NASA Langley Aerothermodynamics Laboratory: Hypersonic Testing Capabilities

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A description of the NASA Langley Research Center's Langley Aerothermodynamics Laboratory (LAL) will be presented in the paper, along with descriptions and details of the facility test techniques and recent upgrades. The LAL consists of three hypersonic blow-down wind tunnels covering Mach numbers of 6 and 10 and unit Reynolds number ranges of 0.5 to 8.3 million per foot as well as a 60-ft Vacuum Sphere Test Chamber. LAL facilities are used to study and define the aerodynamic performance and aeroheating characteristics of flight vehicle concepts. Data collected in the facilities have been used for design and optimization, anchoring computational predictions, generation of aerodynamic databases and design of Thermal Protection Systems. Over the years modifications and enhancements have been made to the facility hardware and instrumentation to increase efficiency, data quality, capabilities and reliability to better meet the programmatic requirements. Recent utilization information illustrates the need for the capabilities associated with these facilities. Recent test programs include the Space Shuttle Program, Crew Exploration Vehicle/Orion/Multi-Purpose Crew Vehicle, Hypersonic International Flight Research Experimentation (HIFiRE), Mars Science Laboratory, Hypersonic Inflatable Aerodynamic Decelerator System (HIADS) and X-51 among others and usage has been split between NASA, Commercial Crew, Department of Defense and private company programs. Plans for future improvements to the facility infrastructure and instrumentation will also be presented.

Nomenclature

h	Enthalpy based Heat transfer coefficient (slug/ft^2 s) ($\dfrac{\dot{q}}{H_{aw}-H_{w}}$)
h_{ref}	reference heat-transfer coefficient using Fay-Riddell calculation
H	Stagnation enthalpy (BTU/lb$_m$)
k	boundary-layer trip height (in)
L_{ref}	reference length (in)
M	Mach number
P	pressure, psia
q	heat transfer rate (BTU/ft^2-sec)
q	dynamic pressure (psi)
R	radius (in.)
Re	unit Reynolds number (1/ft)
S_{ref}	reference area (in^2)
t	time (sec)
T	temperature (°F)
x	axial distance from origin (in)
y	lateral distance from origin (in)

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Greek

α	angle of attack (deg)
β	sideslip angle (deg)
γ	ratio of specific heats
δ	boundary-layer height (in)
δ_{BF}	control surface deflection (deg)
μ	viscosity
ρ	density (lb_m/in^3)

Subscripts

$1, \infty$	freestream conditions
2	static conditions behind normal shock
t,2	stagnation conditions behind normal shock
aw	adiabatic wall
n	model nose
t,1	reservoir condition
w	wall
θ	boundary-layer momentum thickness (in)

I. Introduction

The late 1990's saw a significant focus on hypersonics, brought on primarily by programs such as the Hyper-X/X-43 program[1,2], X-33[3], X-34[4,5] and X-38[6,7]. The focus on Reusable Launch Vehicles (RLV) made the understanding of the hypersonic aerodynamics and aerothermodynamics a key focus. Although a number of these programs were cancelled in the early 2000's, the 2003 loss of the Space Shuttle Orbiter *Columbia* during re-entry and the resulting Accident Investigation and Return-to-Flight (RTF) programs further highlighted the need for understanding of the hypersonic flight regime.[8, 9]

Since the publication of the last facility update in 1998[10], several large scale, agency-level programs have utilized significant resources in the Langley Aerothermodynamics Laboratory (LAL) facilities. The Hyper-X program, in support of scramjet technology development, continued supporting pre-flight development and design of the flight vehicle through 2000. After the loss of the first vehicle, LAL facilities were used to test the booster performance as well as to gather more vehicle data up to and through the successful flights in 2004. With the loss of Space Shuttle Orbiter *Columbia* in 2003, LAL facilities began a campaign in support of the Columbia Accident Investigation initially and the Space Shuttle RTF program later. The period from 2003 until 2006 saw over 3500 wind tunnel runs in the various LAL facilities in support of RTF. These tests both supported the accident investigation as well as tool development, including the Boundary Layer Transition[11] and Cavity Heating Tools[12], used in all remaining flights of the vehicle. The Crew Exploration Vehicle (CEV)/Orion/Multi-Purpose Crew Vehicle (MPCV)[13, 14] began testing in LAL facilities in 2006 and between then and 2011 significant testing supported the study of aerodynamic and aerothermodynamic performance, RCS jet interactions and heating, boundary layer transition characteristics and tension-tie/compression-pad design among other things.

A renewed interest in planetary missions, including the Mars Exploration Rovers, Phoenix Lander and the Mars Science Laboratory (MSL)[15,16], led to a push for the development of Entry, Descent and Landing (EDL) technologies which required testing in the LAL facilities. Significant work was completed in support of the MSL, which successfully landed the rover Curiosity on the Martian surface in 2012, and the Hypersonic Inflatable Aerodynamic Decelerator (HIAD) programs[17], along with a number of other EDL programs.

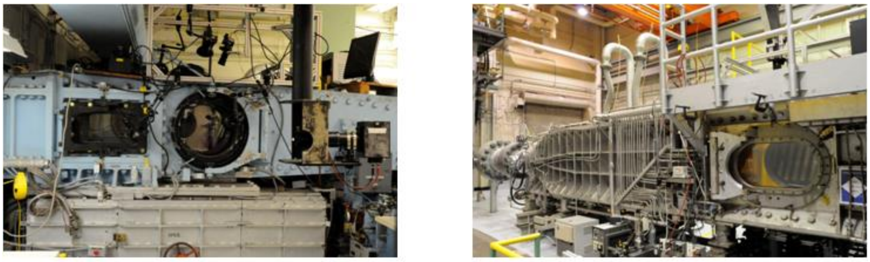
In response to the aerothermodynamic testing requirements for recent and future programs, the NASA Langley Research Center (LaRC) has performed modifications, upgrades, and enhancements to the hypersonic facilities comprising the LAL. Over the last 15 years, facility upgrades have been advocated and accomplished via the Construction of Facilities (CoF) program and other funding sources. This time period also saw the re-evaluation of needs and closing of some of the LAL hypersonic facilities, including the 22-Inch Mach 15/20 Helium Tunnel and the 20-Inch Mach 6 CF_4 Tunnel. Significant upgrades to the instrumentation, signal conditioning and data acquisition systems for the remaining LAL facilities were achieved via the Agency Aeronautical Wind Tunnel Revitalization Program and other funding sources. The emphases of these upgrades were to provide improved flow and data quality, capability, productivity, and reliability.

This paper will provide an update on the LAL facility and instrumentation capabilities. Enhancements to facilities and measurement techniques that have occurred since the publication of the Micol 1998 paper[10] will also be presented. LAL facility-to-facility compatibility, as well as the recent (past 15 years) utilization of these facilities for several high priority and fast-paced programs will be discussed as will future approved and proposed upgrades for the LAL facilities, instrumentation and measurement techniques.

II. Facilities

The LAL (Figure 1) consists of three conventional hypersonic blow-down facilities and a 60-foot vacuum sphere space simulation facility. Each of the blow-down facilities uses heated, dried, and filtered air as its test gas and provides for a variety of free-stream Reynolds Numbers, Re_∞, at the free-stream Mach numbers, M_∞, of 6 or 10.

The 60-Foot Sphere Space Simulator utilizes one of the vacuum spheres for the 31-Inch Mach 10 Tunnel and was designed to achieve conditions similar to outer space in order to test spacecraft and associated components. The LAL facilities have the ability to conduct proprietary, International Traffic in Arms Regulations (ITAR) and classified tests.



20-Inch Mach 6 Tunnel

31-in Mach 10 tunnel

15-Inch Mach 6 High Temperature tunnel

60-Foot Sphere Space Simulator

Figure 1: Langley Aerothermodynamic Labs (LAL) facilities

A. 20-Inch Mach 6 Air

The LAL 20-Inch Mach 6 Tunnel (Figure 2) first became operational in 1958 as the 20-Inch Hypersonic Tunnel. It is a conventional hypersonic blow-down facility utilized for aerodynamic and aerothermodynamic tests as well as for basic fluid dynamic studies, including boundary layer and laminar-to-turbulent transition. Operational air is supplied by a 4250 psi bottle field and a 600 psi bottle field and is preheated using a Joule–Thomson heater upon exiting the 4250 psi bottle field. The 600 psi bottle field is directly fed by the 4250 psi bottle field and used as an accumulator during tunnel operation. Once the air pressure is reduced to the desired line pressure, it is heated to a maximum temperature of 1000°R by an 11.2 Megawatt electrical resistance heater. A double filtering system is employed having an upstream filter capable of capturing particles larger than 10 microns and a second filter rated at 5 microns. The filters are installed between the heater and settling chamber. The settling chamber contains a perforated conical baffle at the entrance and internal screens. A fixed geometry, two-dimensional contoured nozzle is used. The top and bottom walls of the nozzle are contoured and the sides are parallel. The nozzle throat is 0.34 in. by 20 in., the test section is 20.5 in. by 20 in., and the nozzle length from the throat to the test section window center is 7.45 ft. The tunnel is equipped with an adjustable second minimum and exhausts either into combined 41-ft and 60-ft diameter vacuum spheres, and/or a 100-ft diameter vacuum sphere. These vacuum spheres are evacuated by three vacuum pump rooms, each consisting of four vacuum pumps, and through the 100-ft sphere, an annular steam ejector and an Air-Nitrogen pump. The air can also be ejected to the trench (atmosphere) through the use of one of two control valves. This usually occurs during the tunnel preheat stage or when low pressure runs (less than 60 psia) are being performed. The minimum nominal operating pressure is 30 psia and the maximum operating pressure is 475 psia. The maximum run time is 20 minutes with the air ejector though most runs are on the order of a few seconds to a few minutes in duration. See Table 1 for nominal conditions, selected from a continuous regression model that covers the entire operating envelope of the facility, shown in Figure 3. The facility is capable of making 8-12 runs a shift, depending on the run time and operating pressure.

Models are mounted on the injection system located in a housing below the closed test section. The injection carriage is raised mechanically through the use of a hydraulic pump, accumulator and injection cylinder. The strut is attached to the hydraulic ram, which is supported in the cylinder through the use of roller bearings. When adjusting yaw, the ram and strut are rotated within the cylinder. The model control system is computer operated and capable of moving the model through a pitch angle range of -5° to +55° and yaw angles of ±8°. The facility core size is approximately 12-14 inches across, depending on Reynolds number. Injection speed can be adjusted depending on the test technique and model requirements so that models can be injected to the nozzle centerline in as little as 1.5 sec (with acceleration G-Loads of +2.6 to -3.3 G) up to 3.75 sec (with acceleration G-Loads of +0.5 to -0.2 G).

The facility has six optical access ports, two on each side and two on the top of the test section. The front set of top and side windows are located at the model center of rotation point and are made of Corning 7940, Grade 5F, Schlieren quality glass. The top front optical access point can be fitted with a special Zinc Selenide (ZnSe) antireflective-coated window for use during infrared (IR) emission testing. The aft set of top and side windows are located behind the model center of rotation.

The 20-Inch Mach 6 Tunnel was calibrated in 2005 using a compact, efficient experiment developed using formal Design of Experiments (DoE) methods.[18] The resulting data were used along with response surface modeling techniques to create a continuous regression model of the post-normal-shock stagnation pressure (PT2) as a function of the facility total pressure and temperature as well as the longitudinal location within the test section. The facility was calibrated over a range of total pressure from 30 to 480 psia, total temperatures from 805 to 935 deg R, and a longitudinal distance of 24 inches along the test section. The 2005 calibration of the facility is believed to be the first usage of DoE in a wind tunnel calibration. The experiment utilized far fewer design points than prior experiments, but covered a wider range of the facility operating envelope while revealing interactions between factors not captured in previous calibrations. A series of points chosen randomly with the design space was used to verify the accuracy of the regression model.

A free-stream pressure fluctuations study[19] was conducted in 2012 using a pitot rake outfitted with Kulite pressure transducers. Tunnel pressure noise was seen to increase with decreasing Reynolds number and was measured in the range of 1%, at a unit Reynolds number of $7x10^{6}$/ft, up to 1.5%, at a unit Reynolds number of $1.5x10^{6}$/ft.

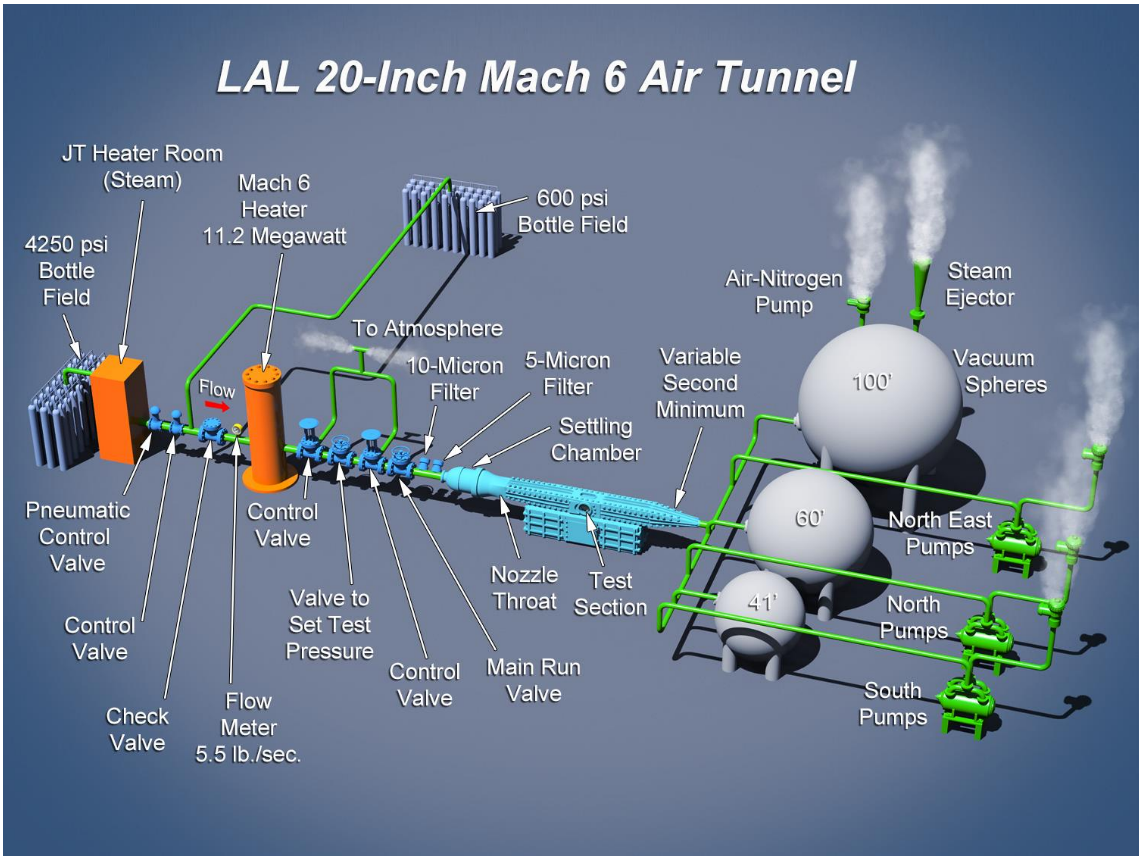


Figure 2: LAL 20-Inch Mach 6 Tunnel

Table 1: Nominal Conditions for LAL 20-Inch Mach 6 Air Tunnel

$P_{t,1}$, psi	$T_{t,1}$, °R	P_∞, psi x 10^{-2}	T_∞, °R	q_∞, psi	V_∞, ft/s	M_∞	Re_∞, ft^{-1} x10^6	Re_2, ft^{-1} x10^5	ρ_2/ρ_∞	$P_{t,2}$, 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

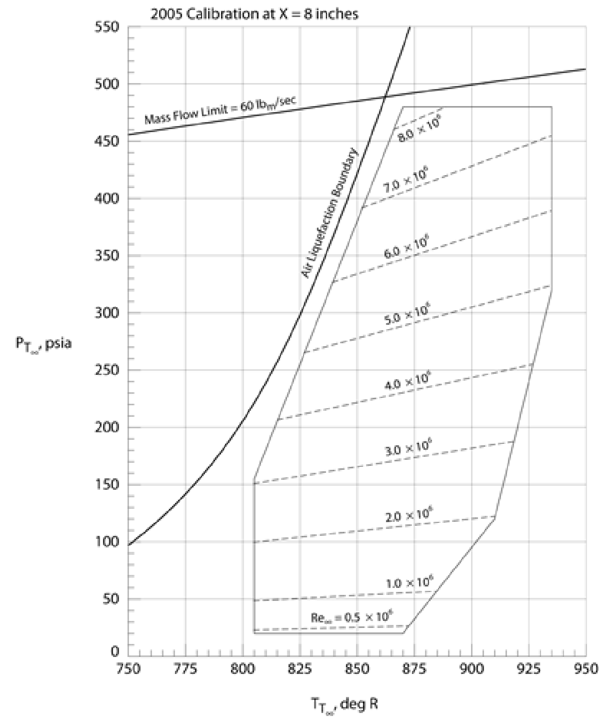


Figure 3: Operating Envelope for the 20-Inch Mach 6 Air Tunnel

B. 31-Inch Mach 10 Air

The LAL 31-Inch Mach 10 Tunnel (Figure 4) first became operational in 1957 as the Continuous-Flow Hypersonic Tunnel and was converted to a conventional hypersonic blow-down facility in the 1970's. The tunnel is utilized for aerodynamic and aerothermodynamic tests as well as for basic fluid dynamic studies, including boundary layer and laminar-to-turbulent transition.

Operational air is supplied by the center 5000 psi system and an 865 ft^3, 4400 psi bottle field. The 4400 psi bottle field is directly fed by the center air through a 20-micron filter and used as an accumulator during tunnel operations. Test air passes through a 10-micron filter and is reduced to the desired run pressure before flowing through a 12.5 Megawatt electrical resistance heater located in a vertical pressure vessel, which heats the air to a maximum temperature of 2080°R. A 5 micron in-line filter is located between the heater and settling chamber. The 12 in. diameter settling chamber is equipped with screens at the upstream end and is faired into the upstream end of a square cross section nozzle with a 1.07 in. square throat. The throat section is one piece, fabricated from uncoated beryllium copper and backside water-cooled with a de-ionized cooling water system operating at 500 psia. The test section is 31 in. square, and the nozzle length from the throat to the test section window center is 17 ft. The tunnel is equipped with an adjustable second minimum and a water cooled heat exchanger. The tunnel exhausts into a 41-ft diameter (36,000 ft^3) vacuum sphere. Attached to the 41-ft sphere are two additional vacuum spheres, another 41-ft diameter (36,000 ft^3) and a 60-ft diameter sphere (113,000 ft^3, also referred to as the 60-Foot Sphere Space Simulator) and an annular steam ejector. The 60-ft and second 41-ft vacuum spheres are evacuated by three sets of vacuum pumps (the primary set consisting of four 750 ft^3 vacuum pumps and two auxiliary sets, one with two 750 ft^3 and two 1000 ft^3 vacuum pumps and the other with two 1000 ft^3 vacuum pumps). The high pressure air system and the vacuum system are shared with the 15-Inch Mach 6 High Temperature Tunnel. The maximum run time is 2 minutes utilizing all vacuum spheres and pumps. See Table 2 for nominal conditions. The facility is capable of making 5-8 runs a shift, depending on the run time and pressure.

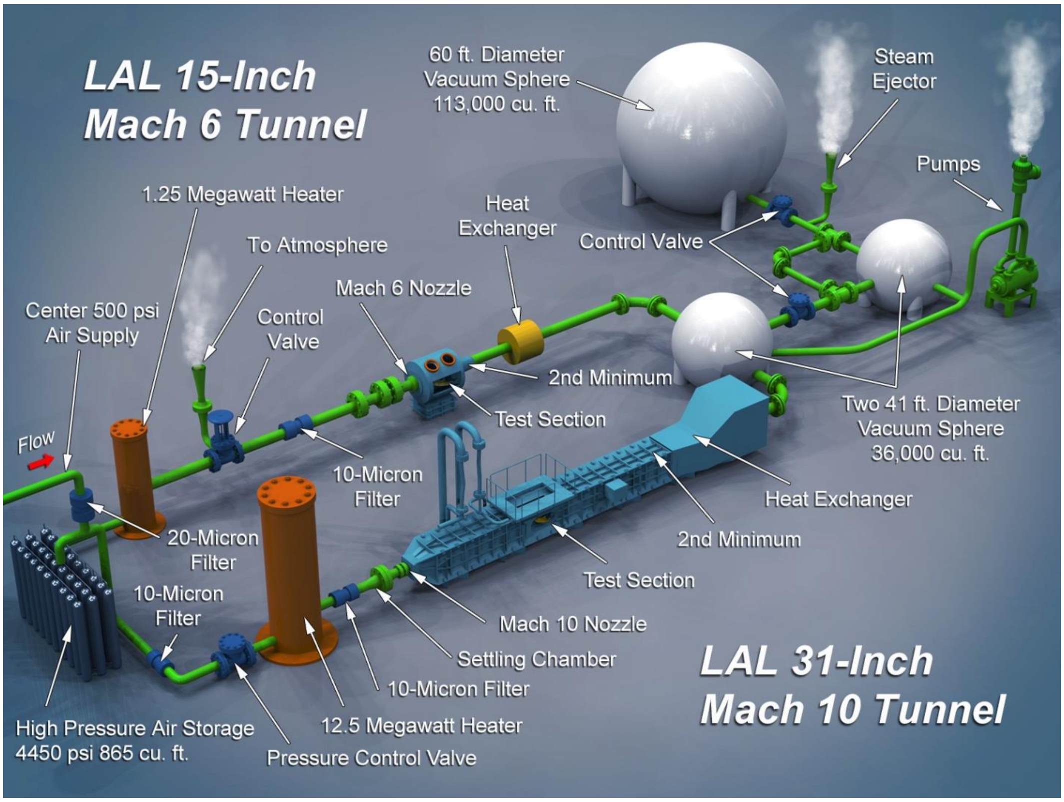


Figure 4: LAL 31-Inch Mach 10 and 15-Inch Mach 6 High Temperature Tunnels

Models are supported on a hydraulically-operated, sidewall-mounted injection system. The model control system is computer operated and capable of moving the model through a pitch angle range of -45° to +45°. The facility core is 12-14-in. The yaw angle range is ±5° which must be mechanically set prior to each run and cannot be changed during a run. Injection speed can be adjusted depending on the test technique and model requirements so that models can be injected to the nozzle centerline in as little as 1.25 sec (with acceleration G-Loads of +2.6 to -3.3 G) up to 4.2 sec (with acceleration G-Loads of +0.4 to -0.3 G).

Table 2: Nominal Conditions for LAL 31-Inch Mach 10 Air Tunnel

$P_{t,1,}$ psi	$T_{t,1,}$ °R	P_∞, psi x 10^{-2}	T_∞, °R	q_∞, psi	V_∞, ft/s	M_∞	Re_∞, ft^{-1} x10^6	Re_2, ft^{-1} x10^5	ρ_2/ρ_∞	$P_{t,2}$, 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

The facility has three rectangular optical access ports, on the top, bottom and one side of the test section. The windows are centered at the model center of rotation and are made of Schlieren quality glass. The top access point can be fitted with a special ZnSe antireflective-coated window for use during IR testing.

A study involving the mapping of the supersaturation region was conducted in 2012[20]. The study, using a pitot pressure probe, total temperature probe and laser Rayleigh scattering, was one of the first studies in which quantitative measurements of the clustering in the freestream density were obtained in a Mach 10 wind tunnel. The study failed to find evidence of a single fixed boundary at the edge of the supersaturation region where condensation prevents operation of or quantitative measurements in hypersonic wind tunnels. Based on this study, expansion of the facility operating envelope may be acceptable but further investigations will be required.

C. 15-Inch Mach 6 High Temperature Air

The 15-Inch Mach 6 High Temperature Tunnel (Figure 4) first became operational in 1991. The tunnel was converted from the former Mach 10 Hypersonic Flow Apparatus to provide the capability of testing in Mach 6 air at higher reservoir temperatures[21]. It is a conventional hypersonic blow-down facility utilized for aerodynamic and aerothermodynamic tests as well as for basic fluid dynamic studies, including boundary layer and laminar-to-turbulent transition. The high pressure air system and the vacuum system are shared with the 31-Inch Mach 10 Tunnel.

Operational air is supplied by the center 5000 psi system and an 865 ft^3, 4400 psi bottle field. The 4400 psi bottle field is directly fed by the center air through a 20-micron filter and used as an accumulator during tunnel operations. Test air is reduced to the desired run pressure before flowing through a 1.25 Megawatt electrical resistance heater located in a vertical pressure vessel, which heats the air to a maximum temperature of 1500 °R. The flow rate through the heater is 3 to 16 lb_m/sec for typical runs. A 10 micron in-line filter is located between the heater and settling chamber. The settling chamber is of conventional design and consists of a pressure vessel and 3 stainless steel mesh screens. The pressure vessel is 36 inches long and has an Inconel liner with an inside diameter of 7 inches. The settling chamber and the piping connecting the heater to the settling chamber are covered by an outer layer of insulation to minimize heat loss from the test gas in its travel from the heater to the nozzle. The uncooled axisymmetric contoured Inconel nozzle consists of three pieces and has a throat diameter of 1.81 in., a nozzle exit diameter of 14.57 in., and length of 75.6 in. The heater, settling chamber and nozzle are designed for a maximum temperature of 2060 °R.

The tunnel has a walk-in open-jet test section approximately 6 feet long, 6 feet wide and 7.25 feet high. The flow exhausts into this vacuum chamber, traverses the model test area, and is collected approximately 18 inches downstream of the nozzle exit into a variable area diffuser equipped with adjustable second minimum and a water cooled heat exchange. The tunnel exhausts into the same two 41-ft diameter and one 60-ft diameter spheres as the 31-Inch Mach 10 facility. During the preheat process, air is diverted to atmosphere through the use of a control valve located between the heater and the filter.

Models are supported on a hydraulically-operated, injection/retraction support mechanism. The model control system is computer operated and capable of moving the model through a pitch angle range of -10° to +50° and yaw angles between ±10°. The tunnel is equipped with numerous optical access ports, including three 29 in. x 23 in. windows, located on each side and on the top of the tunnel and four 5.5 in. diameter circular windows (two on each side) located approximately 45° above the model. The maximum run time is 90 seconds utilizing all vacuum spheres and pumps. See Table 3 for nominal conditions. The facility is capable of making 4-8 runs a day, depending on the run time and pressure.

Results obtained via pitot-pressure surveys revealed good uniformity both radially and axially. The facility core is approximately 14 inches at 1 inch from the nozzle exit and shrinking to approximately 9 inches at 11 inches from the nozzle exit, shown in Figure 5and Figure 6.

D. 60-Foot Sphere Space Simulator

The 60-Foot Sphere Space Simulator was designed to achieve vacuum levels and atmospheric conditions similar to that found in outer space to support experiments which require simulated space and planetary conditions for the testing of spacecraft and associated components. Some of the studies that have been conducted in the simulator have been spacecraft separation in fixed-position and free-fall, de-spin and tumbling, nozzle and jet plume studies, solid and liquid propulsion capabilities and tests of pyrotechnic devices. In addition, the simulator has been integrated into the vacuum system of the 31-Inch Mach 10 and 15-Inch Mach 6 High Temperature Tunnels (increasing the run-time capability of both tunnels to approximately 2 minutes).

The facility consists of a vacuum sphere, a three-stage vacuum pumping system, support buildings and the electrical, air and cooling water supply systems required to activate and sustain the vacuum pumping process. The diameter is 60.75 ft, providing a total internal volume of 117,391 ft^3. A pressure level of $2\text{x}10^{-4}$ torr, a simulated altitude of approximately 60 miles, is attainable after about nine hours of pumping.

Experiments are monitored by cameras and data recorders through viewing ports from appended exterior structures at the sphere's equator and top. Access to these appended structures is normally via elevator but a backup ladder does extend from ground level.

Table 3: Nominal Conditions for LAL 15-Inch Mach 6 High Temperature Tunnel

$P_{t,1}$, psi	$T_{t,1}$, °R	P_∞, psi x 10^{-2}	T_∞, °R	q_∞, psi	V_∞, ft/s	M_∞	Re_∞, ft^{-1} x10^6	Re_2, ft^{-1} x10^5	ρ_2/ρ_∞	$P_{t,2}$, 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

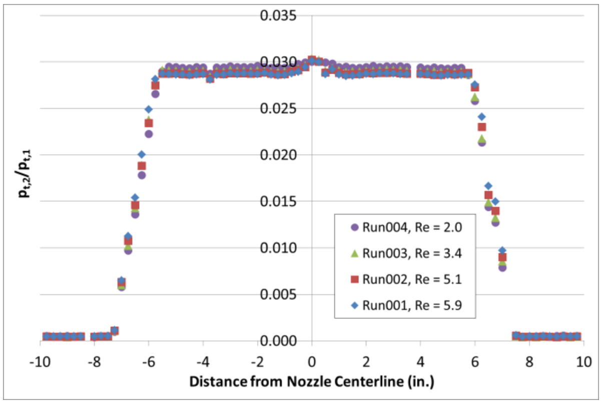


Figure 5: Pitot pressure profile 1-in from nozzle exit for 15-in Mach 6 High Temperature Tunnel

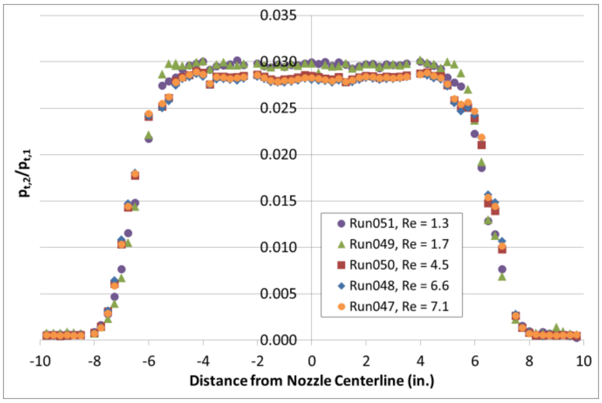


Figure 6: Pitot pressure profile 11-in from nozzle exit for 15-in Mach 6 High Temperature Tunnel

E. Similarities and Synergy

Thanks to common instrumentation and hardware in the various LAL facilities, test programs are able to take advantage of testing in multiple LAL facilities with the same or similar models and set ups. As shown in Table 1, the unstart pressure loads (Pt_2) in the 20-Inch Mach 6 Air Tunnel are the highest of the three LAL facilities, meaning that a model designed to safely operate in that facility can be used in the 15-Inch Mach 6 High Temperature or in the 31-Inch Mach 10 Air Tunnels. Similar test core sizes mean that most models can be easily deigned to fit in all three facilities.

Instrumentation is generally transferable between facilities. The strain gage balances, global phosphor thermography systems, high speed data acquisition hardware, high speed Schlieren cameras, oil flow equipment, etc. are routinely moved from one tunnel to another, along with the models. Static data acquisition hardware is designed to be compatible at each facility and produce outputs in the same formats to further aid test programs that test in multiple facilities and make the training of test engineers and technicians on the new equipment easier. Data output files are computed and transferred within minutes of the run, further aiding the fast-paced testing that has been associated with a number of the programs and allowing for real-time decision making after each run when required (such as boundary layer transition onset studies).

The synergism between the facilities allows for an array of simulation parameters to be examined by using combinations of the facilities. Table 4 is a comparison of three hypersonic simulation characteristics (M_∞, Re_∞ and T_w/T_{aw}) and a description of what facilities could be utilized to measure the effects of each.

Table 4: Synergism of LAL Test Facilities

To measure effect of	For given	Test in	And
M_∞	Re_∞	20” Mach 6	31” Mach 10
M_∞	Re_∞, T_w/T_{aw}	31” Mach 10	15” Mach 6 HT
Re_∞	M_∞, T_w/T_{aw}	All Facilities	
T_w/T_{aw}	M_∞, Re_∞	20” Mach 6	15” Mach 6 HT

III. Model Instrumentation and Test Techniques

A. Force and Moment

A balance is an instrument with foil strain gages in specific locations to measure the forces and moments acting on a model. LAL facilities have the capability to use one force, five moment (1F/5M); five force, one moment (5F/1M); and three force, three moment (3F/3M) balances.

Balances used most frequently in the LAL facilities are either sting or strut supported and cover a range of diameters from 0.5 to 1.25 inches, with a wide range of maximum design loads. These balances are applicable to blunt, high drag models as well as slender, high lift models. The balances are water cooled, have five component (including flow through balances to support propulsion simulation tests such as RCS jet interaction studies) or six components and require an excitation voltage of 5 volts. Straight and bent stings as well as blade mounted struts of various shapes and sizes are available to allow testing over a wide range of angles of attack.

Prior to testing, balance calibrations are performed by applying known loads to the balance and recording the resulting bridge outputs. The process is repeated for a sufficient number of independent loads to allow determination of the coefficients in the math model. All balances are calibrated in the standard balance axis system. The Single Vector System (SVS) calibration technique utilized (and developed at NASA Langley) allows balance calibration so to be completed in three days as compared to three weeks.

The general test procedure used in LAL tunnels is to verify the performance of the balance by check loading all six components of the balance during the setup of a wind tunnel test. The check load data are compared to the formal calibration data prior to the final installation of the model to assure the balance is operating within acceptable tolerances. The output data are run through first and second order interactions to obtain the calculated loads and compared to the actual loads applied. A tare run with the model mounted to the balance is performed over the desired angle of attack range prior to the test series for use in data reduction. Dummy runs with an Angle Measurement System (AMS) package mounted on top of the model are also performed. These runs compare the AMS measured angles with the calculated model angles after the sting-balance deflection corrections and check that the tare loads are being subtracted correctly.

LAL currently has the capability to use the AIAA balance calibration standard as well as previously used internal LaRC standards. The data reduction capabilities allow for the use of additional calibration math models and balance calibration types (AIAA force and moment), pressure tare correction, simultaneous vector (multiple data points) loads computations and the computation of absolute delta. Additional benefits of the data reduction capabilities are that it enables a seamless transition to the new LaRC balance data reduction matrix format and will enable easy future upgrades since LAL facilities will be poised to receive a common set of updated balance Data Reduction Matrix (DRM) and load computation modules.

The balance reduction code has the following capabilities:

a) A common DRM reader such as the industry standard AIAA (6x90) matrix can be read and the coefficients utilized by the existing software. In particular, this capability includes backward compatibility with the LaRC 6x27 calibration matrix.

b) Ability to perform first order and non-linear computations utilizing the full AIAA matrix for the following calibration matrix types: AIAA/LaRC direct read, AIAA moment, AIAA force, and LaRC moment. These balance calibrations types result in different outputs: 3F3M, 5M1F or 5F1M, which are automatically converted to 3F3M (if required). The computations for direct read and LaRC moment (6x27) are an existing capability, while the additional calibration terms (6x90) enable a wider spectrum of calibration math models to be utilized.

B. Pressure

1. *Discrete gages*

Pressure data are commonly measured using electronically scanned pressure (ESP) piezoresistive (silicon) sensors. The modules are controlled through Pressure Systems, Inc. (PSI) model 8400 measurement systems, with a normal capability of 512 channels of pressure measurements. ESP modules typically contain 32 ports per module and are available at pressure ranges from 10 inch water column (WC) to 100 psi. The typical modules that are used in LAL facilities are the 10-in. WC, 1psi, 5 psi and 15 psi.

2. *Kulite*

Multi-range, variable-capacitance, diaphragm-type transducers are used for certain applications (e.g., freestream disturbance measurements and other semi-high frequency measurements in the boundary layer and on the surface of models). These sensors use a force-summing device to convert the pressure into a displacement proportional to the pressure. The displacement to the electrical transduction element generates the electrical output of the transducer. Kulite piezoresistive pressure transducers combine the force summing device and the transduction element into a micro-machined, dielectrically isolated silicon or silicon carbide (ultra high temperature applications) diaphragm.

Transducers are available with a variety of pressure ranges. Reference pressure options include:

1. Absolute – (psia)
2. Gauge - (psig)
3. Differential - (psid)
4. Differential Sealed Reference – (psid)

Currently the 31-Inch Mach 10 Tunnel has the capability to acquire 12 channels of pressure transducer data. The 20-Inch Mach 6 Tunnel has the capability to acquire 32 channels of data and the 15-Inch Mach 6 High Temperature Tunnel has the capability to acquire 8 channels of pressure transducer data. Additional channels and/or higher sampling frequencies can be obtained using the HBM Genesis HighSpeed Data Acquisition system, discussed later.

3. *Piezoelectric Pressure Sensor*

The Piezoelectric Pressure Sensor (PCB) is a piezoelectric quartz sensor designed by the manufacturer to be a dynamic sensor. The quartz crystals of the sensor generate a charge when pressure is applied. This charge eventually leaks to zero, at a rate which is dependent on the electrical insulation's resistance. The PCB 132A31 has a discharge time constant of 45 μsec and a resolution of $1\text{x}10^{-6}$ psi with measurement range of 50 psi and a maximum dynamic pressure of 800 psi.. The resonant frequency of the sensor is above 1 MHz and the sensor out is high-pass filtered with a 3-dB cutoff frequency at 11 kHz with a specified sensitivity of ±30% or 140 mV/psi. These sensors have been shown to have a flat response to 300 kHz. The sensor diameter is 0.125 inches, but the sensing element is a 0.030 x 0.030-in square. Because of the high frequency response of the sensors, the PCB132s are able to help characterize boundary layer transition by measuring the growth and breakdown of instability waves, though more extensive calibrations are required for this effort.

4. *Pressure Sensitive Paints*

Pressure Sensitive Paints[22] (PSP) allow global surface pressure measurements to be made using a charge coupled device (CCD) camera. The PSP coating is made up of oxygen-sensitive luminescent molecules that are dispersed in oxygen-permeable polymer binders and applied to the model surface using conventional paint spraying techniques. The PSP formulation used by LAL is one that was developed in the Advanced Sensing and Optical Measurement Branch at NASA LaRC. The oxygen-permeable layer is made from a co-polymer of trifluoroethylmethacrylate and isobutylmethacrylate (FEM), in which platinum meso-tetra(pentafluorophenyl)porphine [Pt(TfPP)] is dissolved. Prior to coating the models, a white acrylic primer is applied to the surface to act as a basecoat to enhance adhesion of the FEM topcoat as well as to enhance scattering of the luminescence intensity back to the camera

The coated models are illuminated using ultraviolet (UV) light emitting diodes (LEDs). The luminescence emission from the entrapped oxygen-sensitive molecules is then captured using CCD cameras with spectral band-pass filters to distinguish between the excitation (UV) and emission signals. The emission usually occurs in the orange to red region of the visible spectrum (~590 - ~650 nm). Because the emission intensity is inversely proportional to the amount of oxygen present at the PSP surface, paint regions with a lower concentration of oxygen will have greater emission intensity. Since oxygen is a fixed component in air, the emission intensity can be correlated to the total pressure at the model surface. To compensate for intensity non-uniformities caused by effects other than pressure (e.g. paint application), a ratio of a reference image (taken at isobaric and isothermal condition, usually with no flow in the wind tunnel) to the “wind-on” image (image taken at condition) is used.

There are two methods for acquiring PSP data, the "intensity-based" method and the "lifetime-based" method. In the "intensity-based" method, reference data are acquired in a tunnel off condition (wind-off, prior to the start of the run) and then acquired at specific tunnel conditions during the run (wind-on). This method is the most common method of acquiring PSP data. In the "lifetime-based" method, excitation is achieved through a modulated light source and images are acquired with a high-speed intensified or interline transfer CCD camera system. The decay is approximated by taking two or more images at different times during and after the pulsed excitation period and integrating photons using a fixed gate width (period of time that has been predetermine to maximize the pressure sensitivity). The first image is the reference image, collected either during the excitation period or shortly after. The second image is taken at a later time, at least equal to the gate period, ensuring maximum pressure sensitivity.

C. Heat Transfer/Temperature

1. *Two-Color Relative-Intensity Phosphor Thermography*

The two-color relative-intensity phosphor thermography measurement technique is the standard method to obtain global aeroheating data in the LAL facilities. The historical background of the technique and model manufacturing is discussed in Refs. 23-25. This technique uses a mixture of two phosphors, zinc cadmium sulfide and lanthanum oxysulfide, mixed with a colloidal silica binder and applied to a slip-cast silica ceramic model using an air brush to a final coating thickness of approximately 0.001 in. When illuminated with ultraviolet light, the zinc cadmium sulfide fluoresces in the green portion of the visible spectrum and the lanthanum oxysulfide fluoresces in the red portion. The intensity of the light illuminated is dependent upon the amount of incident ultraviolet light and the local surface temperature on the model.

Intensity images are acquired at a rate of 30 frames per second (fps) (shown in Figure 7) using an acquisition system consisting of a PC based computer with a low-cost frame grabber that is programmed using National Instruments (NI) LabVIEW[26] and an 8 bit, 3-CCD camera. The image resolution is 640 x 480 pixels. The acquired images are converted to temperature mappings via a temperature-intensity calibration. The temperature calibration uses the ratio of the red and green components of the illuminated light, while taking into account the response of the acquisition system and tunnel window transmisivity to construct a lookup table which converts the intensities to temperature values. Each batch is calibrated after mixing and is valid over a temperature range from 18 °C (525 °R) to 160 °C (780 °R).

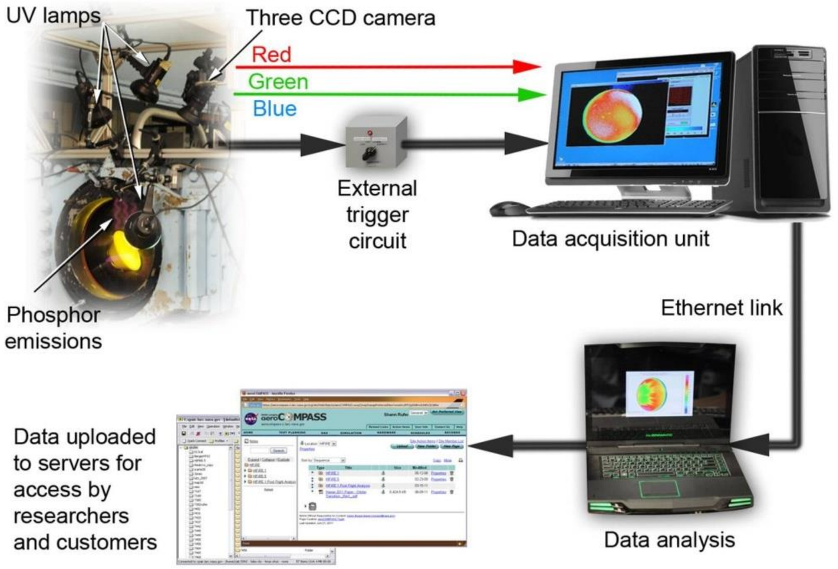


Figure 7: Illustration two-color relative-intensity phosphor thermography acquisition system.

The temperature data from the images taken at selected times during the wind tunnel run are compared to a pre-run image and then reduced to an enthalpy based heat transfer coefficient globally on the model, or at every pixel on the image, using a one-dimensional semi-infinite slab heat conduction technique. An example of the global phosphor thermography test technique on the Space Shuttle Orbiter configuration is shown in Figure 8

Some of the advantages of this technique over conventional transient thin-skin calorimeter and thin-film resistance methods are that:

- The global resolution of temperature/heating data provides detailed information of specific surface flow features over the viewing region. Surface heating is determined in a global sense, at every point on the model surface within view of the camera and at various times during the run.
- The fabrication method used produces a coating which does not require re-application between runs, thereby significantly enhancing the efficiency of the phosphor technique.
- The slip-casting method is a rapid process whereby, in three to four weeks, a full array of inexpensive models can be fabricated, complete with various perturbations needed for a configuration build-up scheme such as variable nose radii and control flap deflections.

2. *Co-Axial Thermocouples*

A thermocouple is a sensor that measures temperature. It consists of two different types of metals, joined together at one end. When the junction of the two metals is heated or cooled its resistance changes. The resistance can then be correlated back to a temperature. The LAL facilities use a Uniform Temperature Reference (UTR) to connect the thermocouples to the data system. Each UTR is equipped with a Resistance Temperature Detector (RTD) to be used as the reference junction temperature during the conversion of voltage to temperature.

Currently the 31-Inch Mach 10 Tunnel has the capability to acquire 255 channels of thermocouple data. The 20-Inch Mach 6 Tunnel has the capability to acquire 156 channels of data and the 15-Inch Mach 6 High Temperature Tunnel has the capability to acquire 120 channels of thermocouple data.

3. *Thin Film*

Thin-film sensors are used to measure surface temperatures during a wind-tunnel test, with the surface heat transfer rates being calculated later using the recorded temperature time histories. For a conventional thin film gage, the sensor is typically either a platinum or palladium film and the substrate is a thermally insulating material such as Macor or quartz. An example of a thin film model is shown in Figure 9.

The sensor is designed so that the thickness of the sensing element is much less than that of the substrate, causing the sensing element to have a negligible effect on the heat transfer to the substrate. The temperature measured by the sensing element can be considered identical to the temperature at the surface of the substrate. When the One-Dimensional Hypersonic Aero-Thermodynamic (1DHEAT) Data Reduction Code[27] is used to reduce the acquired temperature data to heating rates, it is assumed that there is no lateral conduction through the substrate and that heat is conducted only in the direction normal to the surface. Additionally, test specific 2D and axisymmetric analysis codes can be used to reduce the data.

LAL facilities can use either two wire or four wire thin films gages. With the current data system, thin film data can be acquired at a rate of 500 Hz or more. The NEFF 600 supplies the 1 mA current that is used to power the gage. The 31-Inch Mach 10 Tunnel has the capability to acquire 255 channels, the 20-Inch Mach 6 Tunnel has the capability to acquire 156 channels, and the 15-Inch Mach 6 High Temperature Tunnel has the capability to acquire 120 channels of thin-film gages.

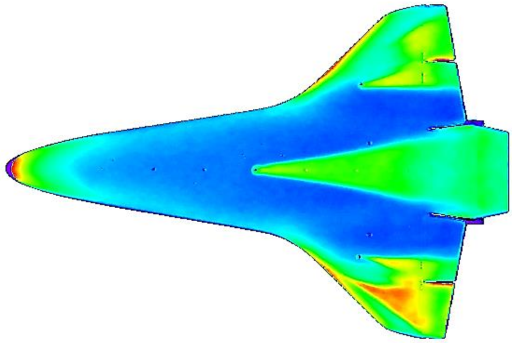


Figure 8: Phosphor thermography data taken on the Space Shuttle Orbiter

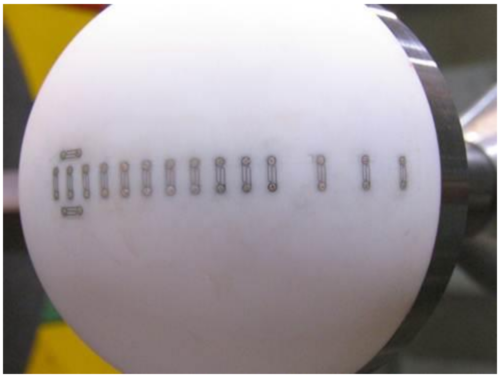


Figure 9: Hemisphere model instrumented with thin film gages

4. *Thin Skin*

Thermocouples, usually chromel-alumel or iron-constantan, are used to measure temperature on the back face of the thin-skin section and are welded to the inside surface of the model. The measured temperature time history is used along with the thermal properties of the skin and average skin thickness, to determine the heat transfer rates. The 31-Inch Mach 10 Tunnel has the capability to acquire 255 data channels, the 20-Inch Mach 6 Tunnel has the capability to acquire 156 data channels and the 15-Inch Mach 6 High Temperature Tunnel has the capability to acquire 120 data channels of thin-skin gages. 1DHEAT is used to reduce the acquired raw data to heating rates.

5. *Infrared*

The surface temperature of a model may be calculated based on its radiation observed at infrared wavelengths[28]. LAL has commercially built infrared imaging system consisting of a FLIR System ThermaCAM SC 3000 camera, a high capacity PC-Card, and a pc-based computer using the FLIR System Thermocam Researcher software. The SC 3000 employs a Stirling-cooled, Type GaAs, Quantum Well Infrared Photodetector (QWIP), at 320x240 pixels and can acquire temperature data from -20°C to +1500°C (-4°F to 2732°F) (divided into 4 temperature ranges). It has an accuracy of ±1% (for measurement ranges up to +150°C) and ±2% (for measurement ranges above +150°C). It employs atmospheric transmission correction (automatic, based on inputs for distance, atmospheric temperature and relative humidity), optics transmission correction (automatic, based on signals from 5 internal sensors) and automatic emissivity correction (variable from 0.1 to 1.0 or select from listings in pre-defined materials list). The camera has a field of view/min focus distance of 20°x15° /0.3m with a spatial resolution (IFOV) of 1.1 mrad and an image acquisition frequency of 50/60 Hz non-interlaced. The camera has video outputs of RS170 EIA/NTSC or CCIR/PAL composite, S-video, and a 14-bit digital serial link. When using the camera in conjunction with the computer system and the Researcher software it has an image output of a 14-bit radiometric IR digital image (includes header file with all radiometric data) and 8-bit standard bitmap (BMP) (image only or image with screen graphics). The images can also be saved as comma-separated values (CSV) file that includes the temperature value at each pixel.

The top windows of the 31-Inch Mach 10 and the 20-Inch Mach 6 Air Tunnels can be fitted with special ZnSe antireflective-coated windows for use during IR testing.

6. *Temperature Sensitive Paints*

Temperature Sensitive Paints[22] (TSP) allow global surface temperature measurements to be made using a CCD camera. The test technique is similar to the two-color relative-intensity phosphor thermography measurement technique, except that the phosphor system is designed to work at higher temperatures. The TSP technique is generally used at lower temperature ranges and can be used more effectively in areas that do not see significant temperature changes during a run.

The TSP formulation process is comparable to PSP, except that the luminescent molecules are chosen to maximize temperature sensitivity and are dispersed in an oxygen impermeable binder, which is used to limit the quenching by oxygen. Because of this, all quenching occurs through non-radiative temperature effects. The TSP formulation used in LAL facilities is based on a formulation developed in the Advanced Sensing and Optical Measurement Branch at NASA LaRC. The oxygen impermeable layer is a clear urethane sealant in which the luminophore ruthenium trisbypyridine (Rubpy) is dissolved. The coating is applied over the same white acrylic primer basecoat as the PSP coating.

The coated models are illuminated using near UV to blue wavelength light. Data acquisition techniques for TSP are the same as for PSP. An example of the use of TSP to determine the effects of a protuberance in the Mach 10 Tunnel is shown in Figure 10.

D. Flow Field Visualization

1. *Planar Laser-Induced Fluorescence*

Planar laser-induced fluorescence[29-31] (PLIF) is a planar flow visualization technique that can be used to provide three-dimensionally spatially-resolved off-body visualization of boundary layers and other hypersonic flow phenomena (as shown for the RCS jet data on the Orion/MPCV/CEV in Figure 11). A portable PLIF system (Figure 12) has been developed and utilized in the LAL 31-Inch Mach 10 Tunnel to investigate the hypersonic flow over surface protrusions (creating laminar-to-turbulent boundary layer transition[29]), reaction control system (RCS) effects on the flow field[30] as well as wake flow phenomena.[31]

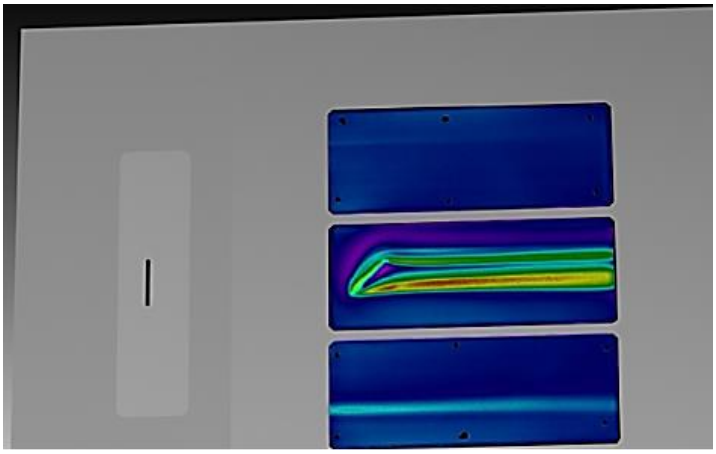


Figure 10: TSP measurement of protuberance effects in Mach 10 Tunnel

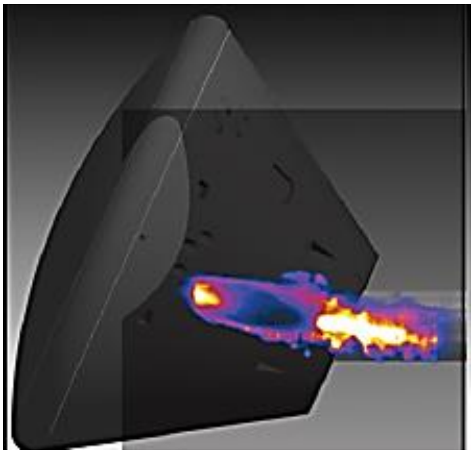


Figure 11: PLIF data on the Orion/MPCV/CEV RCS jets

Figure 12: PLIF system in the 31-Inch Mach 10 Tunnel

To use the PLIF technique, a fluorescing gas is introduced or seeded into the flow either at or upstream of the area of interest. This allows the flow field around and downstream of the area of interest to be visualized. Nitric oxide (NO) is currently used for the fluorescing gas since it has favorable gas dynamic and spectroscopic properties though iodine PLIF has also been used in the 31-Inch Mach 10 Tunnel. NO molecules are excited by an ultra-violet (226 nm) laser sheet operated at 10 Hz for ~10 nsec pulse durations and the resulting fluorescence is captured with intensified CCD cameras (Princeton Instruments PI-MAX II CCD cameras with 512x512 pixel resolution). The facility and instrumentation setup generally permits either the model to be pitched or yawed or for the laser sheet to be moved over the model surface during a run, allowing for post-test three-dimensional recreation of the flow-field behavior. A custom built MHz-rate PLIF system, with a maximum frame rate of 1 MHz (160x160 pixels) has been tested in the 31-Inch Mach 10 Tunnel. Additionally, a molecular tagging velocimetry (MTV) technique is under development and consists of 25 lenses to focus the laser sheet into 25 lines.

2. *Schlieren*

The LAL facilities are equipped with pulsed white-light, Z-pattern, single-pass Schlieren systems for visualization of flow-field shock structures.

The 31-Inch Mach 10 Tunnel Schlieren system has an approximately 5.75 in. diameter field of view. The system was modified in 2008 to include a PC-based digital video system to acquire video and still frame images. It has the ability to acquire uncompressed video at 30 fps using a CameraLink-controlled 1 megapixel 8-bit grayscale digital video camera at an exposure time of 150 μs. Still images are acquired via a Kodak SLR/n 13.5 megapixel digital still camera at the request of the operator. The acquired video and still images can be copied to a CD/DVD or to USB storage devices.

The 20-Inch Mach 6 Tunnel Schlieren system has an approximately 15 in. diameter field of view. The camera and the light source are line-driven at 60 Hz. Video is captured through the use of a video camera (768×493 pixels) and recorded to DVD through a Digital Video (DV) recorder. Single frames are captured via a 13.5 megapixel, Kodak SLR/n at the request of the operator. An example of Schlieren data from the 20-Inch Mach 6 Air Tunnel is shown in Figure 13.

The 15-Inch Mach 6 High Temperature Tunnel can be equipped with a temporary system with an approximately 5.75 in. diameter field of view. Video is captured through the use of a video camera recorded to a DV recorder.

High-speed Schlieren video can be obtained utilizing a Vision Research Phantom 9 or Phantom 12 high-speed digital camera. The cameras have a maximum resolution of 1632x1200 and 1280 x 800 respectively and are capable of frame rates of up to 1000 and 6000 fps respectively when at full resolution and up to 150,000 and 680,000 fps at reduced resolutions. Still images can then be extracted from acquired videos.

Zoom Schlieren[32] (where lenses are used to magnify a smaller region of interest) is available and can be obtained using the Kodak SLR, Phantom 9 or Phantom 12 cameras.

E. Surface Flow Visualization

1. Oil Flow

Oil flow is a widely used flow visualization technique that gathers information on the model's surface flow field patterns and is generally performed on models to expand the understanding of force and moment, pressure, and thermal mapping/heat transfer measurements. Models are painted black and then coated with one or more oils of various viscosities, depending on the geometry, test conditions, model orientation, etc. A green phosphorescent pigment powder or a mixture of oil and white pigment is applied to the model surface immediately before the run. As quickly as possible, in order to minimize drying and/or gravitational effect, the model is injected into the flow. Shear forces at the surface of the model will cause the powder or oil pigment mixture to move and show the near surface streamline patterns, flow separation and reattachment lines among other flow phenomena. The movement of powder/oil on the surface of the model during the injection and retraction process is usually insignificant enough to allow detailed post-run images to be taken of the flow patterns on the model’s surface. An example of oil flow data using the white pigment method is shown in Figure 14.

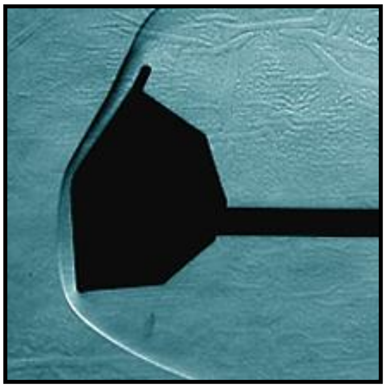


Figure 13: Mars Entry Vehicle Schlieren

Figure 14: Oil flow testing of an attached ballute model

F. Data Acquisition and Recording Systems

Data are acquired using a 256-channel, 16-bit, 50 kHz or 100 kHz aggregate throughput rate, amplifier per channel, analog-to-digital (A/D) system manufactured by the NEFF Instrument Corporation. The system has programmable gains and filters per channel and an internal clock (System 620/series 600). A typical sampling rate is 30 samples per second for each channel, although sampling rates can be adjusted depending on the test technique and model requirements. The system is calibrated using an onboard calibration card with a static accuracy of 0.02% full scale ±2 μV. Pressure data are commonly measured using ESP piezoresistive (silicon) sensors. The modules are controlled through PSI model 8400 measurement systems, with a normal capability of 512 channels of pressure measurements. ESP modules are available with different pressure ranges and typically contain 32 ports per module.

The LAL Acquisition Program (AQU) is written in the HTBasic programming language. The AQU controls the NEFF and the ESP during setup, data acquisition and retrieval. It also has a module that is used for in-place calibrations of instruments.

Data reduction is done through the LAL Data Reduction Program (DRP). This program incorporates mV to Engineering Units (EU) conversion, The Global Wind Tunnel Force Data Reduction Program (GFP)[33] and GASPROPS for determination of tunnel flow conditions[34].

Since 1980, the LAL Data Reduction Program (DRP) software code had been written in the legacy language Rocky Mountain Basic, which was later converted to HTBasic in 2002. In 2012, the reduction program was converted to the MathWorks' programming language MATLAB[35], and implemented in all LAL facilities. The DRP is a series of MATLAB function libraries that are used to reduce aerospace test data for test flow conditions (all testing), water-cooled, 5 and 6-component strain gage balances (aerodynamic loads), ESP system (surface pressures) and discrete instrumentation (heat transfer studies). This modular format allows for quick program modifications and the implementation of any changes to all the facilities. The coding allows for the setting of checkpoints throughout the reduction process to follow variables for troubleshooting purposes. The program also has the ability to easily handle the implementation of any additional customer requested equations. Beginning in 2013, the program was modified with the capability to read and use the upcoming LaRC balance calibration matrix format standard and to enable the computations of loads for the most commonly used balance calibration types.

For those tests requiring higher sampling frequencies than the tunnel systems can accommodate, an HBM Genesis HighSpeed Data Acquisition System, Gen5i, can be utilized. The Gen5i is a robust, portable DAQ integrated on a high end PC. The Gen5i has slots for five input modules with up to 40 channels of various capabilities. The current system has three HiSpeed100M modules and one Basic1M iso module. Each of the HiSpeed100M modules is capable of collecting four channels of data at rates up to 100 MHz and 15-bit resolution. The Basic1M iso module allows for eight channels at rates up to 1MHz at a 16-bit resolution. An additional high speed data acquisition system, capable of sampling rates of 50,000 samples/sec or higher is also available and has been utilized in pressure and force and moment testing. The system is based on NI and Labview and has 8 channels.

IV. Recent Upgrades and Enhancements

Major improvements and upgrades to the facilities over the last approximately 15 years are detailed below. In addition, a more comprehensive list of enhancements and upgrades is shown in Table 5 and details the changes that have affected capability, productivity, reliability, safety and security for each facility.

A. Installation of the Balance Load Monitoring System in LAL Facilities

The Balance Load Monitoring System (BLMS) was installed in the LAL facilities in 2003, allowing test personnel to monitor balance loading during model installation and tunnel runs, decreasing the likelihood of damage or loss of the balance due to overload. The BLMS was a cost-effective replacement for the Balance Dynamic Display Unit (BDDU) that had been used since 1986. The BLMS is a data acquisition and analysis system for displaying and monitoring real-time loads on 6-component, strain gage balances. It consists of a standard PC, a NI PCI data acquisition card, a NI SCXI chassis with a filter module and a relay module, and the LabVIEW based BLMS application software. Designed to accept the buffered analog outputs from the tunnels data acquisition system, the BLMS monitors each individual component load on the balance. The measured loads are evaluated using the "Ames-BLAMS” algorithm. Alarm events are activated at two levels of severity (80% and 100% of rated load), activating external visual and audible alarm devices located at the model prep-area and in tunnel control room. The system also has an alarm for the balance excitation voltage.

B. 12.5 MW Heater Power Supply for 31-Inch Mach 10 and 15-Inch Mach 6 High Temperature Air Tunnels

12.5 MW Heater Power Supply for the 31-Inch Mach 10 and 15-Inch Mach 6 High Temperature Air Tunnels was upgraded in 2002 to improve stagnation air temperature control loop repeatability, accuracy, and response time and to control stagnation temperature to within ±1% of set point for improved data quality. This project provided a new Silicon Controlled Rectifier (SCR) power supply and updated control, reducing operator interface requirements and moving closer to achieving facility control automation. The project included the installation of a new solid-state converter, harmonic filters, controls, and related ancillary equipment to provide variable power to the heaters giving improved reliability of the transformer tap changer and switchgear mounted isolation breaker.

Table 5: Facility Enhancements and Upgrades

Facility	Capability	Productivity	Reliability	Safety/Security
20-Inch Mach 6 Air	Full Field IR Window	Yaw System Calibration System Control Room Makeover	Balance Load Monitoring System DH transformer Installed LED Schlieren System Light Source Re-machined Settling Chamber	Control Room Makeover Control Room Security System Installed Security Camera System
31-Inch Mach 10 Air	Model Control System Schlieren System Laser Interlock System IR Window	Model Control System Kirk Keys System for High Pressure Valves Install Work Platform	Balance Load Monitoring System 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	Installed Security Camera System Kirk Keys System for High Pressure Valves
15-Inch Mach 6 High Temperature Air	Installed Low Noise Settling Chamber Schlieren System	Environmentally Controlled Area for Tunnel	Balance Load Monitoring System 12.5 MW Heater Power Supply Upgrade Injection PLC Heater in Enclosure Replace Preheat Valves	Environmentally Controlled Area for Tunnel
60-Foot Sphere Space Simulator	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

C. Upgrade/replacement of 31-Inch Mach 10 Air Tunnel Model Control System

The 31-Inch Mach 10 Air Tunnel Model Control System (MCS) was upgraded in 2012. The upgrade/replacement modernized the MCS controls and provided a graphical user interface (GUI). It also improved reliability and functionality and reduced costly maintenance of antiquated controls. The finished design is based on an industry standard servo control method utilizing two interactive control loops, an inner velocity control loop and an outer position control loop. Both loops have mechanisms to read a set point, receive feedback and generate an error signal that is appropriately amplified (PID) and sent as a command signal to the positioner. The pitch axis utilizes a Kinetix motor and has a built-in incremental encoder and brake and is torque controllable. The pitch range is ±90° with a resolution of ±0.01°. The position encoder is a rotary type with a resolution on the pitch axis of 0.0004°/count. The system has the ability to inject and retract the model, adjust the velocity and acceleration of the injection and retraction motions, adjust the position, speed and acceleration of the model pitch and run a sequence (table) of desired pitch settings. It also controls the model injection box equalization valves, vent valve and the operation of the hydraulic pump.

V. Future Upgrades and Enhancements to Facilities

A. Replace instrumentation wiring in the 20-Inch Mach 6 Air Tunnel

Due to wear and tear damage to the instrumentation wiring and connectors inside the model support housing, a project has been initiated to replace and/or upgrade the wiring to the 20-Inch Mach 6 Air Tunnel. This project will address issues due to worn-out connectors and degraded wiring, corroded connections, floating shielding on the cables inside the model support housing, shields on the cables have been twisted together and terminated outside the model support housing and any signal/data cables inside and outside of the model support housing that have degraded from years of use in a harsh environment. The project will simplify the wiring, while at the same time aligning the channel count with current and future sensor and instrumentation requirements. Low frequency cabling will be replaced to allow the collection of higher frequency data (higher than 1 KHz) without signal degradation. The thin-film patch panels will be modified to allow the senses to be passed through directly to the sensor for greater accuracy when measuring voltage across a constant current device.

B. Purchase and install new computers and software to replace NEFF hardware

The existing LAL data acquisition systems (DAS) are PC based systems with a NEFF Instrument Corporation 500/600 data acquisition front end and a PSI model 8400 measurement systems (ESP) for measuring pressures. The LAL AQU is written in the HTBasic programming language and controls the NEFF and the ESP during setup, data acquisition and retrieval. It also has a module for in-place calibrations of instrumentation. Due to the age of the NEFF 500/600 technology as well as the announced closing of NEFF Instruments, acquiring the necessary parts and expertise for repairs and replacements is becoming increasingly difficult. Currently, parts are removed from older, unused systems to maintain the operational ones. The replacement of both the front end and the acquisition system will modernize the DAS, improving reliability and accuracy and allowing for an increase in sampling rates.

The replacement DAS is based on NI hardware, Precision Filters 28000 signal conditioning units and programmed with NI LabVIEW. It will have 256 analog input channels at a sampling rate at 100 Hz or 142 channels at a sampling rate of 200 KHz. It will support a maximum of 16 analog input channels with maximum sampling rates of 15M samples/sec/channel for signal frequencies in the 1 KHz to 500 KHz range. The system's filters are 4-pole Low-pass programmable with two programmable selectable filters, “flat” and “pulse”. A “flat” filter is identical to a Butterworth and is best for spectral analysis applications with 2 Hz to 2.046 KHz in 1 Hz steps and 2.2 KHz to 100 KHz in 200 Hz steps. A “pulse” filter is similar to a Bessel filter and is ideal for time domain applications including transients (shock) with 1 Hz to 1.023 KHz in 1 Hz steps and 1.1 KHz to 100 KHz in 100 Hz steps. The signal conditioning units can support but are not limited to Kulite (high speed 4-arm bridge), thin-film, balances (1-arm, 2-arm, 4-arm), RTD and/or PRT, thermocouples via the UTR Box, and generic voltage devices up to +/-10 volts. The replacement DAS will have the ability to perform instrument calibration utilizing a programmable National Institute of Standards and Technology (NIST) traceable standard.

C. Upgrade/replacement of the 20 in Mach 6 Tunnel Model Support Control System (MSCS)

The 20-Inch Mach 6 Tunnel MSCS is nearing the end of its life and beginning to exhibit failures with limited replacement parts and expertise to repair available. The upgrade/replacement will provide for the modernization of the MSCS to improve the reliability/functionality and reduce costly maintenance of antiquated controls. The position encoders for pitch and yaw will be rotary type with a resolution of 0.0004°/count on the pitch axis and 0.0003°/count on the yaw axis. The pitch drive system will have rollers to stabilize strut base, a redesigned pitch drive using a motor to driven gear, will be external for easy adjustment, and will have increased speed, load capacity and positioning resolution. The yaw drive system will have precision, preloaded slewing ring and “Outrigger” support rollers. It will have an increased gear drive ratio, less bearing load and will incorporate a low backlash “floating gear” arrangement to increase positioning resolution. The injection system will use preloaded roller guides, an increased number of rail/guide sets and couple length (upper to lower guide sets) and will eliminate carriage-mounted supplemental guides. A conceptual design was approved by NASA's Aeronautics Test Program (ATP) as an FY 12 maintenance project. The Conceptual Design Document was completed in June 2013. A MSCS 100% Upgrade Design was approved by ATP as a FY13 project and is scheduled to be completed in July 2015.

D. Upgrade/replacement of the 20 in Mach 6 Tunnel Model Support Control System (MSCS)

A DoE calibration experiment, similar to the one completed in the 20-Inch Mach 6 Air Tunnel, is planned for the 31-Inch Mach 10 Tunnel and will cover a much wider range of total temperature than previous calibrations, thus widening the operating envelope of the facility. A new calibration rake was designed and fabricated for the 31-Inch Mach 10 Tunnel. The new rake features an interchangeable probe design that will allow different types of probes – pitot pressure, total temperature, static pressure, and flow angularity – to be easily installed on the rake. The calibration experiment is currently scheduled for January 2015.

VI. Future Upgrades and Enhancements to Instrumentation and Test Techniques

A. Pressure System UG/Optimus & Gen 2 Module UP

The Optimus Data System is a pressure scanning system that was designed specifically for wind tunnels. Pressure is measured with ESP Miniature Pressure Scanners or the new MicroScanners and converted to a digital value using measurement values calculated within the Optimus System Processor. Communications from processor to computer are via Ethernet at data rates up to 1Gbps. Communications between the pressure scanners and system processor are through a fiber cable to remove interference due to cross-talk between scanners (inside injection box) to and from the Optimus (outside the injection box).

The Optimus Project will provide greater accuracy, quicker calibrations and better acquisition rates compared to the current ESP 8400 system. The ESP-32HDDTC Gen 2 miniature pressure scanners have throughput of 1 kHz, with a resolution of ±0.001% full scale. The static accuracy for the full range of 5 to 150 psid is ±0.03% and for a range from 10 inch WC to 2.5 psid is ±0.06% full scale. The modules are digitally temperature compensated (DTC), requiring fewer calibrations and providing for higher accuracy measurements. The total thermal effect at the full range of 5 to 150 psid is ±0.002% and at 10 inch WC to 2.5 psid is ±0.004% full scale/°C. The Pressure Calibration Unit (PCU) provides precise pressure to the scanners for the purpose of performing calibration or pre-test verification with a system accuracy better than ±0.03% full scale

The project was initialized on August 2013 with the purchase of Measurement Specialties' Optimus Pressure Measurement System components for implementation in the 31-Inch Mach 10 Air Tunnel. System implementation design, software development and available hardware installation are currently ongoing. All hardware purchases and their installation in the tunnel are expected to be completed by February 2014.

B. High Temperature Global Phosphor Thermography

A new phosphor formulation is being developed which will increase the maximum measureable temperature for the system from 160 °C (780 °R) to 300 °C (1030 °R). This will allow for better characterization of heating data near stagnation regions, in turbulent boundary layers or in other areas that exceed the maximum range of the current formulation.

C. Continuous Sweep Aerodynamic Force and Moment Data

A process under development in the LAL facilities will allow for continuous pitch and yaw sweeps during aerodynamic force and moment testing. This allows for shorter run times (less heating to the model, sting and balance), increased run productivity (less time required to pump down the vacuum spheres between runs) and increased data (current pitch-pause method limits data to predetermined set angles during a run as opposed to all angles in the range during continuous sweep).

D. Metallic Surface Integration into Ceramic Models

A capability under development will allow for metallic model components to be integrated into ceramic models. This has the advantage of allowing for configurations that cannot be fabricated from cast ceramics (i.e. very sharp leading edges) to be made with metal instead and used in phosphor thermography models. The tradeoff is that the metallic regions will not generate heating data using the phosphor system, though the use of IR is being investigated.

VII. Facility Utilization

Over the years, the LAL test facilities have been involved in a number of major flight programs, including but not limited to the Space Shuttle, Hyper-X, X-33, X-34, X-38, X-51, Falcon HTV, HiFIRE, CEV/Orion/MPCV, HIADS and MSL. Significant aerodynamic and/or aerothermodynamic testing was completed on these programs and some of the major impacts are listed below:

- Space Shuttle: Over 3500 runs between 2003 and 2011 focused on the Columbia Accident Investigation, Space Shuttle Return-To-Flight (RTF), on-orbit assessments and support of the Boundary Layer Transition (BLT) Flight Experiment and Hypersonic Thermodynamic Infrared Measurements HYTHIRM teams. Wind tunnel data was used in the determination of the cause of the STS-107 Columbia accident. Major RTF contributions include the creation of the Cavity Heating and Boundary Layer Transition Tools, used to determine the condition and readiness for re-entry of the Orbiter TPS on each post-STS 107 mission.
- Hyper-X: Over 2500 runs were completed between 1998 and 2007 in support of the Hyper-X program, with the majority occurring prior to the first flight in 2000 and then in preparation for the final two flights in 2004. Major LAL contributions to the program include the design and testing of the boundary layer

transition trips used on the inlet to force turbulence and aerodynamic testing to gain a better understanding of the X-43 flight properties and performance when mounted to the Pegasus booster.

- X-33: Over 2200 runs were completed in support of the X-33 program between 1998 and 1999. Testing supported the understanding of aerodynamics and aerothermodynamic performance.
- Orion: Almost 1400 wind tunnel runs were completed between 2006 and 2011 in support of the CEV/Orion/MPCV program. Testing aided in the determination of aerodynamic and aerothermodynamic performance as well as effects of RCS jets and BLT effects.
- X-38: Over 850 runs were completed between 1998 and 2001 in support of the X-38 program. Testing included the aerodynamics and aeroheating for the vehicle design.
- EDL: This class of entry vehicle, including programs like MSL, Mars Sample Return Orbiter, HIADS, etc. accounted for over 1800 runs and supported the understanding of re-entry heating and shape effects.

VIII. Summary

The LAL consists of three hypersonic blown-down to vacuum tunnels and a vacuum test facility. The 20-Inch Mach 6 and 31-Inch Mach 10 tunnels were designed, built and first utilized in the late 1950's and early 1960's and are the Agencies only resource for continuous, unvitiated hypersonic aerodynamic, aeroheating and fluid dynamic testing capability. Between the three tunnels, Mach numbers of 6 and 10 and Reynolds numbers of 0.25 to $8.3\text{x}10^6$/ft can be attained.

This paper presented an update to the descriptions of the facilities, instrumentation and capabilities currently in the LAL complex as well as future work planned. This includes:

1. Detailed descriptions and diagrams of the 31-Inch Mach 10, 20-Inch Mach 6 and 15-Inch Mach 6 High Temperature Air Tunnels (including operating pressures, temperatures, and freestream conditions) as well as the 60-ft Vacuum Sphere. Compatibility and synergy between the facilities was discussed.
2. Descriptions of instrumentation and test technique capabilities used in the tunnels to measure forces and moments, heating, pressure, surface and flow-field characteristics, etc. These include intrusive and non-intrusive techniques. Data acquisition systems were also described.
3. A summary of the major facility and instrumentations upgrades, improvements and projects over the last 15 years was presented.
4. A summary of the upcoming and planned facility and instrumentation improvements was included.
5. The recent (last 15 years) utilization of the LAL facilities was included and the major test programs as well as some of the major impacts of that testing were discussed.

The collection of the LAL facilities provides a unique and valuable capability for past, current and future hypersonic ground testing needs. Aerodynamic and aerothermodynamic testing, as well as flow physics studies allow for a better assessment of the performance of advanced hypersonic flight vehicles and provide necessary benchmarking data for computational techniques.

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