Langley Aerothermodynamic Labs: Testing Capabilities

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Outline

• Introduction and Motivation
• Facilities
• Test Techniques
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  – Pressure
  – Heat Transfer
  – Flow Field Visualization
  – Surface Flow Visualization
  – Data Acquisition System
• Recent Upgrades
• Planned Upgrades
  – Facility
  – Test Technique
• Facility Utilization
• Summary
Introduction and Motivation

• Hypersonic focus in 1990’s, 2000’s (Hyper-X/X-43 program, X-33, X-34, X-38, etc.)
• Reusable Launch Vehicles made understanding of aero/aeroheating key
• 2003 loss of Columbia, accident investigation/Return-to-Flight highlighted need
• Renewed planetary mission interest (Mars Exploration Rovers, Phoenix Lander, MSL), led push for EDL technologies, tested in LAL facilities
• Modifications, upgrades, enhancements to LAL facilities in response to testing requirements
• Re-evaluation of needs led to closing of 22-In Mach 15/20 Helium, 20-In Mach 6 CF$_4$ Tunnels
• Upgrades to instrumentation, signal conditioning, data acquisition systems achieved to improve flow/data quality, capability, productivity, and reliability
20-Inch Mach 6 Air Tunnel

- Operational in 1958 as 20-Inch Hypersonic Tunnel
- Conventional hypersonic blow-down facility
- Double filtering system (10 and 5 microns)
- Fixed geometry, 2D contoured Invar nozzle
  - Top/bottom walls contoured, sides parallel
  - Throat is 0.34 in. by 20 in.
- Test section 20.5 in. by 20 in.
- Exhausts to 100-ft, 60-ft and 41-ft vacuum spheres
- Operating Conditions:
  - Pressure 30-475 psia
  - Reynolds numbers: $0.5 \times 10^6$/ft – $8.3 \times 10^6$/ft
  - Temperatures: 410 °F to 475 °F
- Max run time of 20 minutes though most runs are seconds to a few minutes
- Injection system located below closed test section
- Angle of attack range of -5° to +55° and sideslip range of ±8°
- Core size is ~12-14 inches
- Six optical access ports, two on each side and top
- Tunnel pressure noise was in the range of
  - 1% (at Re of $7 \times 10^6$/ft)
  - 1.5% (at Re of $1.5 \times 10^6$/ft)
31-Inch Mach 10 Air Tunnel

- Operational in 1957 as Continuous-Flow Hypersonic Tunnel
- Conventional hypersonic blow-down facility
- Three air filters (20-, 10- and 5-micron)
- Exhausts into 60-ft and two 41-ft vacuum spheres
- Square nozzle with 1.07 in. square throat (backside water-cooled)
- Three rectangular optical access ports (top, bottom and side of test section)
- Test section is 31-in. by 31-in.
- Max run time is 2 minutes
- Operating Conditions:
  - Pressure 150-1450 psia
  - Reynolds numbers: $0.25 \times 10^6/ft$ – $2.0 \times 10^6/ft$
  - Temperatures: 1315 °F to 1350 °F
- The facility core is 14-in.
- Hydraulically, sidewall-mounted injection system
  - Angle of attack range of -45° to +45°
  - Sideslip range is ±5°
• Operational in 1991 (converted from Mach 10 Hypersonic Flow Apparatus)
• Capability of testing Mach 6 air at higher reservoir temperatures
• Conventional hypersonic blow-down facility, open-jet test section
• Two air filters (20-micron, 10 micron)
• Uncooled axisymmetric contoured Inconel nozzle
  – Throat diameter: 1.81 in.
  – Nozzle exit diameter: 14.57 in
  – Variable Area Diffuser Diameter: 18 inches
• Test core:
  – ~14 inches at 1 inch from nozzle exit
  – ~9 inches at 11 inches from nozzle exit
• Exhausts into two 41-ft, one 60-ft vacuum spheres (same as 31-Inch Mach 10)
• Operating Conditions: Maximum run time is 90 seconds
  – Pressure 100-550 psia
  – Reynolds numbers: $0.5 \times 10^6$/ft – $8.0 \times 10^6$/ft
  – Temperatures: 400 °F to 810 °F
• Hydraulically-operated, injection/retraction support mechanism
  – Angle of attack range: -10° to +50°
  – Sideslip range: ±10°
• Optical access: three 29x23 in. rectangular windows, four 5.5 in. dia. circular windows
31-Inch Mach 10 and 15-Inch Mach 6 High Temperature Air Tunnels

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60-Foot Sphere Space Simulator

• Designed to achieve vacuum levels and atmospheric conditions similar to outer space to support experiments requiring simulated space/planetary conditions

• Studies include
  – spacecraft separation in fixed-position, free-fall
  – de-spin and tumbling
  – nozzle and jet plume studies
  – solid and liquid propulsion capabilities
  – pyrotechnic devices

• Can be isolated from 41-ft spheres, simulator/tunnel can run at same time

• Diameter is 60.75 ft, total internal volume of 117,391 ft³

• Pressure level of 2\times10^{-4} \text{ torr} (simulated altitude of ~60 miles) attainable after ~9 hours pumping

• Experiments monitored by cameras and data recorders through viewing ports at sphere equator/top
• LAL facilities can use one force, five moment (1F/5M), five force, one moment (5F/1M) and three force, three moment (3F/3M) balances
• Sting (straight or bent) or strut supported, 0.56 in outer diameter
• Range of design loads for blunt/high drag and/or slender/high lift models
• Water cooled, five and six components, 5-volt excitation voltage
• Calibrated prior to testing, verified during set up
• Tare run with model mounted to balance performed over angle of attack range
• LAL currently uses AIAA calibration standard and internal LaRC standards
Discrete Pressure Instrumentation

ESP
• Electronically Scanned Pressure
• Pressure ranges in LAL are 10 in. WC, 1 psi, 5 psi and 15 psi.
• Capacity for 512 channels

Kulite
• Channels: 31-Inch Mach 10 (12), 20-Inch Mach 6 (32), 15-Inch Mach 6 High Temperature (8)
  Multi-range, variable capacitance diaphragm-type transducers
• Kulite piezoresistive pressure transducers combine force summing/transduction element into
  micro-machined, dielectrically isolated silicon or silicon carbide diaphragm
• Resonant frequencies between 100 and 300 kHz (depending on specific type of Kulite)

Piezoelectric Pressure Sensor (PCB)
• Dynamic sensor generates charge when pressure applied. Charge leaks to zero at rate
  dependent electrical insulation's resistance
• Useful for measuring frequencies between 11kHz and 1MHz
• Sensor diameter 0.125 in but the sensing element is 0.030x0.030-in square
• Characterize boundary layer transition by measuring growth/breakdown of instability waves

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Pressure Sensitive Paints (PSP)

- PSPs allow global surface pressure measurements using CCD camera
- Oxygen-sensitive luminescent molecules in oxygen-permeable polymer binder applied with conventional paint spraying
- White acrylic primer basecoat (enhances adhesion and scattering of luminescence intensity)
- Illuminated using UV LEDs
- Luminescence emission captured on CCD cameras with spectral band-pass filters to distinguish between excitation (UV) and emission signals.
- Emission in orange/red region of visible spectrum (~590 - ~650 nm)
- Emission intensity inversely proportional to amount of oxygen present at surface
  - Lower oxygen concentration has greater emission intensity
  - Correlated to total pressure on surface – ratio of reference and wind-on images

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**Thin Film, Thin Skin and Thermocouples**

**Channels:** 31-Inch Mach 10 (255), 20-Inch Mach 6 (156), 15-Inch Mach 6 High Temperature (120)

**Co-Axial Thermocouples**
- LAL uses UTR to connect thermocouples to data system
- UTR has Resistance Temperature Detector as reference junction temp

**Thin Film**
- LAL facilities can use two wire or four wire gages
- Data can be acquired at 500 Hz or more
- NEFF 600 supplies 1 mA current to power the gage
- 1DHEAT code reduces temps to heating rates.

**Thin Skin**
- Thermocouples measure temps on back face of thin-skin, welded to inside surface
- Temperature time history, thermal properties and average thickness used in 1DHEAT
Global Phosphor Thermography

- Two-color relative-intensity with zinc cadmium sulfide, lanthanum oxysulfide, colloidal silica binder
- Applied to slip-cast silica ceramic model using air brush (~0.001-in thickness)
- Fluoresces under UV light: zinc cadmium sulfide (green), lanthanum oxysulfide (red)
- Intensity dependent on incident UV light, local surface temperature
- Intensity images acquired at 30 fps on 8 bit, 3-CCD camera
- Images converted to temperature mappings via temperature-intensity calibration
- Calibration uses ratio of red/green, response of computer, window transmisivity
- Valid over a temperature range from 18 °C (65 °F) to 160 °C (320 °F)
- Pre-run and run temperature images compared,
  - Reduced to enthalpy based heat transfer coefficient globally on model
  - Uses 1D semi-infinite slab heat conduction technique
- Advantages: global, rapid/inexpensive fabrication, robust coating
Temperature Sensitive Paints

- Similar to phosphor thermography except works at lower temperatures
- Images collected on 14-bit thermoelectrically cooled digital camera (2048x2048 pixels)
- TSP formulation process similar to PSP except luminescent molecules chosen to maximize temperature sensitivity, dispersed in oxygen impermeable binder (limits quenching by oxygen)
- All quenching occurs through non-radiative temperature effects
- Formulation developed by Advanced Sensing and Optical Measurement Branch
- Applied over white acrylic primer
- Illuminated with LED based arrays (400 nm)
Infrared

- Surface temperature of model may be calculated based on radiation at infrared wavelengths
- LAL has infrared imaging system (FLIR System ThermaCAM SC 3000 camera)
- 320x240 pixels, -20 °C to +1500 °C (-4 °F to 2732 °F), divided into 4 temp ranges
- Accuracy of ±1% or ±1 °C (up +150 °C), ±2% or ±2 °C (above +150 °C)
- Atmospheric transmission correction (auto, based on distance, temp, humidity)
- Optics transmission correction (auto, based on signals from 5 internal sensors)
- Emissivity correction (auto, variable from 0.1 to 1.0 or pre-defined materials list)
- Image acquisition frequency of 50/60 Hz non-interlaced
- 14-bit radiometric IR digital image (includes radiometric data), 8-bit standard bitmap
- Can also be saved as CSV including temperature value at each pixel.
- Top windows at 31-Inch Mach 10 and 20-Inch Mach 6 can use 9x16 in. IR windows
Planar Laser Induced Fluorescence (PLIF)

- 3D, spatially-resolved, off-body visualization
- Investigate laminar to turbulent BLT, RCS effects, wake flow phenomena
- Nitric Oxide gas used to image flow field off the surface of models
- Laser system operated at 10 Hz, ~10 ns pulse duration, tuned to 226.256 nm wavelength
- Images acquired using 2 Princeton Instruments PI-MAX II CCD cameras (512x512 pixel resolution)
- Laser sheet translated in tunnel, allowing measurements both along and away from surface
- Custom built MHz-rate PLIF imaging system with max frame rate of 1 MHz (160 x 160 pixels)
- MTV capability under development (array of 25 lenses focus laser sheet into 25 lines)
• LAL facilities have pulsed white-light, Z-pattern, single-pass Schlieren systems

• 31-Inch Mach 10 Tunnel
  – ~5.75 in. diameter field of view, digital video system to acquire video and still frame images
  – 30fps video (1 megapixel, 8-bit grayscale digital video camera, 150 μsec exposure time)
  – Still images acquired on 13.5 megapixel Kodak SLR/n

• 20-Inch Mach 6 Tunnel
  – 15 in. dia. field of view, Camera/light source line-driven at 60 Hz
  – Video captured 768 × 493 pixel video camera, recorded to DVD
  – Still images acquired on 13.5 megapixel Kodak SLR/n

• 15-Inch Mach 6 High Temperature Tunnel
  – 5.75 in diameter field of view temporary system
  – Video acquired via video camera and recorded to DV recorder

• High-speed Schlieren utilizing Vision Research Phantom 9 or Phantom 12 cameras
  – Max resolution of 1632x1200 and 1280 x 800 respectively
  – Frame rates up to 1000 and 6000 fps respectively at full resolution
  – Frame rates up 150,000 and 680,000 fps at reduced resolutions
  – Still images can be extracted from acquired videos
Oil Flow

• Flow field patterns for better understanding of force and moment, pressure and heat transfer measurements
• Models painted black, coated with one or more oils of various viscosities (depends on geometry, test conditions, model orientation, etc.)
• Immediately before run, surface coated with either
  – Green phosphorescent pigment powder
  – Oil and white pigment
• Model injected into flow and shear forces at surface cause powder/oil mixture to show near surface streamline patterns, flow separation and reattachment lines, etc.
• Movement of powder/oil during injection/retraction insignificant enough to allow post-run images
Data Acquisition System

- 256-channel, 16 bit, 50 kHz or 100 kHz aggregate throughput rate, amplifier per channel, analog-to-digital (A/D) system manufactured by NEFF Instrument Corporation
- Typical sampling rate is 30 samples per second per channel, can be adjusted
- Pressure data measured using ESP piezoresistive (silicon) sensors (PSI model 8400 measurement system)
- LAL Acquisition Program written in HTBasic, controls NEFF, ESP for setup, acquisition, retrieval
- LAL Data Reduction Program written in MATLAB, incorporates mV-EU conversion, Global Wind Tunnel Force Data Reduction Program, GasProps
- Ability to handle additional customer requested equations
- HBM Genesis HighSpeed Data Acquisition System, Gen5i, for higher sampling frequencies
  - Robust, portable
  - Slots for five input modules (up to 40 channels of various capabilities)
  - Current system: 3 HiSpeed100M modules (4 channels each, 100MHz, 15-bit resolution), 1 Basic1M iso module (8 channels, 1MHz, 16-bit resolution)
Recent Facility Upgrades and Enhancements

Installation of the Balance Load Monitoring System (BLMS)
• Installed in the LAL facilities in 2003
• Monitors balance loading during model installation, tunnel runs
• Decreases likelihood of damage/loss of balance due to overload
• Alarm events activated at 80% and 100% of rated load (visual and audible)

12.5 MW Heater Power Supply, 31-In Mach 10, 15-In Mach 6 High Temperature Air Tunnels
• Upgraded in 2002 to improve stagnation temperature control loop repeatability, accuracy, and response time and control stagnation temperature to within ±1% of set point
• New Silicon Controlled Rectifier (SCR) power supply/updated control

Upgrade/replacement of 31-Inch Mach 10 Air Tunnel Model Control System
• 31-Inch Mach 10 Air Tunnel Model Control System upgraded in 2012
• Modernized controls with graphical user interface (GUI)
• Improved reliability/functionality, reduced costly maintenance of antiquated controls
• Pitch axis utilizes Kinetix motor, built-in incremental encoder and brake, torque controllable
  – Range is ±90º with ±0.01º resolution
  – Position encoder is rotary with 0.0004º/count resolution in pitch axis
  – Inject/retract models, adjust velocity/acceleration/position, model pitch speed/acceleration, table of AoA
  – Controls model injection box equalization valves, vent valve and hydraulic pump.
Replace instrumentation wiring in the 20-Inch Mach 6 Air Tunnel
• Replace and/or upgrade wiring in 20-Inch Mach 6 Air Tunnel
• Will simplify wiring and better align channel count with current/future requirements
• Will allow for higher frequency data (1+ KHz) w/o signal degradation

Purchase/install new computers and software to replace NEFF hardware
• Due to age of NEFF and announced closing of NEFF Instruments, parts/repairs difficult
• NI hardware replacement, Precision Filters 28000 signal conditioning and NI LabVIEW
• 256 (100 Hz sampling rate) or 142 (200 KHz sampling rate) analog input channels
• Max 16 analog input channels, sampling rates up to 15M samples/sec/channel (signal frequencies in 1-500 KHz range)

Upgrade/replacement of the 20 in Mach 6 Tunnel Model Support Control System
• Rotary pitch/yaw position encoders, resolution 0.0004º/count pitch, 0.0003º/count yaw
• 100% Upgrade Design approved by ATP as FY13 project
• Installation scheduled January to June 2015
Future Instrumentation Enhancements

Pressure System UG/Optimus & Gen 2 Module UP

- Optimus Data System is pressure scanning system designed for wind tunnels
- Modules digitally temperature compensated, require fewer calibrations, provide higher accuracy
- Initialized in Mach 10 Tunnel in August 2013, scheduled to complete August 2014

High Temperature Global Phosphor Thermography

- New formulation to increase measurable temperature from 160 °C (320 °F) to 300 °C (570 °F)
- Will allow better characterization near stagnation regions, in turbulent boundary layers, etc.

Continuous Pitch Sweep Aerodynamic Force and Moment Data

- Will allow continuous sweep pitching during aerodynamic force and moment testing
  - Shorter run times (less heating to model, sting, balance)
  - Increased run productivity (less time to pump down the vacuum spheres between runs)
  - Increased data (pitch-pause method limited to preset angles compared to all angles in sweep range)

Metallic Surface Integration into Ceramic Models for Phosphor Thermography Tests

- Capability under development to integrate metallic components into ceramic models
- Advantage: allows sharper leading edges than cast ceramics alone, inlets, etc.
- Disadvantage: metallic regions will not be measured in phosphor system
• Decrease in testing noted in LAL test facilities in recent years
• Brought on by cancellation/conclusion of major flight programs (Space Shuttle, Hyper-X, X-33, X-34, X-38, etc.)

Major testing programs and impacts over the last 15 years include:
• Space Shuttle: 3500+ runs 2003-2011 (Columbia Accident Investigation, Return-To-Flight, on-orbit assessments, support of BLT Flight Experiment and HYTHIRM teams)
  – Wind tunnels used to determine cause of STS-107 Columbia accident
  – Major RTF contributions include Cavity Heating and Boundary Layer Transition Tools
  – Design/test of boundary layer transition trips used to force turbulent flow in inlet
  – Aero testing for better understanding of X-43 flight performance when mounted to Pegasus booster
• X-33: 2200+ runs 1998-1999 supporting aerodynamic/aeroheating performance
• X-38: 850+ runs 1998-2001 supporting aerodynamics/aeroheating performance
• Orion: ~1400 runs 2006-2011 for aerodynamic/aeroheating performance, RCS and BLT effects
• EDL: 1800+ run for programs Including MSL, Mars Sample Return Orbiter, HIADS, etc.
  – Supported understanding of re-entry heating, shape effects, aerodynamics, etc.
Summary

• LAL consists of three hypersonic blown-down tunnels and a vacuum test facility.
  – 20-In Mach 6, 31-In Mach 10 Tunnels designed, built, first utilized in 1950’s and 1960’s
  – 15-In Mach 6 was first utilized in 1991
  – Represent a significant portion agency’s aerothermodynamic testing capability
  – Between three tunnels, Mach numbers of 6 and 10, Reynolds numbers of 0.25-8.0x10^6/ft

• Update to facility, instrumentation and capabilities presented
  – Detailed descriptions/diagrams of tunnels (pressures, temperatures, freestream conditions)
  – Instrumentation/test techniques to measure forces and moments, heating, pressure,
    surface and flow-field characteristics, including intrusive and non-intrusive techniques and
    data acquisition systems
  – Summary of major facility/instrumentation upgrades/improvements/projects for last 16 years
  – Summary of upcoming/planned facility/instrumentation improvements
  – The recent (last 16 years) utilization of LAL including major test programs, impacts

• LAL facilities provide unique and valuable capability for past, current and future hypersonic ground testing needs

• Aerodynamic, aerothermodynamic and flow physics studies provide for performance assessment of advanced hypersonic vehicles and benchmarking data for computational techniques.
Backup Slides
### Operating Conditions

#### 20-Inch Mach 6 Air Tunnel

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#### 31-Inch Mach 10 Air Tunnel

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## Operating Conditions

### 15-Inch Mach 6 High Temperature Air Tunnel

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## Recent Facility Upgrades and Enhancements

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<th>Facility</th>
<th>Capability</th>
<th>Productivity</th>
<th>Reliability</th>
<th>Safety/Security</th>
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<tbody>
<tr>
<td><strong>20-Inch Mach 6 Air</strong></td>
<td>Full Field IR Window</td>
<td>Yaw System Calibration System Control Room Makeover</td>
<td>Balance Load Monitoring System DH transformer Installed LED Schlieren System Light Source Remachined Settling Chamber</td>
<td>Control Room Makeover Control Room Security System Installed Security Camera System</td>
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<tr>
<td><strong>31-Inch Mach 10 Air</strong></td>
<td>Installed Low Noise Settling Chamber Schlieren System</td>
<td>Environmentally Controlled Area for Tunnel</td>
<td>12.5 MW Heater Power Supply Upgrade Injection PLC Heater in Enclosure Replace Preheat Valves</td>
<td>Environmentally Controlled Area for Tunnel</td>
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<tr>
<td><strong>15-Inch Mach 6 High Temperature Air</strong></td>
<td>Installed Viewing Windows Schlieren System</td>
<td>Rehabbed Control Room Added Kirk Key Entry System</td>
<td>Replaced Seals Removed Diffusion Pump System Certified 12 ft Monorail Door</td>
<td>Rehabbed Control Room</td>
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<td><strong>60-Foot Sphere Space Simulator</strong></td>
<td>Installed Viewing Windows Rehabbed Control Room</td>
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TFAWS 2014 – August 4-8, 2014