



## Langley Aerothermodynamic Labs: Testing Capabilities

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- Summary



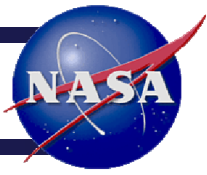
# Introduction and Motivation



- 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  $\text{CF}_4$  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

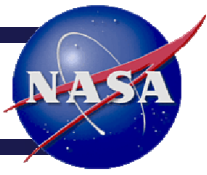


- Operational in 1958 as 20-Inch Hypersonic Tunnel
- Conventional hypersonic blow-down facility
- Double filtering system (10 and 5 microns)
- Fixed geometry, 2D contoured Invar nozzle
  - Top/bottom walls contoured, sides parallel
  - Throat is 0.34 in. by 20 in.
- Test section 20.5 in. by 20 in.
- Exhausts to 100-ft, 60-ft and 41-ft vacuum spheres
- Operating Conditions:
  - Pressure 30-475 psia
  - Reynolds numbers:  $0.5 \times 10^6/\text{ft}$  –  $8.3 \times 10^6/\text{ft}$
  - 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  $-5^\circ$  to  $+55^\circ$  and sideslip range of  $\pm 8^\circ$
- 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  $7 \times 10^6/\text{ft}$ )
  - 1.5% (at Re of  $1.5 \times 10^6/\text{ft}$ )

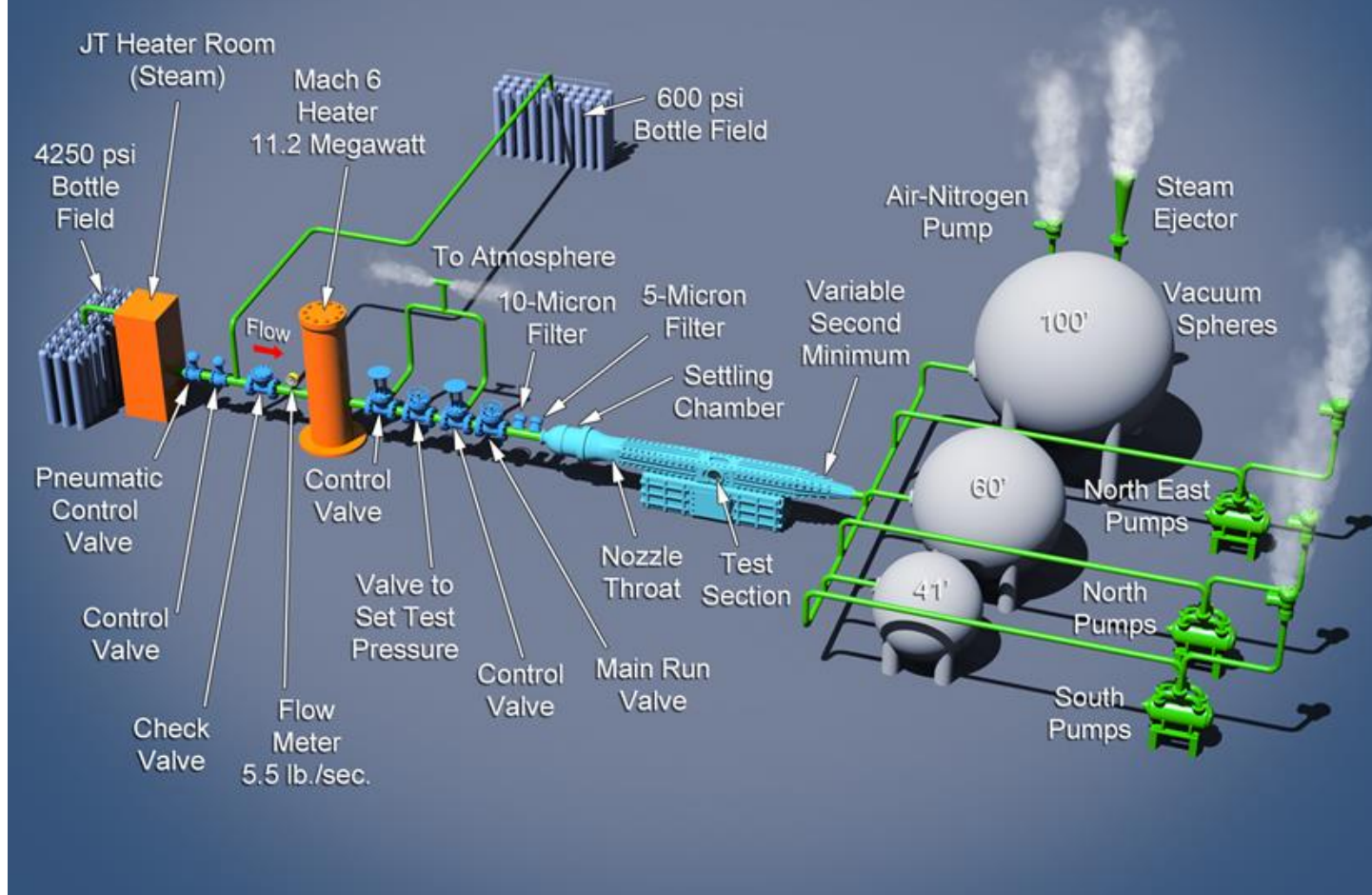




# 20-Inch Mach 6 Air Tunnel

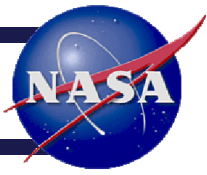


## LAL 20-Inch Mach 6 Air Tunnel





# 31-Inch Mach 10 Air Tunnel

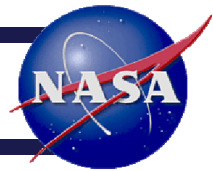


- Operational in 1957 as Continuous-Flow Hypersonic Tunnel
- Conventional hypersonic blow-down facility
- Three air filters (20-, 10- and 5-micron)
- Exhausts into 60-ft and two 41-ft vacuum spheres
- Square nozzle with 1.07 in. square throat (backside water-cooled)
- Three rectangular optical access 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:  $0.25 \times 10^6/\text{ft}$  –  $2.0 \times 10^6/\text{ft}$
  - Temperatures: 1315 °F to 1350 °F
- The facility core is 14-in.
- Hydraulically, sidewall-mounted injection system
  - Angle of attack range of  $-45^\circ$  to  $+45^\circ$
  - Sideslip range is  $\pm 5^\circ$



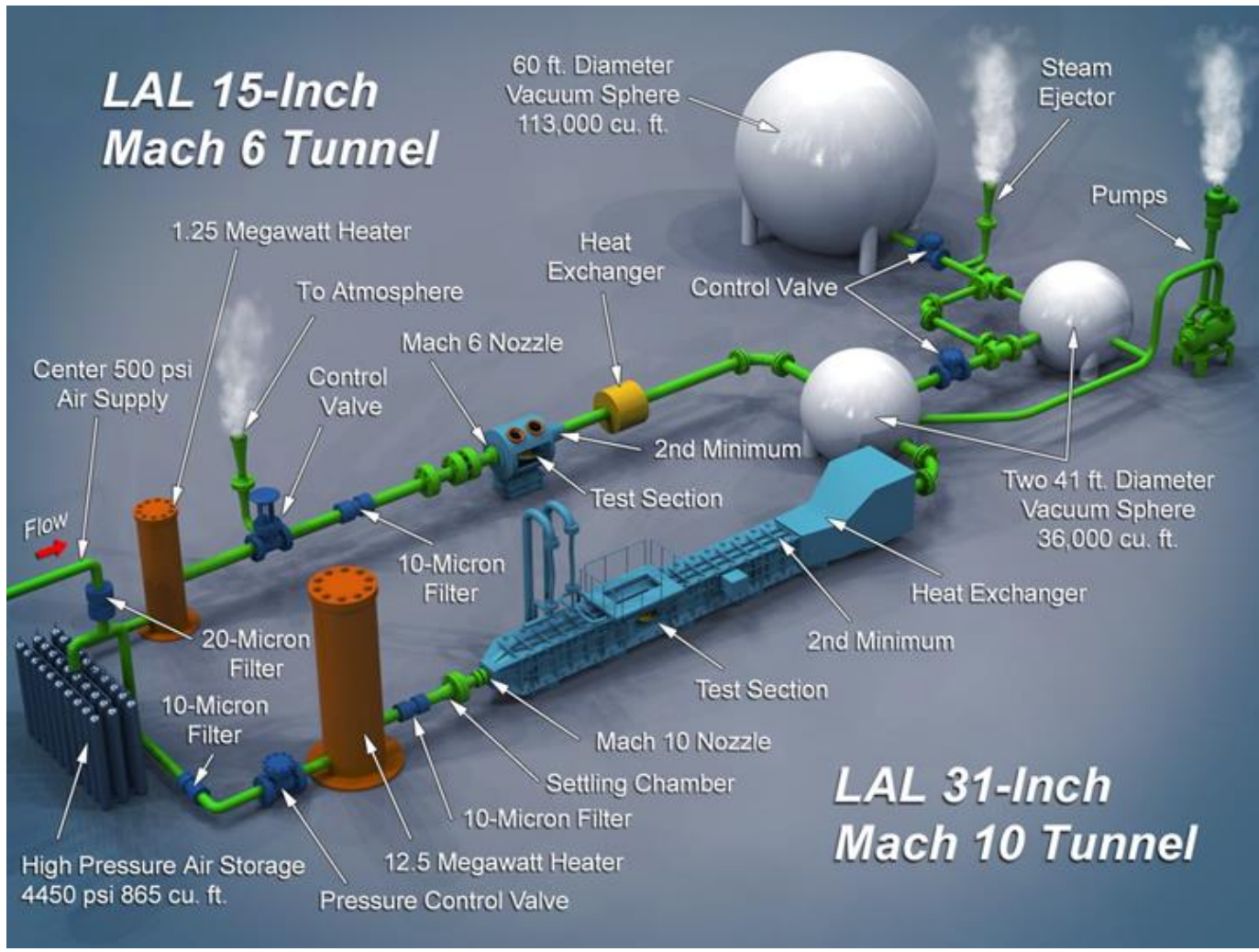


# 15-Inch Mach 6 High Temperature Air Tunnel



- 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:  $0.5 \times 10^6/\text{ft}$  –  $8.0 \times 10^6/\text{ft}$
  - Temperatures: 400 °F to 810 °F
- Hydraulically-operated, injection/retraction support mechanism
  - Angle of attack range:  $-10^\circ$  to  $+50^\circ$
  - Sideslip range:  $\pm 10^\circ$
- Optical access: three 29x23 in. rectangular windows, four 5.5 in. dia. circular windows









# 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 ft<sup>3</sup>
- Pressure level of  $2 \times 10^{-4}$  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





# Force and Moment



- 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



## ESP

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

## Kulite

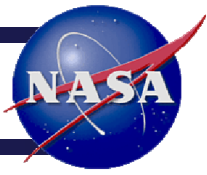
- Channels: 31-Inch Mach 10 (12), 20-Inch Mach 6 (32), 15-Inch Mach 6 High Temperature (8) Multi-range, variable capacitance diaphragm-type transducers
- Kulite piezoresistive pressure transducers combine force summing/transduction element into micro-machined, dielectrically isolated silicon or silicon 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



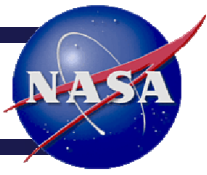
# Pressure Sensitive Paints (PSP)



- 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



# 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***

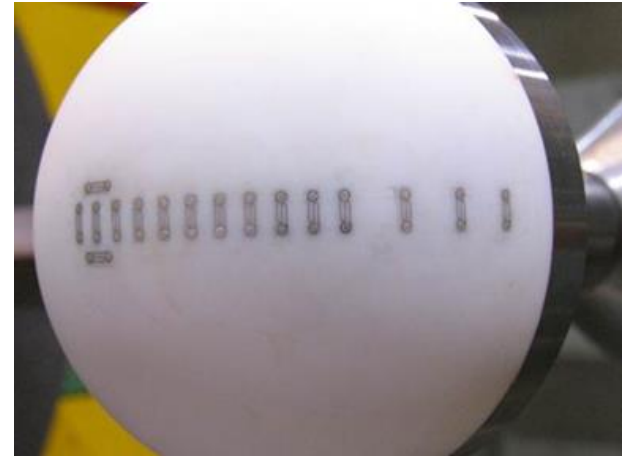
- LAL uses UTR to connect thermocouples to data system
- UTR has Resistance Temperature Detector as reference junction temp

## ***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.

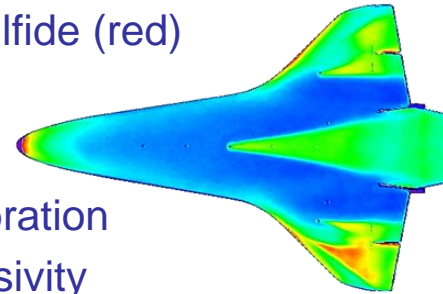
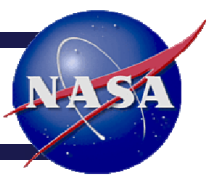
## ***Thin Skin***

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

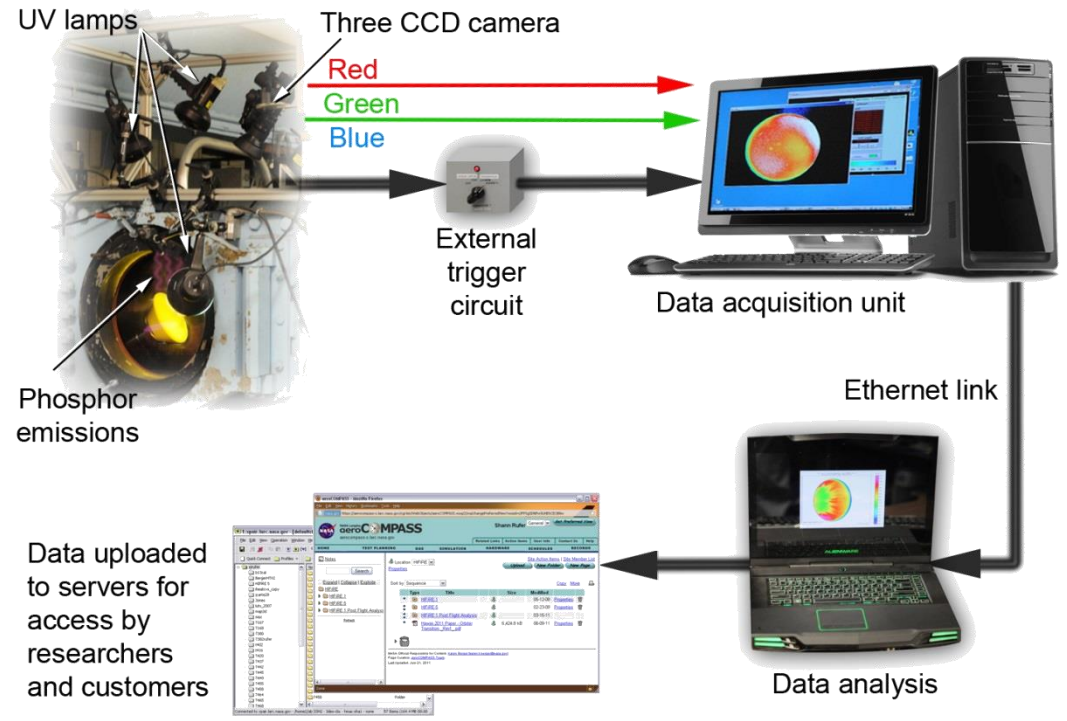




# Global Phosphor Thermography

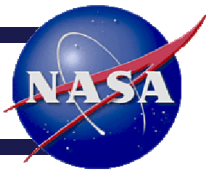


- Two-color relative-intensity with zinc cadmium sulfide, lanthanum oxysulfide, colloidal silica binder
- Applied to slip-cast silica ceramic model using air brush (~0.001-in thickness)
- Fluoresces under UV light: zinc cadmium sulfide (green), lanthanum oxysulfide (red)
- Intensity dependent on incident 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 transmissivity
- 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

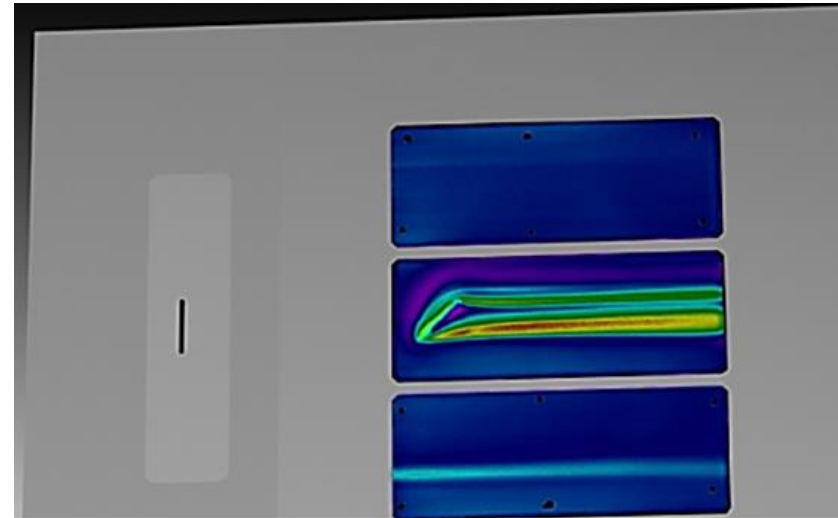




# Temperature Sensitive Paints

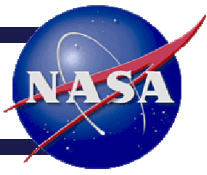


- Similar to phosphor thermography except works at lower temperatures
- Images collected on 14-bit thermoelectrically cooled digital camera (2048x2048 pixels)
- TSP formulation process similar to PSP except luminescent molecules chosen to maximize temperature sensitivity, dispersed in oxygen impermeable 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

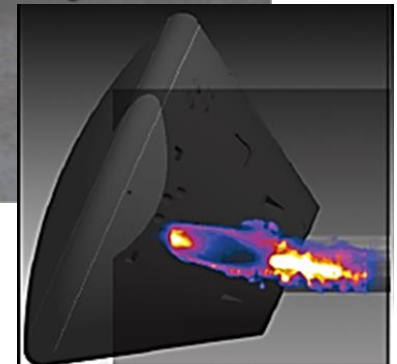
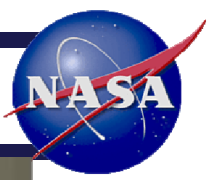


- Surface temperature of model may be calculated based on radiation at infrared wavelengths
- LAL has infrared imaging system (FLIR System ThermaCAM SC 3000 camera)
- 320x240 pixels, -20 °C to +1500 °C (-4 °F to 2732 °F), divided into 4 temp ranges
- Accuracy of  $\pm 1\%$  or  $\pm 1$  °C (up +150 °C),  $\pm 2\%$  or  $\pm 2$  °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





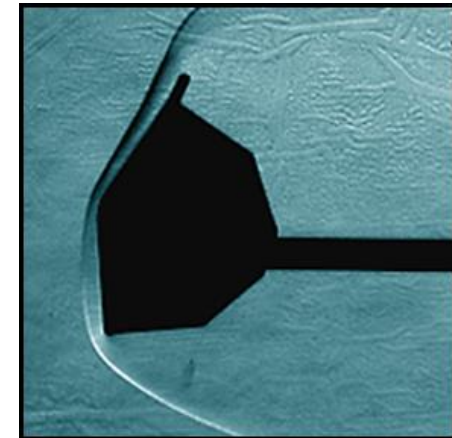
# Planar Laser Induced Fluorescence (PLIF)



- 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  $\mu$ sec 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  $\times$  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 1632 $\times$ 1200 and 1280  $\times$  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

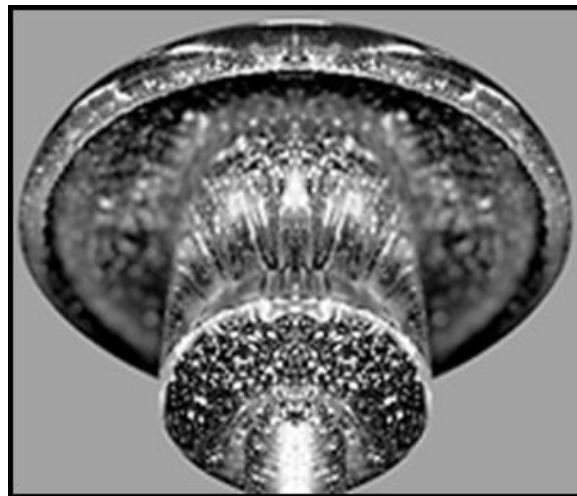




# Oil Flow

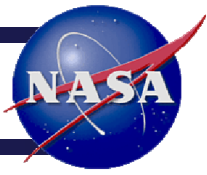


- Flow field patterns for better understanding of force and moment, pressure and heat transfer measurements
- Models painted black, coated with one or more oils of various viscosities (depends on geometry, test conditions, model orientation, etc.)
- Immediately before run, surface coated with either
  - 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

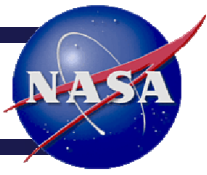




# Data Acquisition System



- 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)



## **Installation of the Balance Load Monitoring System (BLMS)**

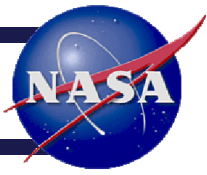
- Installed in the LAL facilities in 2003
- Monitors balance loading during model installation, tunnel runs
- Decreases likelihood of damage/loss of balance due to overload
- Alarm events activated at 80% and 100% of rated load (visual and audible)

## **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  $\pm 1\%$  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  $\pm 90^\circ$  with  $\pm 0.01^\circ$  resolution
  - Position encoder is rotary with  $0.0004^\circ/\text{count}$  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 0.0004°/count pitch, 0.0003°/count yaw
- 100% Upgrade Design approved by ATP as FY13 project
- Installation scheduled January to June 2015



## **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**

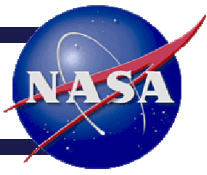
- Will allow continuous sweep pitching during aerodynamic force and moment testing
  - Shorter run times (less heating to model, sting, balance)
  - Increased run productivity (less time to pump down the vacuum spheres between runs)
  - Increased data (pitch-pause method limited to preset angles compared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



# Facility Utilization



- 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
- Hyper-X: 2500+ runs 1998-2007 (mostly before first flight in 2000, before final flights in 2004)
  - 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.

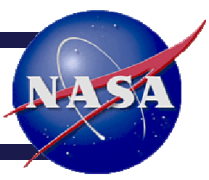




# Summary



- 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  $0.25-8.0 \times 10^6/\text{ft}$
- 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

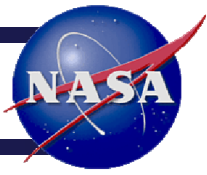
$P_{t,1}$ , psi	$T_{t,1}$ , °R	$P_{\infty}$ , psi x 10 <sup>-2</sup>	$T_{\infty}$ , °R	$q_{\infty}$ , psi	$V_{\infty}$ , ft/s	$M_{\infty}$	$Re_{\infty}$ , ft <sup>-1</sup> x10 <sup>6</sup>	$Re_2$ , ft <sup>-1</sup> x10 <sup>5</sup>	$\rho_2/\rho_{\infty}$	$P_{t,2}$ , psi
30	870	2.40	112.56	0.56	3012	5.79	0.58	1.03	5.23	1.05
60	885	4.25	110.62	1.03	3039	5.89	1.07	1.85	5.26	1.92
125	910	8.12	111.66	2.04	3086	5.96	2.05	3.54	5.28	3.80
190	920	12.31	112.37	3.09	3109	5.99	3.07	5.26	5.28	5.74
250	910	16.19	110.82	4.07	3092	6.01	4.05	7.03	5.28	7.57
365	935	23.11	112.98	5.86	3131	6.03	5.67	9.82	5.29	10.88
475	935	29.60	113.00	7.52	3135	6.04	7.37	12.58	5.29	13.98
475	870	30.16	105.43	7.60	3012	6.03	8.26	13.94	5.28	14.12

## 31-Inch Mach 10 Air Tunnel

$P_{t,1}$ , psi	$T_{t,1}$ , °R	$P_{\infty}$ , psi x 10 <sup>-2</sup>	$T_{\infty}$ , °R	$q_{\infty}$ , psi	$V_{\infty}$ , ft/s	$M_{\infty}$	$Re_{\infty}$ , ft <sup>-1</sup> x10 <sup>6</sup>	$Re_2$ , ft <sup>-1</sup> x10 <sup>5</sup>	$\rho_2/\rho_{\infty}$	$P_{t,2}$ , psi
350	1775	1.00	93.68	0.66	4593.40	9.68	0.53	0.49	5.96	1.22
720	1790	1.89	92.23	1.27	4614.60	9.81	1.04	0.93	5.97	2.36
1300	1790	3.19	90.35	2.20	4618.30	9.93	1.82	1.61	5.97	4.07
1450	1790	3.52	90.26	2.43	4626.10	9.96	2.03	1.78	5.98	4.51



# Operating Conditions

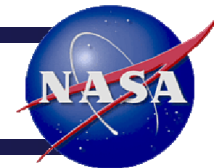


## 15-Inch Mach 6 High Temperature Air Tunnel

$P_{t,1}$ , psi	$T_{t,1}$ , °R	$P_{\infty}$ , psi x 10 <sup>-2</sup>	$T_{\infty}$ , °R	$q_{\infty}$ , psi	$V_{\infty}$ , ft/s	$M_{\infty}$	$Re_{\infty}$ , ft <sup>-1</sup> x10 <sup>6</sup>	$Re_2$ , ft <sup>-1</sup> x10 <sup>5</sup>	$\rho_2/\rho_{\infty}$	$P_{t,2}$ , psi
100	935	6.95	117.29	1.70	3141	5.92	1.60	2.83	5.27	3.17
100	1060	6.91	133.41	1.70	3351	5.92	1.31	2.42	5.29	3.15
135	935	9.16	116.49	2.26	3142	5.94	2.14	3.76	5.28	4.21
150	1210	9.98	151.70	2.48	3594	5.95	1.56	3.02	5.33	4.61
200	870	13.28	107.58	3.30	3029	5.97	3.51	5.98	5.27	6.14
200	960	13.21	118.72	3.29	3187	5.97	3.01	5.24	5.29	6.12
200	1210	13.05	150.83	3.26	3595	5.97	2.06	3.97	5.34	6.06
275	935	17.94	115.12	4.49	3144	5.99	4.29	7.46	5.28	8.35
275	960	17.91	118.22	4.49	3187	5.99	4.11	7.22	5.29	8.34
300	870	19.62	107.14	4.91	3029	5.99	5.24	8.88	5.27	9.12
300	1210	19.23	149.96	4.83	3597	5.99	3.08	5.89	5.34	8.99
400	870	25.90	106.86	6.50	3028	6.01	6.96	11.78	5.28	12.08
400	910	25.79	111.60	6.49	3100	6.01	6.49	11.13	5.28	12.05



# Recent Facility Upgrades and Enhancements



Facility	Capability	Productivity	Reliability	Safety/Security
<b>20-Inch Mach 6 Air</b>	Full Field IR Window	Yaw System Calibration System Control Room Makeover	Balance Load Monitoring System DH transformer Installed LED Schlieren System Light Source Remachined Settling Chamber Balance Load Monitoring System	Control Room Makeover Control Room Security System Installed Security Camera System
<b>31-Inch Mach 10 Air</b>	Model Control System Schlieren System Laser Interlock System IR Window	Model Control System Kirk Keys System for High Pressure Valves Install Work Platform	12.5 MW Heater Power Supply Heater Lining Replacement Model Control System Hydraulic Filtering System Rebuild Model Injection Box Bearings Replace 8B DI Water Filter Assembly Balance Load Monitoring System	Installed Security Camera System Kirk Keys System for High Pressure Valves
<b>15-Inch Mach 6 High Temperature Air</b>	Installed Low Noise Settling Chamber Schlieren System	Environmentally Controlled Area for Tunnel	12.5 MW Heater Power Supply Upgrade Injection PLC Heater in Enclosure Replace Preheat Valves	Environmentally Controlled Area for Tunnel
<b>60-Foot Sphere Space Simulator</b>	Installed Viewing Windows Rehabbed Control Room	Rehabbed Control Room Added Kirk Key Entry System	Replaced Seals Removed Diffusion Pump System Certified 12 ft Monorail Door	Rehabbed Control Room