MEASUREMENTS IN REGIONS OF SHOCK WAVE/TURBULENT BOUNDARY LAYER INTERACTION ON DOUBLE CONE AND HOLLOW CYLINDER/FLARE CONFIGURATIONS FROM MACH 5 TO 8 AT FLIGHT VELOCITIES FOR OPEN AND “BLIND” CODE EVALUATION/VALIDATION

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• Program Objectives and Design of Experimental Program

• Double Cone and Hollow Cylinder/Flare Configuration used in Studies

• Experimental Facilities and Test Conditions for “Blind” Validation Studies

• Measurements in Shock Interaction Regions over Cone/Flare Configuration and Effects of Major Flow Parameters

• Measurements on the Hollow Cylinder/Flare Configuration and Effects of Major Flow Parameters

• Summary of Results
Program Objectives and Experimental Program Design

- Obtain Detailed Heat Transfer and Pressure Measurements in Regions of Shock Wave/ Fully Turbulent Boundary Layer Interactions to Evaluate Models of Turbulence Employed in RANS and LES Codes.

- Conduct Program at Duplicated Mach 5, 6, 7 and 8 Flight Velocities and in Cold Flows on Models the Size of Typical Flight Vehicles.


- Flows which are Tripped to obtain Turbulent Boundary Layer on Two Dimensional Models or on Tunnel Walls are Poorly Defined and do not make Good Evaluation Cases.
Large Double Cone and Hollow Cylinder/Flare Models Employed in Experimental Studies to Produce Measurements for “Blind” Validation Test Cases
## Summary of Performance of LENS II Hypervelocity Ground Test Facilities

### LENS I
- **Velocity Range (ft/sec)**: 3,000 – 15,000
- **Altitude (kft)**: 25 – 300
- **Mach Numbers**:
  - 7 – 16 (true duplication)
  - 16 – 24 (Re-M only)
- **Reynolds Numbers (1/ft)**: $10^4$ – $10^8$
- **Test Time (ms)**: up to 25 ms
- **Nozzles**:
  - Mach 7 – 9 (44” Exit)
  - Mach 9 – 16 (44” Exit)
  - Mach 15 – 24 (72” Exit)

### LENS II
- **Velocity Range (ft/sec)**: 2,500 – 10,000
- **Altitude (kft)**: SL - 200
- **Mach Numbers**:
  - 3 – 10
  - Reynolds Numbers (1/ft): $10^5$ – $10^9$
  - Test Time (ms): up to 100 ms
  - Nozzles:
    - Mach 3 – 5 (42” Exit)
    - Mach 5 – 7 (60” Exit)
    - Mach 7 – 10 (72” Exit)

### LENS XX
- **Velocity Range (ft/sec)**: 8,000 – 40,000
- **Altitude (kft)**: SL - 250
- **Mach Numbers**:
  - 8 – 25
  - Reynolds Numbers (1/ft): $10^3$ – $10^9$
  - Test Time: up to 4 ms
Velocity/Altitude of LENS Tunnels showing Cold and Velocity Matching Test Points for “Blind Validation” Studies

- Large Cone Flare Flight (Velocity) Matching Conditions
- Large Cone Flare Cold Flow Conditions
- Large Hollow Cylinder Flare Flight (Velocity) Matching Conditions
- Large Hollow Cylinder Flare Cold Flow Conditions
Cold and Velocity Matching Flight Test Points for “Blind Validation” Studies on Mach Number/Reynolds Number Plot for LENS Tunnels

- Large Cone Flare Flight (Velocity) Matching Conditions
- Large Cone Flare Cold Flow Conditions
- Large Hollow Cylinder Flare Flight (Velocity) Matching Conditions
- Large Hollow Cylinder Flare Cold Flow Conditions

LENS I
LENS II
48” Tunnel
Cone Flare and Hollow Cylinder Flare Configurations and Heat Transfer and Pressure Instrumentation Employed in Experimental Program
Flow initiated through tunnel at 56 milliseconds. Each Line Represents the Average of 4 milliseconds. Mean data for the test case was taken from 72 to 92 milliseconds. Standard deviation will be provided with dataset.
# Flight Matching and Cold Flow Freestream Conditions Employed in SWTBLI Studies on Large Cone Flare Configuration

<table>
<thead>
<tr>
<th>Run Number</th>
<th>Mach Number</th>
<th>Velocity (ft/sec)</th>
<th>Temperature (deg R)</th>
<th>Density (slugs/ft^3)</th>
<th>Reynolds Number Based on Cone</th>
<th>Tw/To</th>
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Cone/Flare Mach 5 Cold Flow, $Re_L = 120 \times 10^6$

- Mach 5.1, $U_\infty = 2923$
- $Tw/To = 0.63$
- $Re# = 120 \times 10^6$
Cone/Flare Mach 5 Flight Velocity Flow, \(Re_L \approx 35 \times 10^6\)

- Mach 5.0, \(U_\infty \approx 4844\),
- \(Tw/To \approx 0.24\), \(Re# \approx 35 \times 10^6\)

Graph showing pressure and heat flux data with axial location in inches.
Cone/Flare Mach 6 Cold Flow, $Re_L = 45 \times 10^6$

- Mach 6.0, $U_\infty = 3055$
- Tw/To = 0.61, $Re\# = 45 \times 10^6$

Graph showing pressure and heat transfer data.
Cone/Flare Mach 6 Warm Flow, Re\textsubscript{l} 24\times10^6

- Mach 6.0, \(U_\infty\) 5177,
- Tw/To 0.22, Re\# 24\times10^6
Cone/Flare Mach 6 Flight Velocity Flow, $Re_L 37 \times 10^6$

Run 45 Pressure, Mach 6.0, $U_\infty 6077$, Tw/To 0.17, Re# $37 \times 10^6$

Run 45 Heat Flux

Graph showing pressure and heat transfer along axial location.
Effect of Velocity / $T_w/T_o$ on Magnitude of Interaction – Large Cone Flare

Run 33, 3055 ft/sec

Run 45, 6076 ft/sec
Effect of Mach Number on Magnitude of Interaction – Flight Matching Flow – Large Cone Flare

Run 28, Mach 5

Run 34, Mach 6
Cone/Flare Mach 7 Cold Flow, $Re_L \approx 37 \times 10^6$

- Mach 7.0, $U_\infty \approx 3863$
- $Tw/To \approx 0.40$
- $Re\# \approx 37 \times 10^6$
Cone/Flare Mach 7 Flight Velocity Flow, $Re_L 12 \times 10^6$

- Mach 7.0, $U_\infty 7209$,
- $Tw/To 0.13$, $Re# 12 \times 10^6$
Cone/Flare Mach 8 Cold Flow, $Re_L = 34 \times 10^6$
Cone/Flare Mach 8 Warm Flow, \( \text{Re}_L 12 \times 10^6 \)

- Mach 8.0, \( U_{\infty} 5737 \),
- \( Tw/To 0.25 \), \( \text{Re}# 12 \times 10^6 \)
Cone/Flare Mach 8 Flight Velocity Flow, \( \text{Re}_L 11 \times 10^6 \)

- Mach 8.0, \( U_\infty 6898 \)
- \( T_w / T_o 0.14 \)
- \( \text{Re}_\# 11 \times 10^6 \)
Effect of Velocity / $T_w/T_o$ on Magnitude of Interaction – Large Cone Flare

Run 37, 4205 ft/sec

Run 40, 5736 ft/sec

Run 41, 7898 ft/sec
### Large Hollow Cylinder Flare Test Cases for Flight Matching and Cold Flow Freestream Conditions

<table>
<thead>
<tr>
<th>Run Number</th>
<th>Mach Number</th>
<th>Velocity (ft/sec)</th>
<th>Temperature (deg R)</th>
<th>Density (slugs/ft(^3))</th>
<th>Reynolds Number Based on Cone</th>
<th>Tw/To</th>
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<td>4.49E-05</td>
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</table>
Hollow Cylinder/Flare Mach 5 Flight Velocity Flow, $Re_L \times 32 \times 10^6$

- Mach 5.0, $U_\infty = 4774$,
- $Tw/To = 0.25$,
- $Re# = 32 \times 10^6$
Hollow Cylinder/Flare Mach 5 Flight Velocity Flow, $Re_L 63 \times 10^6$

- Mach 5.0, $U_\infty 4766, \quad Tw/To 0.25, \quad Re# 63 \times 10^6$

Graph showing pressure and heat transfer as a function of axial location.
Hollow Cylinder/Flare Mach 6 Flight Velocity Flow, $Re_L \times 10^6$

- Mach 6.0, $U_\infty = 5578$
- $Tw/To = 0.20$, $Re = 17 \times 10^6$
Hollow Cylinder/Flare Mach 6 Flight Velocity Flow, $Re_L = 53 \times 10^6$

- Mach 6.0, $U_\infty = 5496$,
- Tw/To = 0.20, Re# = 53$ \times 10^6$
Reynolds Number Effect - Large Hollow Cylinder Flare

Run 11, 17x10^6

Run 13, 53x10^6
Hollow Cylinder/Flare Mach 7 Flight Velocity Flow, $Re_L 17\times10^6$

- Mach 7.0, $U_\infty 6869,$
- Tw/To 0.14, $Re# 17\times10^6$
Hollow Cylinder/Flare Mach 8 Flight Velocity Flow, \( \text{Re}_L 11 \times 10^6 \)

- Mach 8.0, \( U_\infty = 7115 \),
- \( Tw/To = 0.14 \), Re\# 11 \times 10^6
Summary of Results

• Unique Sets of Detailed Surface Measurements in Regions of Shock Wave Boundary Layer/ Fully Turbulent Boundary Layers have been obtained to Evaluate RANS and LES Prediction Methods at Flight Velocities for Mach numbers from 5 to 8 and in Cold Flows.

• Axi-symmetric Cone/Flare and Hollow Cylinder/ Flare Models the size of typical flight vehicles were employed to produce well-defined turbulent flows well upstream of the interactions and well-defined boundary conditions for the Computations.

• Measurements where made for a range of flow parameters over both Configurations to evaluate whether the large effects of Velocity / Tw/To, and Mach number and the small effect of Reynolds number observed in the program could be replicated by the prediction methods.