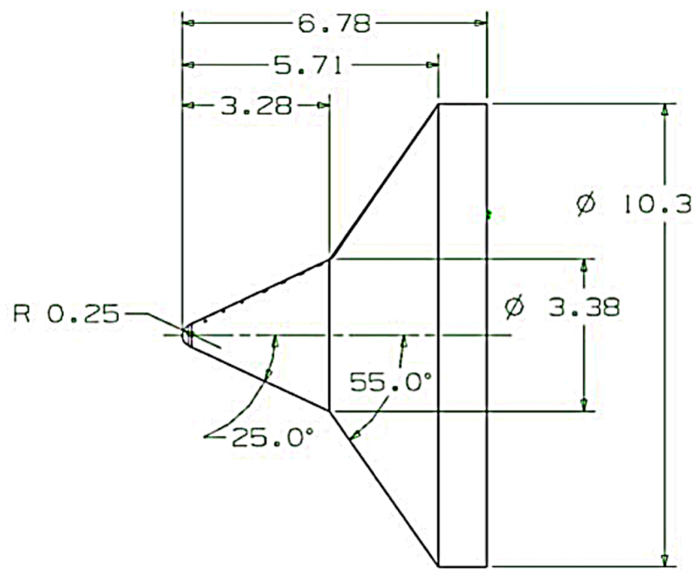
LENS-XX Test Conditions for New Hollow Cylinder Flare and Double Cone Models



Gas	Total Enthalpy (MJ/ kg)	Unit Reynolds Number
air	10	380e+3 / m [120e+3 /ft]
air	13.5	300e+3 / m [90e+3 /ft]
air	17	240e+3 / m [70e+3 /ft]
N2	10	380e+3 / m [120e+3 /ft]
N2	17	240e+3 / m [70e+3 /ft]
air	10	200e+3 / m [65e+3 /ft]
air	13.5	150e+3 / m [45e+3 /ft]
air	17	120e+3 / m [35e+3 /ft]



SMALL HOLLOW CYLINDER FLARE



SMALL DOUBLE CONE

Thought Provoking Questions on Shock Wave / Transitional-Turbulent Boundary Layer Interaction

- Can RANS/DES Calculations be Employed to Capture the Key Mechanism's Associated with Fully Turbulent Separated Regions Induced by Shock Wave /Turbulent Boundary Layer Interaction.
- What Turbulent Measurements are Required Evaluate Models of Turbulence Employed in the RANS/DES codes .
- Which instrumentation sets (we are currently developing hot wires/films and high frequency pitot probes) can be used to measure turbulent flow characteristics at velocities from 3,000ft/sec to 8,000 ft/sec.
- Which Experimental Configuration Should be used to Provide Evaluation Measurement for 3D shock Interactions. We are currently employing the CUBRC Combustion Duct and a Fin/Cone Model.

Thought-Provoking Questions on Real-gas Effects

- What are the effects of air/ablation chemistry on shock layer properties and how do they influence on boundary layer transition, vehicle stability and control surface effectiveness?
- Which chemical species can and should be measured in the shock layer to provide insight and quantitative observations to improve models of air chemistry in the CFD codes.
- Which non-intrusive diagnostic instrumentation should be used or developed to interrogate relevant physical quantities within the shock layer flow in LENS-XX?
- Which techniques can be used/developed to measure the parameters controlling gas/surface interaction?