

Rocket Testing

TESTS

- **TYPES OF TESTS** Before any rocket propulsion systems are put into operational use, they are subjected to several different types of tests, many of which are outlined below in the approximate sequence in which they are normally performed.
- Manufacturing inspection and fabrication tests on individual parts (dimensional inspection, pressure tests, X-raying, leak checks, electric continuity tests, electromechanical checks, etc.). These tests are usually done at the factory.
- Component tests (functional and operational on igniters, nozzles, insulation, valves, controls, injectors, structures, tanks, motor cases, thrust chambers, turbopumps, thrust-vector control, etc.). May need special equipment/ facilities.
- Static rocket propulsion system tests (with complete propulsion system) on a test stand: (a) complete propulsion system tests (under rated conditions, off-design conditions, with intentional variations in environment or calibration); (b) with liquid propellants a partial or simulated rocket operation (for proper function, calibration, ignition, operation— often without establishing full thrust or operating for the full duration); for reusable or restartable rocket propulsion systems this can include several starts, long-duration endurance tests, and postoperational inspections and reconditioning; (c) some tests on chemical propulsion systems and nearly all tests on electrical propulsion systems are performed in large vacuum facilities that simulate the high-altitude rarified atmosphere conditions.
- Sutton, George P.; Biblarz, Oscar. Rocket Propulsion Elements. Wiley.

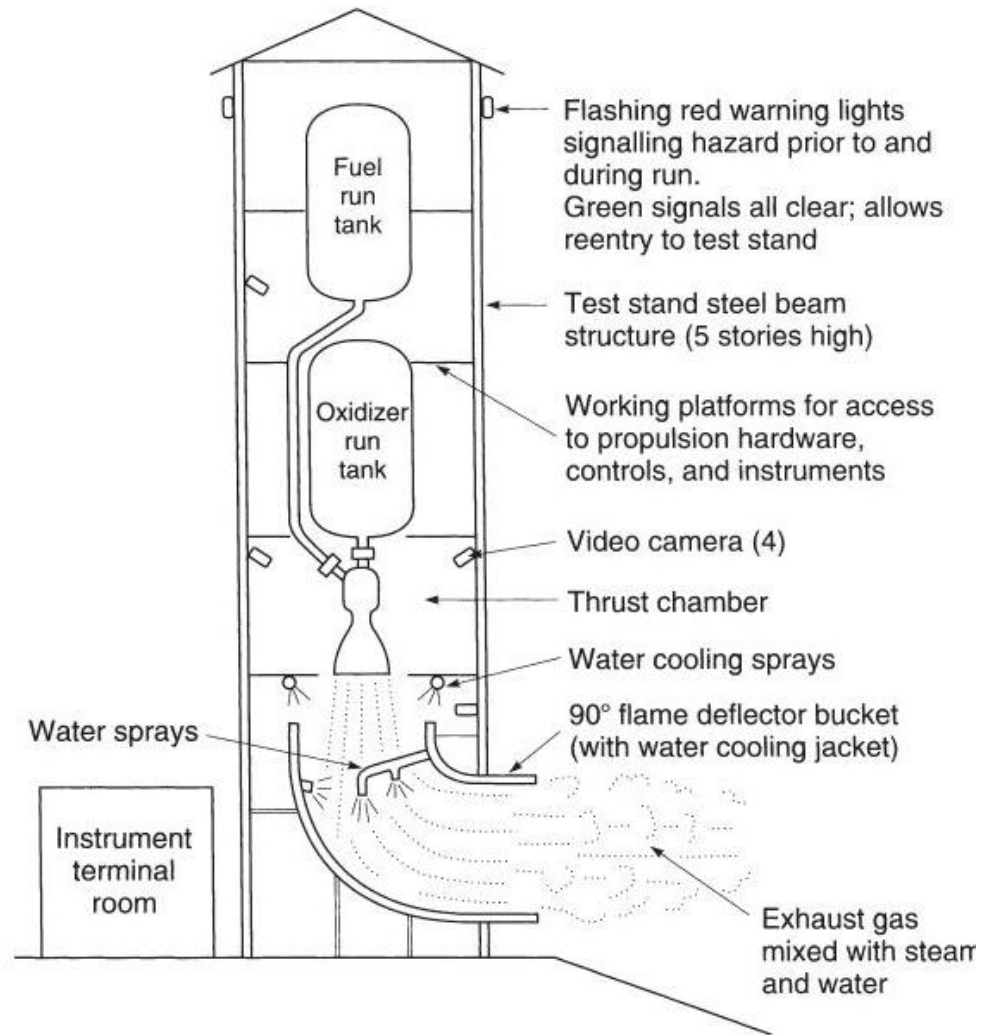
TESTS

- Static vehicle tests (when rocket propulsion system is installed in a restrained, nonflying vehicle or stage) on a vehicle test stand.
- Flight tests: (a) with a specially instrumented or new propulsion system in a developmental flight test vehicle; (b) with a production vehicle.

Each of these five types of tests can be performed on at least three basic program types:

- Research on and development or improvement of a new (or modified) rocket propulsion system, its propellants, materials, or components.
 - Evaluation of the suitability of a new (or modified) rocket engine or novel rocket motor for an alternate specified application or for flight readiness.
 - Production proof tests and quality assurance of existing operational rocket propulsion systems.
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- Sutton, George P.; Biblarz, Oscar. Rocket Propulsion Elements. Wiley.

Testing



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Testing

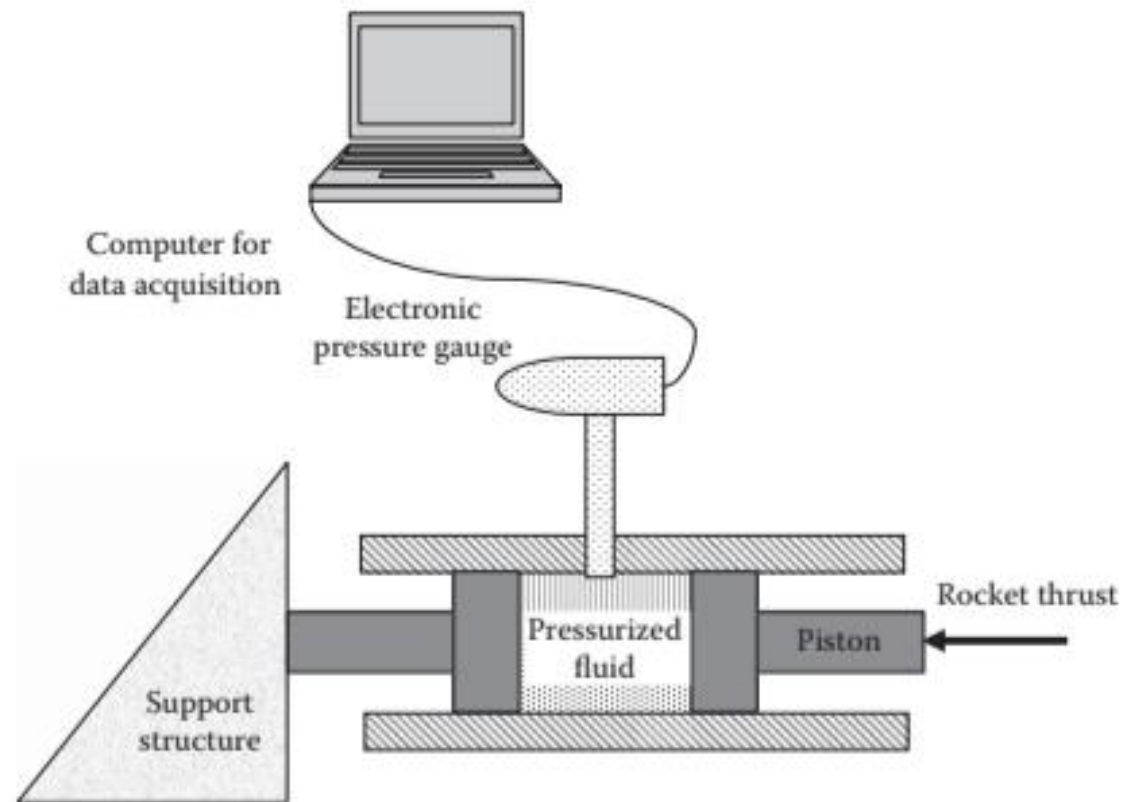


FIGURE 6.13
Hydraulic load cell thrustometer.

T-97 Thrust Measurement System

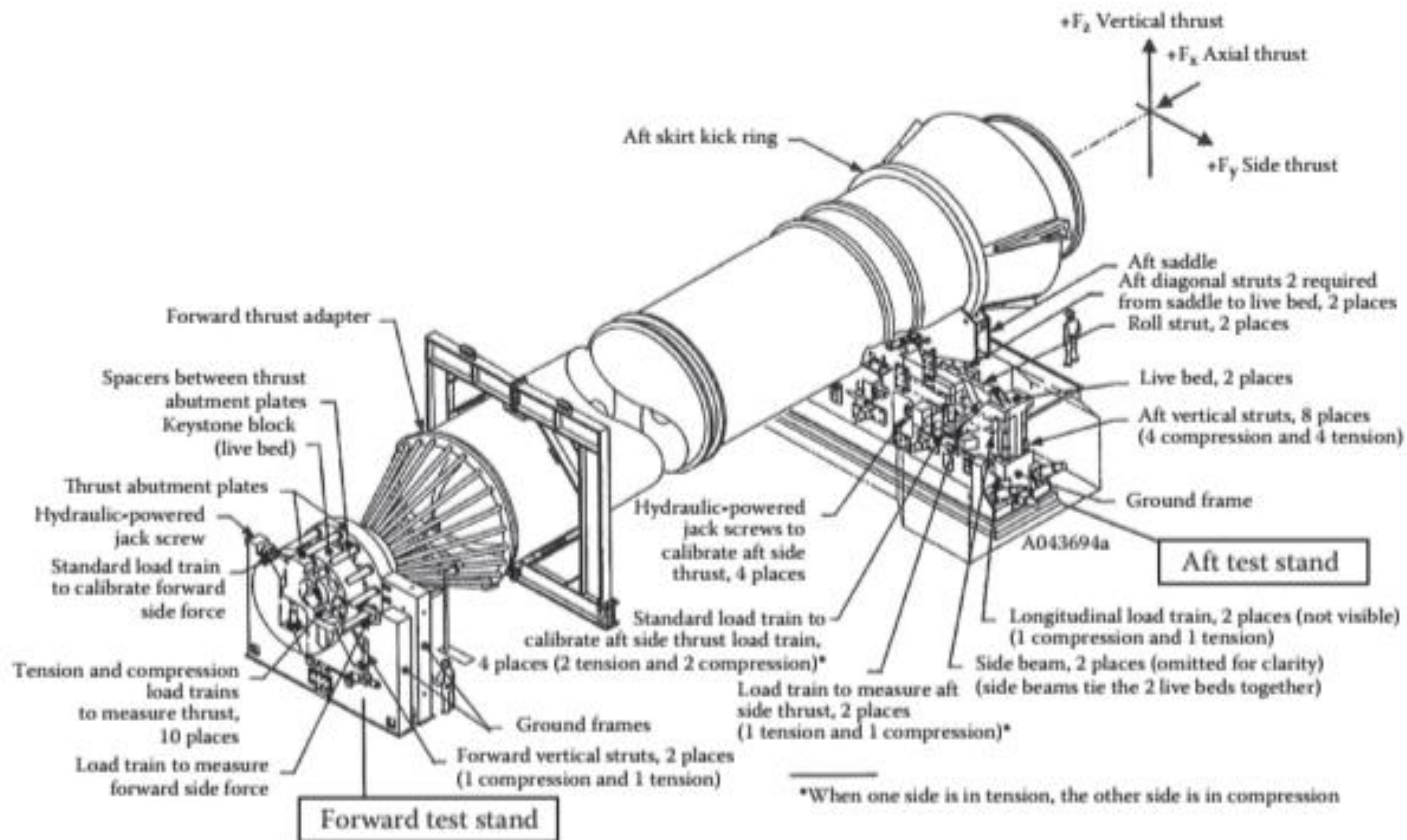


FIGURE 6.16

T-97 Thrust Measurement System for testing SRBs. (Courtesy of NASA.)

Possible Test Parameters

- freestream Mach number
- freestream Reynolds number (and influence on the character of the
- boundary layer)
- freestream velocity
- pressure altitude
- total enthalpy of the flow
- density ratio across the shock wave
- test gas
- wall-to-total temperature ratio
- thermochemistry of the flow field

Types of Ground Test Facilities

- conventional wind tunnels
- shock-heated wind tunnels
- shock tubes
- expansion tubes
- gun tunnels
- arc-heated test facilities
- ballistic, free-flight ranges and tracks

Wind Tunnel Basics

- Wind tunnels are devices that provide air streams flowing under controlled conditions so that models of interest can be tested using them.
- From an operational point of view, wind tunnels are generally classified as low-speed, high-speed, and special-purpose tunnels.
- Low-speed tunnels are those with test-section speed less than 650 kmph.
- Tunnels with test-section speed more than 650 kmph are called high-speed tunnels.
- The tunnels are used to replicate the actions of an object flying through the air or moving along the ground.
- The wind tunnel moves air around an object, making it seem as if the object is really flying.



Wind Tunnel Basics

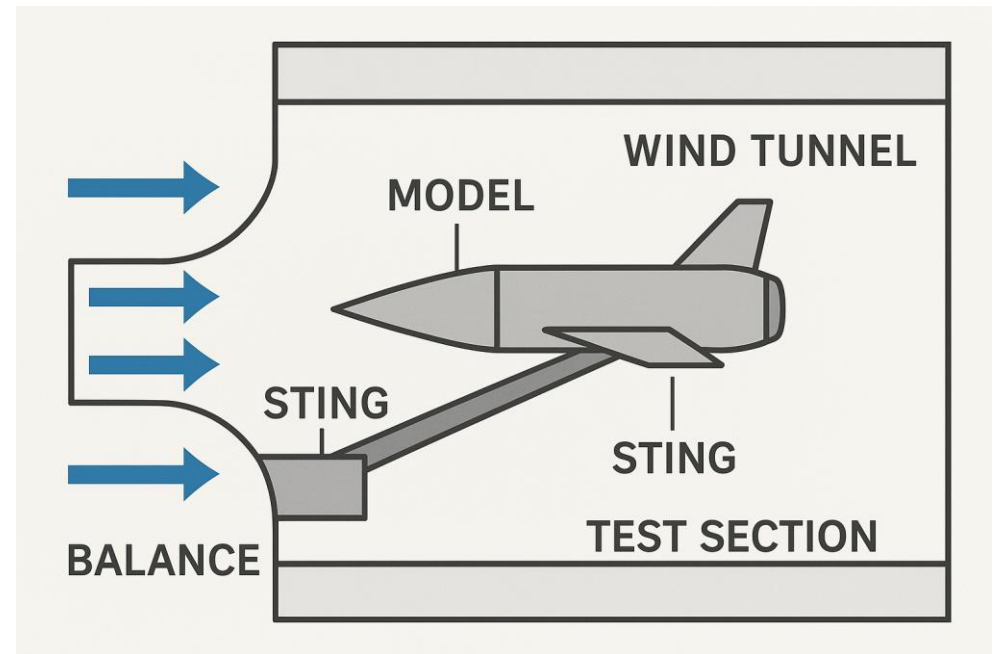
- Most of the time, large powerful fans blow air through the tube.
- The object being tested is held securely inside the tunnel so that it remains stationary and does not move.
- The object can be a small model of a vehicle, or it can be just any part of a vehicle.
- It can be a full-size aircraft or spacecraft. It can even be a common object like a tennis ball.
- The air moving around the stationary object shows what would happen if the object was moving through the air.
- The motion of the air can be studied in different ways; smoke or dye can be placed in the air and can be seen as it moves around the object.

Wind Tunnel Basics

- Colored threads can also be attached to the object to show how the air moves around it.
- Special instruments can often be used to measure the force of the air exerted against the object.
- In some wind tunnel tests, the aerodynamic forces on the model are measured.
- In some wind tunnel tests, the model is instrumented to provide diagnostic information about the flow of air around the model.
- In some wind tunnel tests, flow visualization techniques are used to provide diagnostic information about the flow around the model.

Wind Tunnel - Sting

In fluid mechanics, particularly in aerodynamic and wind tunnel testing—a sting is a slender support structure used to hold a test model (such as an aircraft or missile shape) in the wind tunnel while minimizing flow disturbance.



Wind tunnel sizes

- **Small Research Tunnels**
- **Test Section Size:** 0.1–1 meter (diameter or width).
- **Use:** Basic aerodynamic studies, component testing, and academic research.
- **Example:** University subsonic tunnels with 30–50 cm test sections.
- **Medium-Scale Aerospace Tunnels**
- **Test Section Size:** 1–4 meters.
- **Use:** Testing scaled-down models of aircraft, rockets, and spacecraft.
- **Examples:**
 - NASA Langley's 4-foot by 4-foot Supersonic Unitary Plan Facility.
 - Boeing's transonic wind tunnel (approx. 3 m test section).
- **Large-Scale Tunnels**
- **Test Section Size:** 5–10 meters (or larger).
- **Use:** High-fidelity aerodynamic testing, sometimes near full-scale models of aircraft components.
- **Examples:**
 - **NASA Ames 40- by 80-foot (12 by 24 m) Subsonic Wind Tunnel** (one of the largest in the world).
 - The European Transonic Wind Tunnel (ETW) with a 2.4 m diameter test section but capable of high Reynolds numbers by using pressurized, cryogenic nitrogen.

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NASA Langley's 20-Inch Mach 6 Tunnel

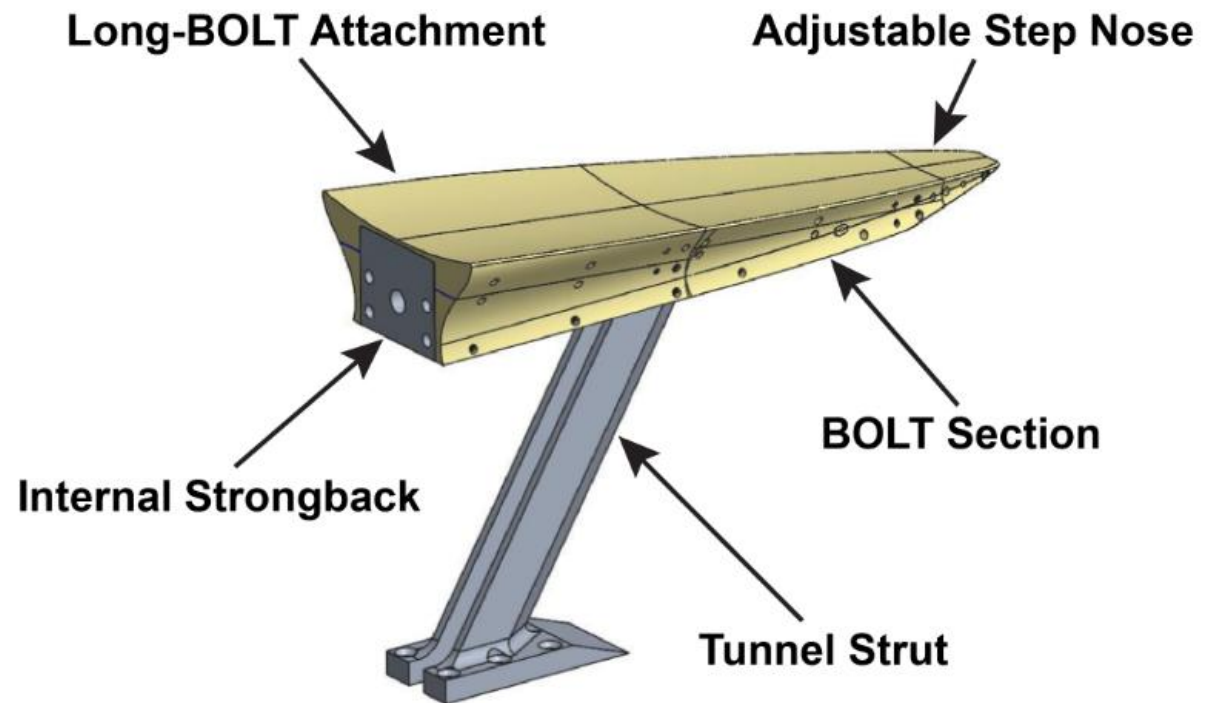
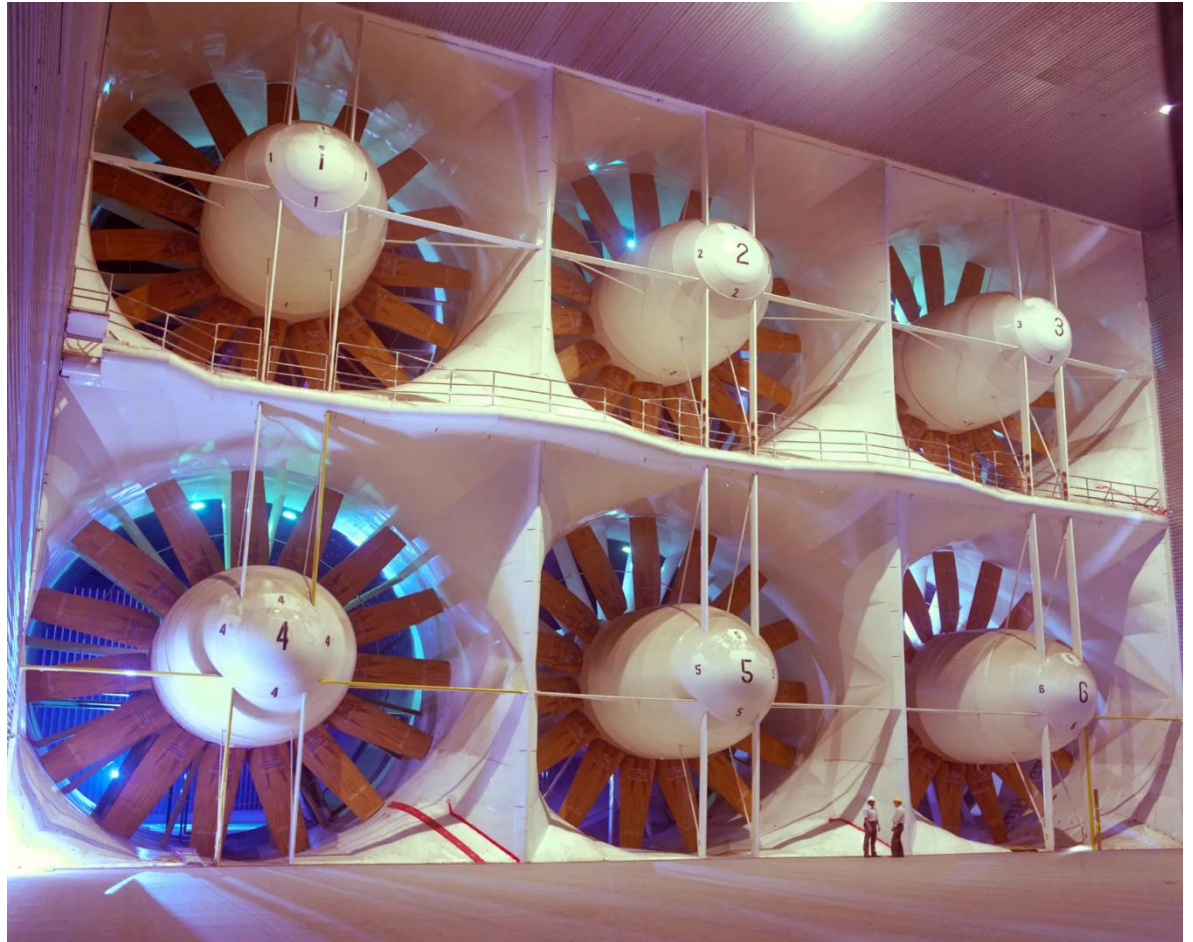


Figure 5. Fully assembled BST model with tunnel support strut.

<https://ntrs.nasa.gov/api/citations/20230003164/downloads/NASA-TM-20230003164.pdf>

NASA Ames 80- by 120- foot Wind Tunnel



<https://ntrs.nasa.gov/api/citations/19840015554/downloads/19840015554.pdf>

NASA Ames 80- by 120- foot Wind Tunnel



<https://www.nasa.gov/centers-and-facilities/ames/testing-on-the-ground-before-you-fly-wind-tunnels-at-nasa-ames/>

FLOW VISUALIZATION

SMOKE FLOW VISUALIZATION

- It is one of the popular techniques used in low-speed flow fields with velocities up to about 30 m/s.
- Smoke visualization is used to study problems such as boundary layers; air pollution problems; design of exhaust systems of locomotives, cars and ships; topographical influence of disposal of stack gases; and so on.

Wind Tunnel Basics

- TUFTS
 - It is used to visualize flow fields in the speed range from 40 to 150 m/s.
 - This technique is usually employed to study boundary layer flow, wake flow, flow separation, stall spread, and so on.
- CHEMICAL COATING
 - It is used to visualize flow with speeds in the range from 40 to 150 m/s.
 - Boundary layer flow, transition of the flow from laminar to turbulent nature, and so on are usually described by this visualization technique



Wind Tunnel Basics

INTERFEROMETER is an optical technique to visualize high-speed flows in the ranges of transonic and supersonic Mach numbers. This gives a qualitative estimate of flow density in the field.

An interferometer works by splitting a coherent light beam (e.g., from a laser) into two paths:

- **Reference Beam:** Passes through a known path (often in air at rest).
- **Test Beam:** Passes through the hypersonic flow inside the test section of the wind tunnel.

When these beams are recombined, any changes in the refractive index of the flow (caused by variations in density, temperature, or shock waves) cause phase shifts. These phase shifts result in interference fringes. By analyzing these fringes, we can determine the changes in optical path length, which are directly related to the flow parameters.

In hypersonic flows (Mach 5 and above), strong shock waves, steep temperature gradients, and rapid changes in density occur. Conventional probes or sensors disturb the flow, so a non-intrusive optical method like interferometry is ideal.

Key applications:

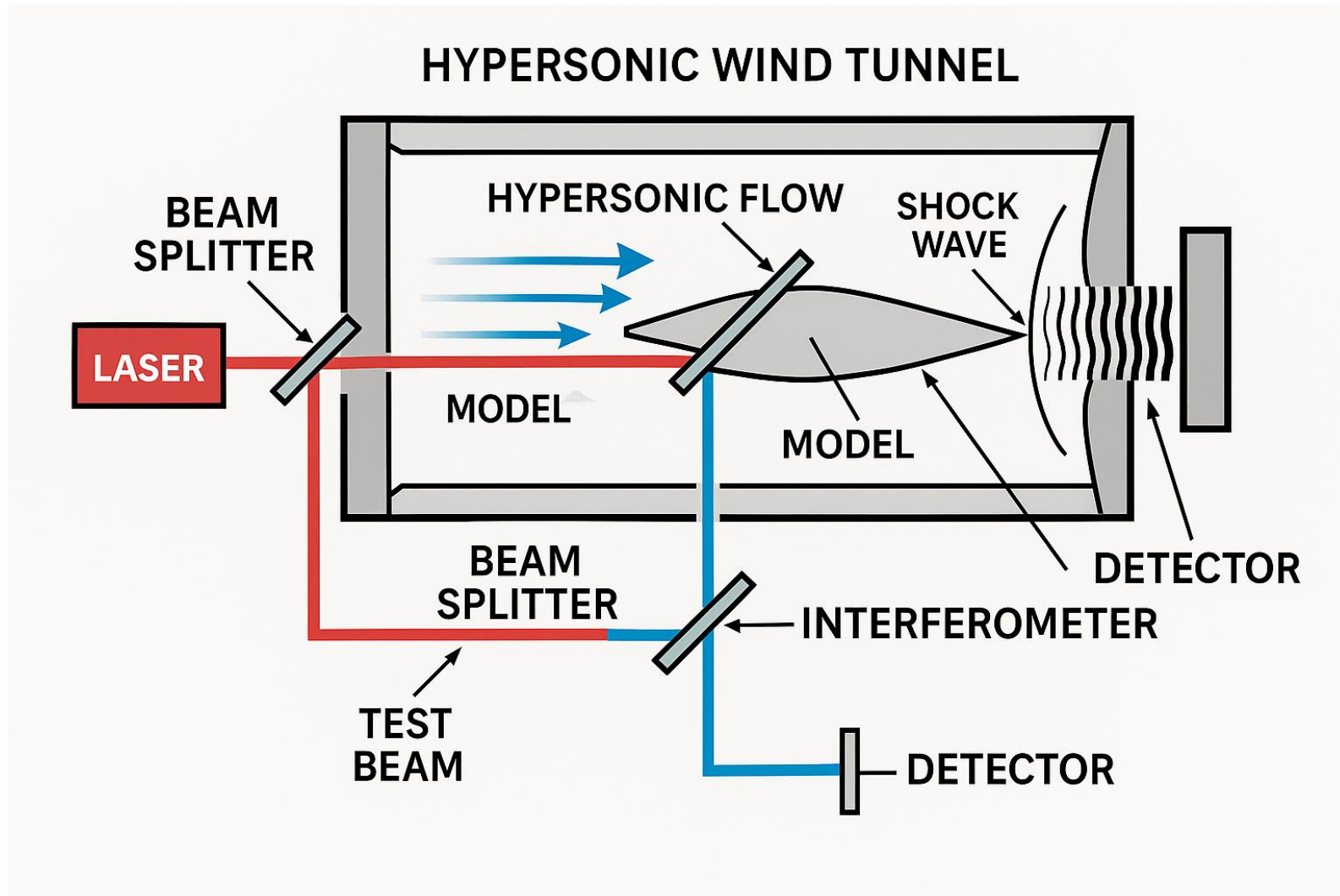
- Shock wave visualization: Interferometers can map shock shapes and positions by detecting abrupt density changes.
- Density measurements: The fringe shift corresponds to changes in refractive index, which can be converted to density distributions using the Gladstone–Dale relation.
- Boundary layer and flow separation studies: Helps visualize thin regions of high gradient near surfaces.
- Transient phenomena: Time-resolved interferometry captures dynamic events like shock-boundary layer interactions.

Wind Tunnel Basics - Interferometer

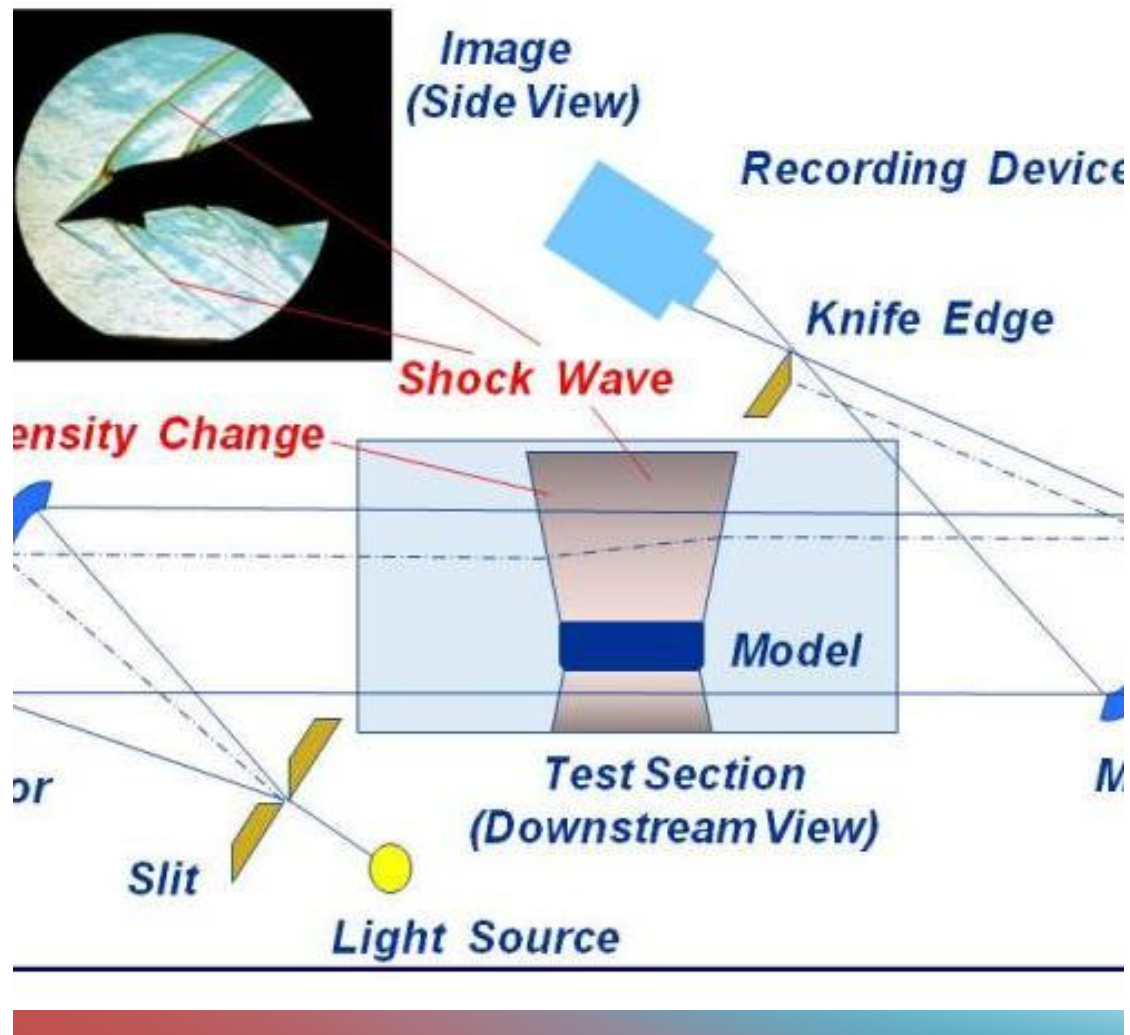
The recorded interference pattern is analyzed using fringe counting or phase-unwrapping algorithms. These techniques translate the optical path differences into quantitative density or temperature fields. Advanced high-speed cameras often accompany modern setups to capture unsteady flow phenomena in real time. Several configurations are employed in hypersonic facilities:

- **Mach-Zehnder Interferometer:** Popular due to its ability to provide a full-field 2D density map of the test section.
- **Twyman-Green or Michelson Interferometers:** Used for simpler setups or when high sensitivity is required.
- **Laser interferometry (e.g., holographic or electronic speckle interferometry):** Enables digital fringe analysis and high spatial resolution.

Wind Tunnel Basics - Interferometer



Schlieren System



Wind Tunnel Basics

SCHLIEREN TECHNIQUE

- It is used to study high-speed flows in the transonic and supersonic Mach number ranges.
- This again gives only a qualitative estimate of the density gradient of the field.
- This is used to visualize faint shock waves, expansion waves, and so on.
- <https://www.grc.nasa.gov/www/k-12/airplane/tunvschlrn.html>

SCHLIEREN SYSTEM

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- The Schlieren method is a technique for visualizing the density gradients in a transparent medium. Figure shows a typical Schlieren arrangement, usually employed for supersonic flow visualization.
 - Light from a source is collimated by the first lens and then passed through the test-section.
 - It is then brought to a focus by the second lens and projected on the screen.
 - At the focal point of the second lens, where the image of the source is formed, a knife-edge (which is an opaque object) is introduced to cut off part of the light.
 - The screen is made to be uniformly illuminated by
 - the portion of the light escaping the knife-edge, by suitably adjusting it to intercept about half the light when there is no flow in the test-section.

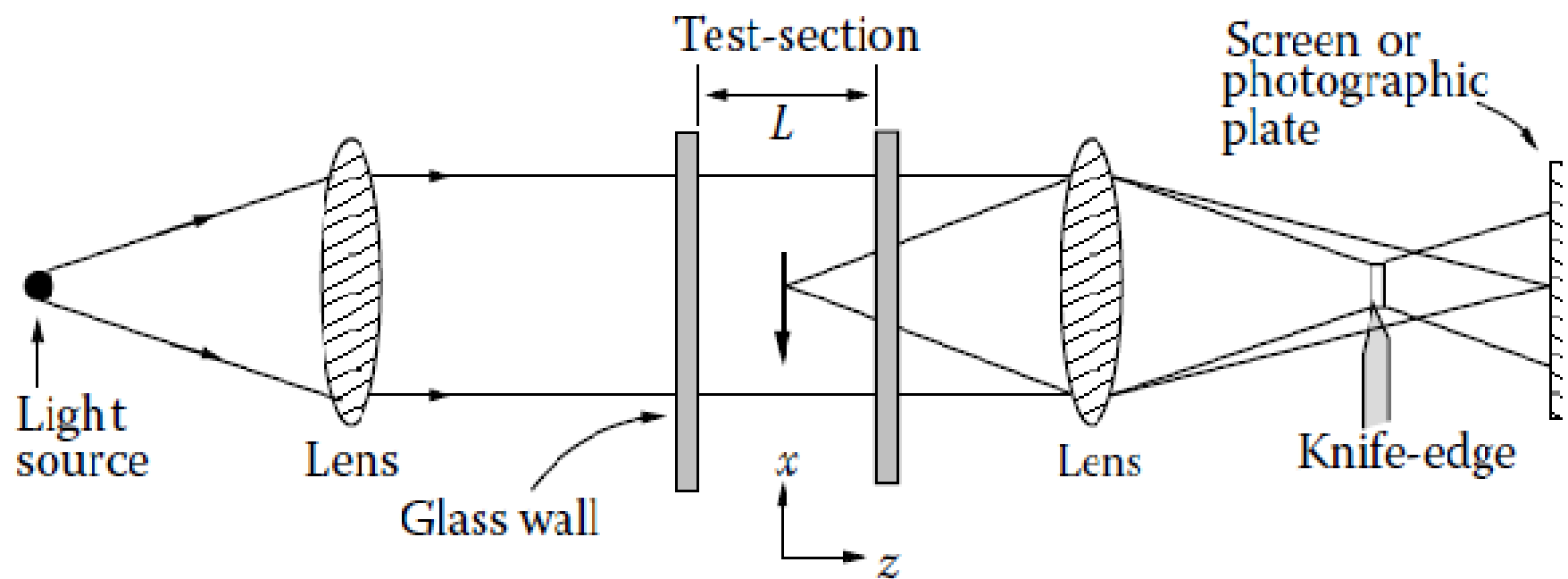
<https://sciencedemonstrations.fas.harvard.edu/presentations/schlieren-optics>

The Schlieren Technique

- The Schlieren technique is an optical method used to visualize variations in fluid density, typically caused by compressible flow phenomena such as shock waves, boundary layers, and thermal plumes. It is widely used in aerodynamics—especially in hypersonic flow studies—because it can clearly reveal features like shock-shock interactions, expansion fans, and wake structures without disturbing the flow.
- **The Schlieren method works based on light refraction:**
 - When light passes through a medium with varying refractive index (which depends on density in gases), its path bends.
 - In high-speed flows, density gradients (such as those around shocks or in boundary layers) cause significant refractive index changes.
 - The Schlieren system makes these otherwise invisible deviations visible by translating them into brightness changes in an image.
- **Key Components**
 - Light Source: A point or slit source of light, often a bright LED or laser.
 - Collimating Optics: Lenses or mirrors that convert the divergent light from the source into a parallel beam.
 - Section: Where the fluid flow occurs, usually in a wind tunnel.
 - Focusing Optics: Another set of lenses or mirrors that refocus the light after it passes through the flow.
 - Knife Edge (or Filter): A blade or filter placed at the focal point to block or partially block refracted light rays, enhancing contrast.
 - Camera or Eye: Captures or observes the Schlieren image.

Variations of the Schlieren Technique

Technique	Feature
Classical Schlieren	Traditional setup with mirrors and knife edge.
Z-type Schlieren	Uses two identical mirrors in a "Z" configuration; compact and widely used in wind tunnels.
Color Schlieren	Uses color filters or prisms to produce colored images representing the direction of density gradients.
Background Oriented Schlieren (BOS)	Digital technique using background patterns and image processing; useful for large-scale tests.

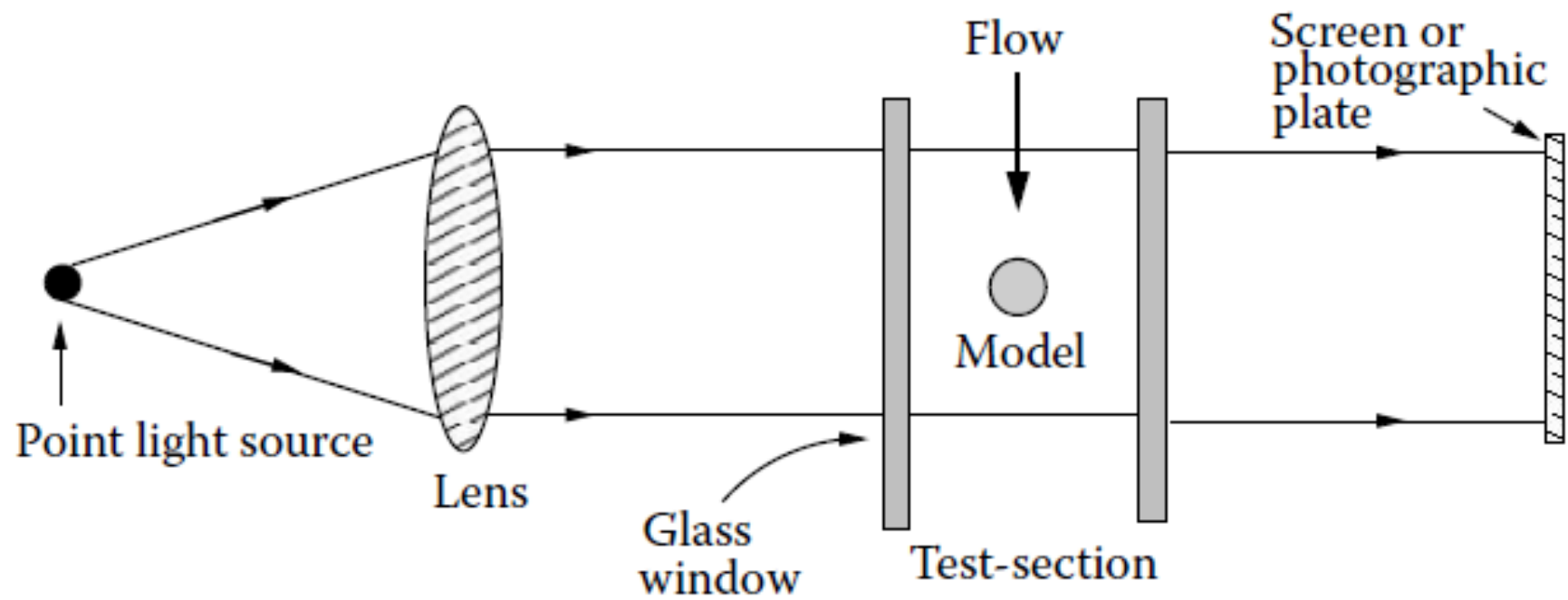


SHADOWGRAPH



- On the Schlieren system the positions of the image points on the viewing screen are not affected by deflections of light rays in the test-section.
- This is because the deflected rays are also brought to focus in the focal plane, and the screen is uniformly illuminated when the knife-edge is not inserted into the light beam.
- On the other hand, if the screen is placed at a position close to the test-section, the effect of ray deflection will be visible.
- This effect, termed the *shadow effect*, is illustrated in Figure.

- SHADOGRAPH SYSTEM



The Shadowgraph Technique

- The shadowgraph technique is an optical flow visualization method used to observe density variations in transparent media, particularly in compressible flows. It is extensively employed in aerodynamics and hypersonic flow studies to visualize flow phenomena like shock waves, expansion fans, shear layers, and thermal plumes. The shadowgraph technique works on the principle of light deflection caused by changes in refractive index due to density variations in the medium:
- When light travels through a region with varying density, its velocity and path are altered due to changes in the refractive index.
- These changes result in variations in light intensity after passing through the flow.
- The intensity differences are recorded as bright and dark regions on a screen or imaging device.

The Shadowgraph Technique

The components are:

- Light Source: A bright and point-like source of light (laser, LED, or flashlamp).
- Collimating Lens or Mirror: Produces a parallel beam of light.
- Test Section: The region containing the flow of interest (typically inside a wind tunnel).
- Imaging Screen or Camera: Captures the shadow pattern created by refracted light.
- (Optional) Focusing optics to sharpen or magnify the image.

It works by

- Light Beam Passage: A collimated light beam passes through the flow field.
- Refraction: Density gradients in the flow deflect the light rays.
- Projection: Deflected rays create bright and dark areas on the imaging screen or camera, forming the shadowgraph image.
- Image Interpretation: Bright areas correspond to light convergence; dark areas correspond to light divergence due to the flow features.

Modern Digital Shadowgraphy

In recent years, **high-speed digital cameras** and advanced image processing have enhanced shadowgraph capabilities.

A light blue downward-pointing arrow indicating a flow from the first box to the second.

Background-Oriented Shadowgraph (BOS): Uses image correlation techniques for more quantitative results.

A light blue downward-pointing arrow indicating a flow from the second box to the third.

Often paired with Schlieren in **dual-visualization setups** for comprehensive flow diagnostics.

Schlieren vs Shadowgraph

Schlieren

Sensitive to **first derivative** of density (density gradient).

More detailed, shows finer structures.

Requires more complex setup.

Shadowgraph

Sensitive to **second derivative** of density (density gradient changes).

Highlights regions of rapid density change like shock edges.

Simpler to set up but lower sensitivity.

Wind Tunnel Basics

SMOKE TUNNEL

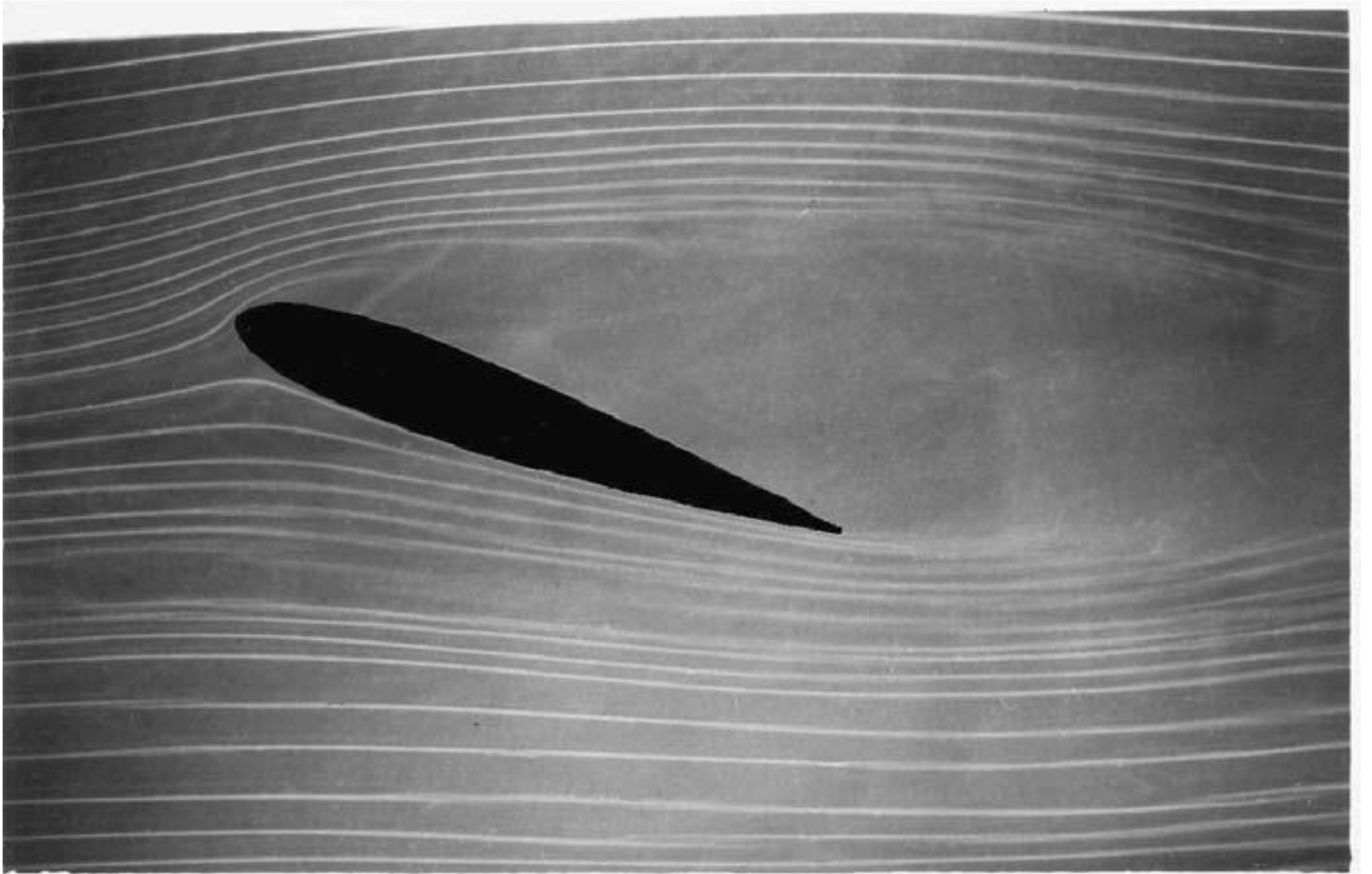
- Flow visualization with smoke is generally done in a smoke tunnel.
- It is a low speed wind tunnel carefully designed to produce a uniform steady flow in the test-section with negligible turbulence.
- Smoke streaks are injected along the freestream or on the surface of the model for visualizing flow patterns.
- White dense smoke is used for this purpose.
- When a beam of light is properly focused on the smoke filaments, the light is scattered and reflected by the smoke particles making them distinguishably visible from the surroundings

Wind Tunnel Basics

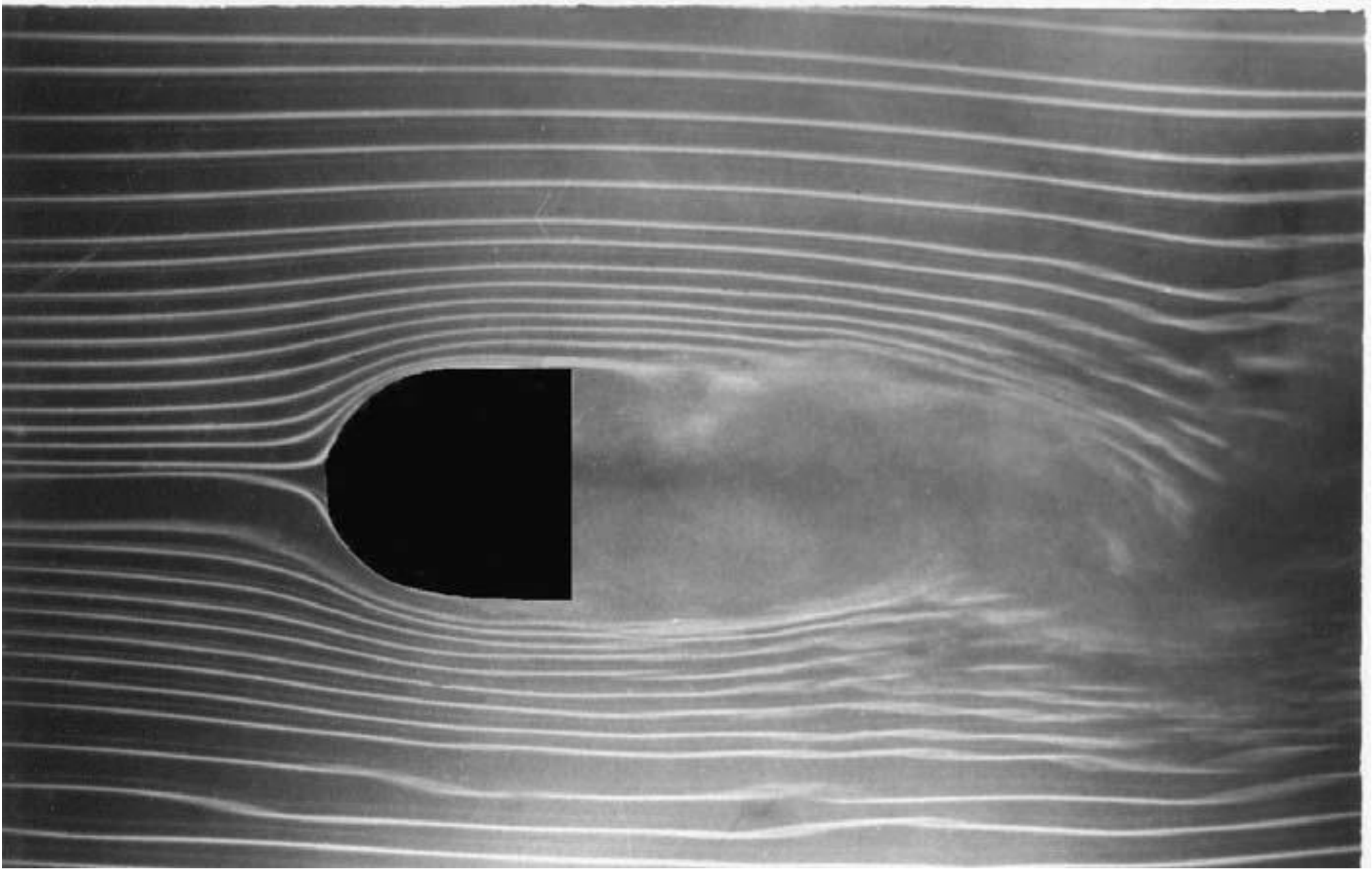
- The smoke tunnel is generally used for demonstrating flow patterns such as flow around bodies of various shapes, flow separation, and the like.
- The quality of the flow pattern depends on the quality of the smoke used.
- For good results, properties of the smoke chosen should have the following qualities.
 - The smoke should be white, dense, nonpoisonous, and noncorrosive.
 - Smoke should have nearly the same density as that of the surrounding air, hence the smoke filaments are not appreciably influenced by gravity.

Wind Tunnel Basics

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- Smoke particles should not disturb the flow in the wind tunnel by formation of deposits on the surface of the models or block the tubes used for smoke injection.
 - Production of smoke should be easily and readily controllable.



Flow Over an Airfoil



Smoke pattern over a blunt body.

Viscous Flow

Another example of a viscous flow case typical in aerodynamics is shown in Fig. 8.2, which is a photograph of a wing being tested in a transonic wind tunnel. The wing has been coated with “oil” so that the surface flowfield can be seen (this concept will be discussed in greater detail in Chapter 9). The purpose of the test is to see if any separation is occurring, since separation will cause additional drag: the photo shows that there is no separation since all of the surface streamlines flow straight back over the wing (the flow in the wind tunnel is from the top of the picture to the bottom). Two other features of the test and flowfield are also of interest. The surface is smooth close to the leading edge because the flow is laminar and there is not enough shear force to move the oil. At about 15 percent of the chord, the surface streamlines suddenly start to be visible. This is because there is a boundary layer trip strip on the wing to force the flow to transition to turbulent flow. This is the classic problem of the wind tunnel not being able to simulate full-scale Reynolds number, hence the need to use artificial means to force the flow to be turbulent. The other feature of interest occurs aft of the mid chord where the oil shows the position of the shock wave, since the shock thickens the oil locally. We can also see that the shock unsweeps slightly as it moves outboard, which is a way to determine how well the wing was designed.

- Cummings, Russell M.; Mason, William H.; Morton, Scott A.; McDaniel, David R.. Applied Computational Aerodynamics: (Cambridge Aerospace Series). Cambridge University Press

Viscous Flow

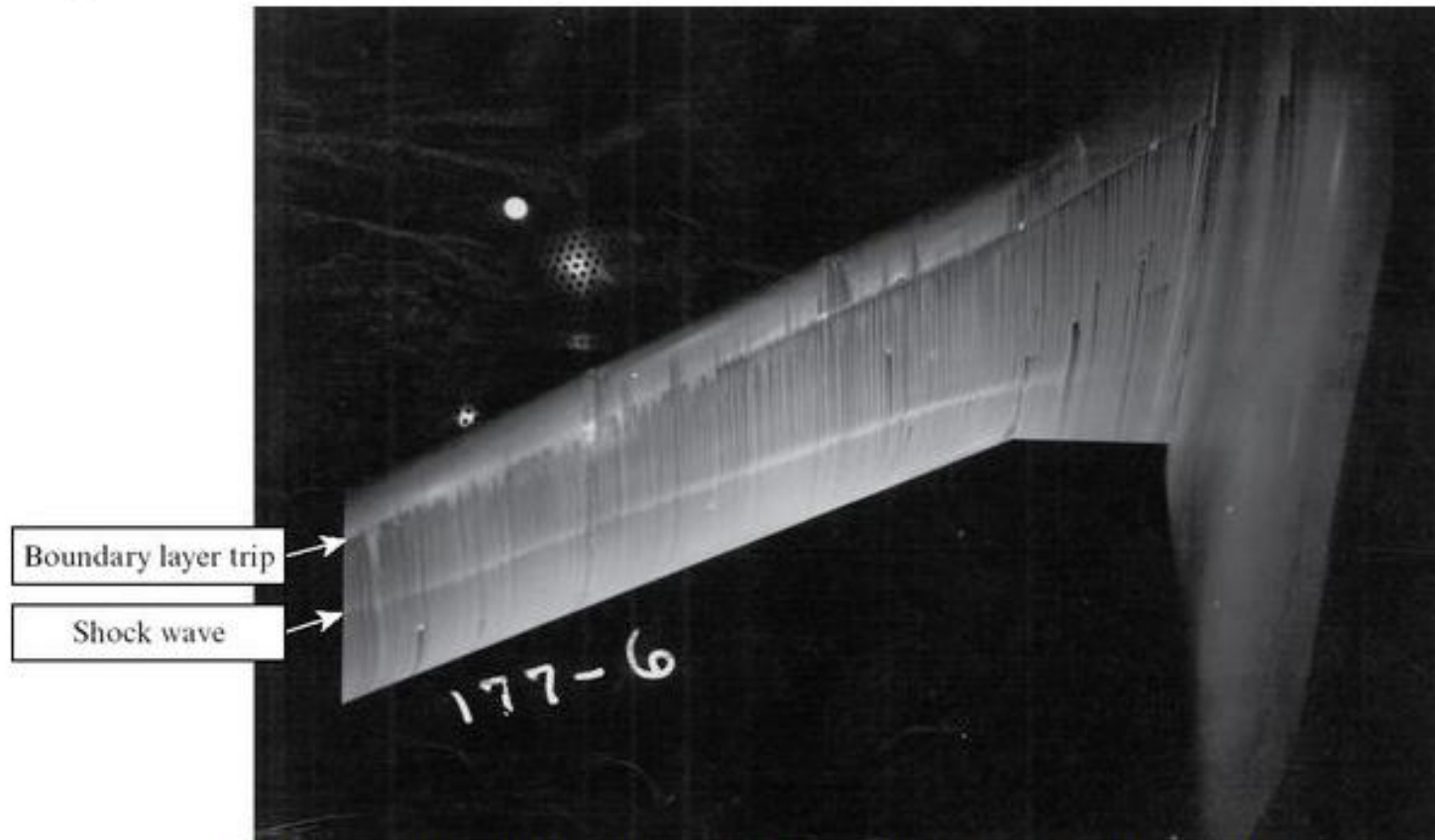


Figure 8.2 Oil flow photo of wing being tested in a wind tunnel at $M = 0.825$, $\alpha = 4^\circ$, $C_L = 0.516$ (Courtesy of Pres Henne of Gulfstream Aerospace Corporation).

- Cummings, Russell M.; Mason, William H.; Morton, Scott A.; McDaniel, David R.. Applied Computational Aerodynamics: (Cambridge Aerospace Series). Cambridge University Press

Wind Tunnel Basics

- COMPRESSIBLE FLOWS
 - For visualizing compressible flows, optical flow visualization techniques are commonly used.
 - Interferometer, Schlieren, and shadowgraph are the three popularly employed optical flow visualization techniques for visualizing shocks and expansion waves in supersonic flows.
 - They are based upon the variation of the refractive index, which is related to the fluid density by the Gladstone–Dale formula and consequently to the pressure and velocity of the flow

Wind Tunnel Basics

- For making these variations visible, three different classes of methods mentioned above are generally used.
- With respect to a reference ray, that is, a ray that has passed through a homogeneous field with refractive index n , the
 - 1. Interferometer makes visible the optical phase changes resulting from the relative retardation of the disturbed rays;
 - 2. Schlieren system gives the deflection angles of the incident rays;
 - 3. Shadowgraph visualizes the displacement experienced by an incident ray that has crossed the high-speed flowing gas.

Wind Tunnel Basics

- These optical visualization techniques have the advantage of being nonintrusive and thereby in the supersonic regime of flow, avoiding the formation of unwanted shock or expansion waves.
- They also avoid problems associated with the introduction of foreign particles that may not exactly follow the fluid motion at high speeds because of inertia effects.
- However, none of these techniques gives information directly on the velocity field.
- The optical patterns given by interferometer, Schlieren, and shadowgraph, respectively, are sensitive to the flow density, its first derivative, and its second derivative.

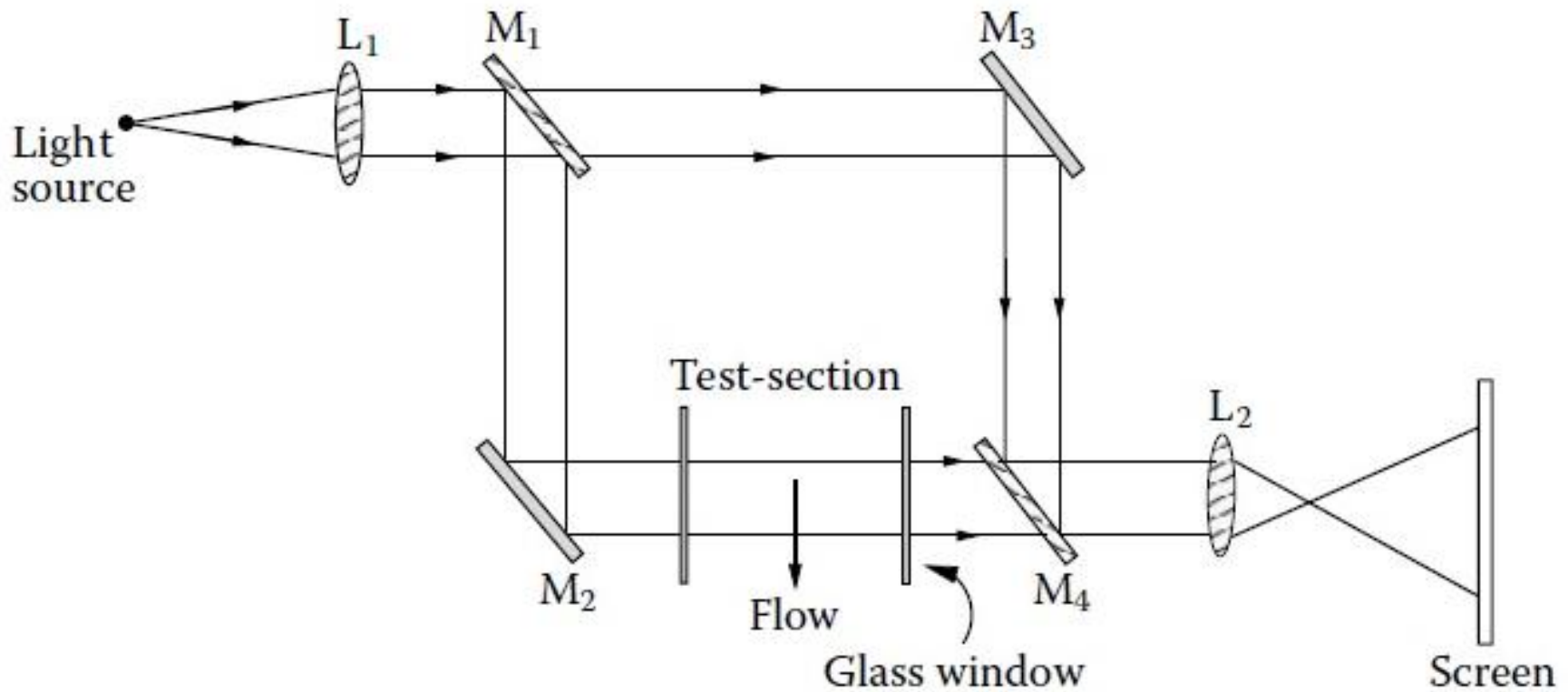
Interferometer

- The interferometer is an optical method most suited for qualitative determination of the density field of high-speed flows.
- Several types of interferometer are used for the measurement of the refractive index, but the instrument most widely used for density measurements in gas streams (wind tunnels) is that attributed to Mach and Zhender.
- The fundamental principle of the interferometer is the following. From the wave theory of light we have
 - $C = f \lambda$
 - where C is the velocity of propagation of light, f is its frequency, and λ is its wavelength.

Formation of Interference Patterns

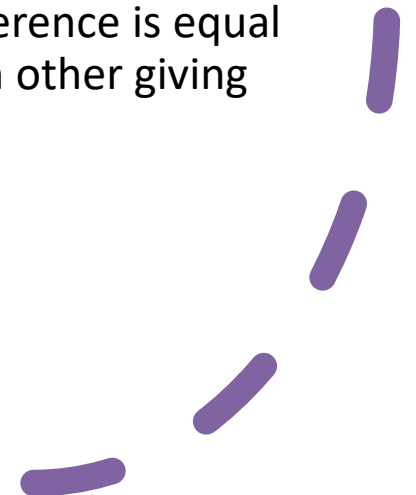
- Fig shows the essential features of the Mach–Zehnder interferometer, schematically.
- Light from the source is made to pass through lens L1 which renders the light parallel.
- The parallel beam of light leaving the lens passes through a monochromatic filter.
- The light wave passes through two paths, 1–2–4 and 1–3–4, before falling on the screen, as shown in the figure.
- The light rays from the source are divided into two beams by the half-silvered mirror M1.
- The two beams, after passing through two different paths (the lengths of paths being the same) recombine at lens L2 and get projected on the screen.

Mach-Zehnder interferometer



Wind Tunnel Basics

- The difference between the two rays is that one (1–3–4) has traveled through room air whereas the other (1–2–4) has traveled through the test-section.
- When there is no flow through the test-section, the two rays having passed through identical paths are in phase with each other and recombine into a single ray.
- Thus, a uniform patch of light will be seen on the screen.
- Now, if the density of the medium of one of the paths is changed (say increased) then the light beam passing through will be retarded and there will be a phase difference between the two beams.
- When the magnitude of the phase difference is equal to $\lambda/2$, the two rays interfere with each other giving rise to a dark spot on the screen.



Wind Tunnel Basics

- From the corpuscular properties of light, we know that when light travels
- through a gas the velocity of propagation is affected by the physical properties
- of the gas.
- The velocity of light in a given medium is related to the velocity of
- light in vacuum through the index of refraction n , defined as
- $$\frac{c_{vac}}{c_{gas}} = n$$
- The value of refractive index n is 1.303 for air and 1.5 for glass.

Wind Tunnel Basics

- The Gladstone–Dale empirical equation relates the refractive index n to the density of the medium as

- $$\frac{n-1}{\rho} = K$$

- where K is the Gladstone–Dale constant, and is constant for a given gas and ρ is the gas density.

Gladstone–Dale constant

The Gladstone–Dale constant is a proportionality constant that relates the refractive index of a gas to its density. It is widely used in optical flow diagnostics such as Schlieren, shadowgraph, and interferometry techniques to connect optical measurements to physical properties like density in compressible flows, including hypersonic and supersonic regimes. The Gladstone–Dale relation is given by:

$$n - 1 = K_{GD} * \rho$$

Where:

n = Refractive index of the gas (dimensionless).

ρ = Density of the gas (kg/m^3).

K_{GD} = Gladstone–Dale constant (m^3/kg).

This relation assumes that the gas behaves as an ideal gas and that density variations are small enough for the relationship to remain linear

The Gladstone–Dale constant depends on:

Gas Type: Different gases have different molecular polarizabilities.

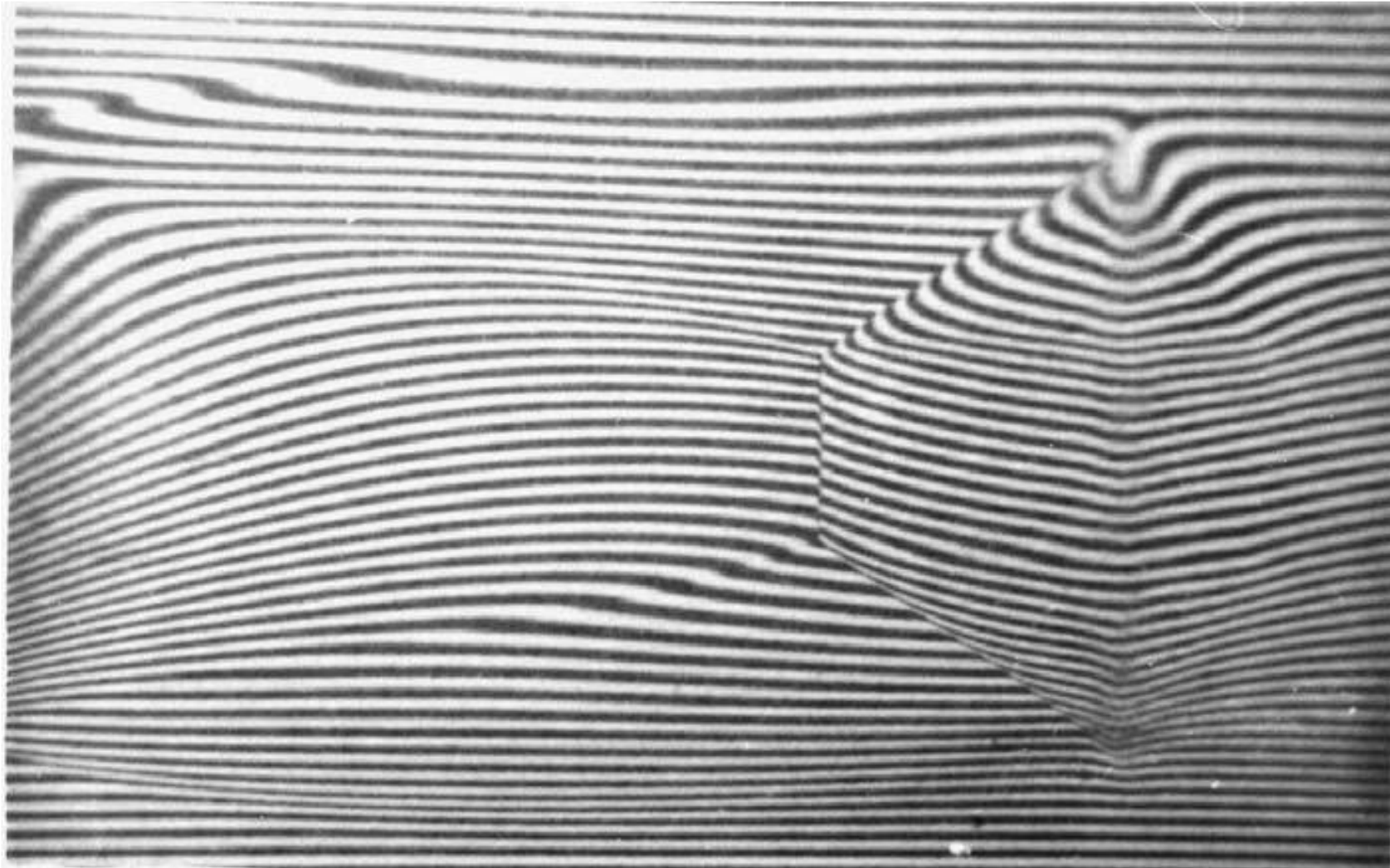
Wavelength of Light Used: Slight dependence on the wavelength, though often weak in air.

Temperature and Pressure: Weak dependence within reasonable flow conditions.

Wind Tunnel Basics

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- Hence, if there is appreciable difference in the density the picture on the screen will consist of dark and white bands, the phase difference between the consecutive dark bands being equal to unity.
 - A interferogram of a two-dimensional supersonic jet is shown in Figure .
 - It is seen that, far away from the jet axis, the fringes (dark and white bands) are parallel, indicating that the flow field is of uniform density (in this case, the zone is without flow).
 - The mild kinks in the fringes are the locations of density change.
 - Those who are familiar with free jet structure can easily observe the barrel shock, the Mach disk, and the reflection of the barrel shock from the Mach disk.

Interferogram of a two-dimensional supersonic jet at $M = 1.62$

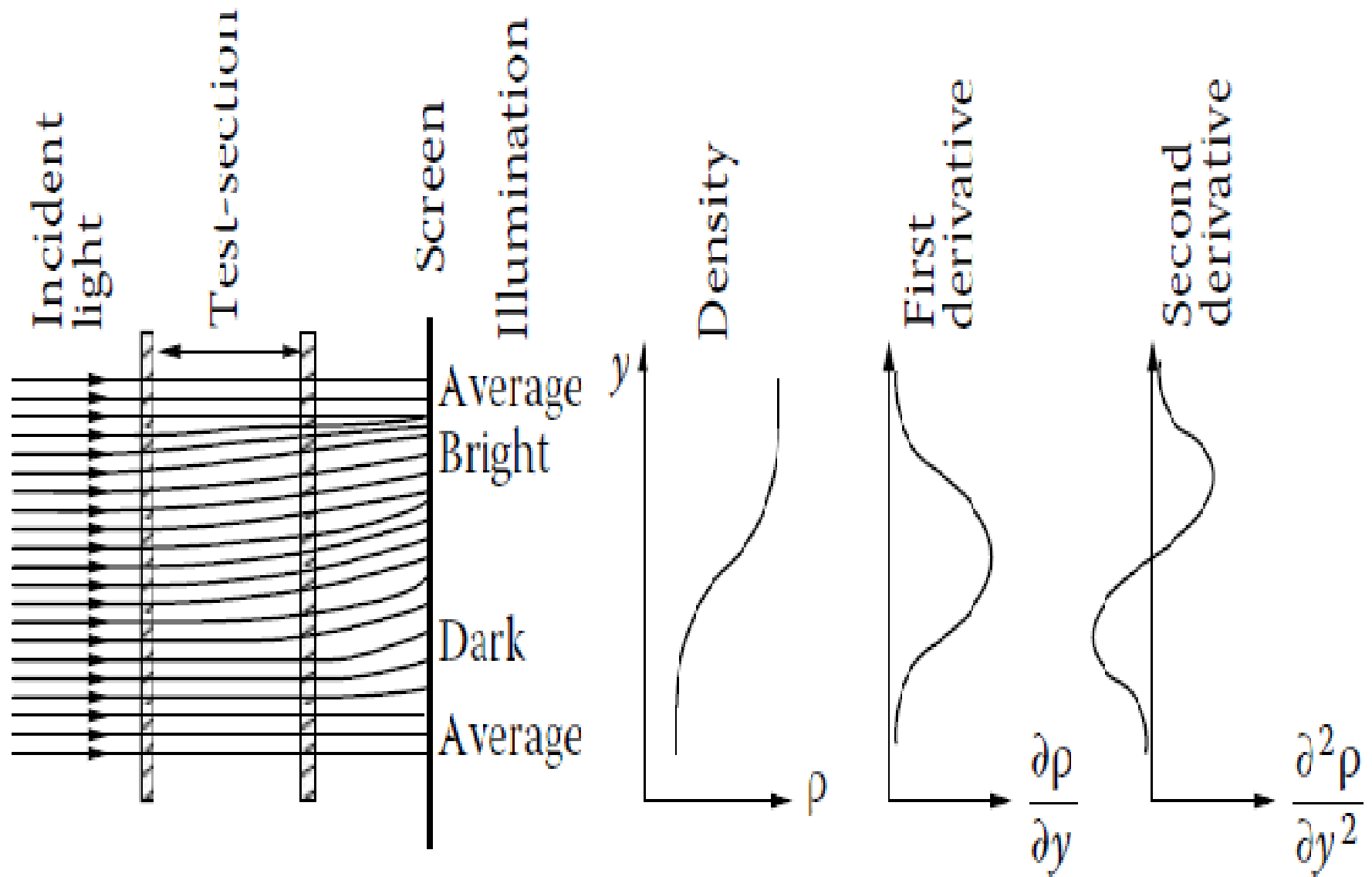


Wind Tunnel Basics

- For the sake of simplicity, for instance, let us assume the test-section to be two dimensional, with each light ray passing through a path of constant air density.
- When flow is taking place through the test-section, the light rays will be deflected, because any light ray passing through a region in which there is a density gradient normal to the light direction will be deflected as though it had passed through a prism.
- In other words, if the medium in the test-section is homogeneous (constant density) the rays from the source will continue in their straight-line path.
- If there is a density gradient in the medium, the rays will follow a curved path, bending toward the region of higher density and away from the region of lower density.

Wind Tunnel Basics

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- Therefore, depending on the orientation of the knife-edge with respect to the density gradient, and on the sign of the density gradient, more or less of the light passing through each part of the test-section will escape the knife-edge and illuminate the screen.
 - Thus, the Schlieren system makes density gradients visible in terms of intensity of illumination.
 - A photographic plate at the viewing screen records density in the test-section as different shades of gray.



The shadow effect.

Wind Tunnel Basics

- On the screen there are bright zones where the rays crowd closer and dark zones where the rays diverge away.
- At places where the spacing between the rays is unchanged, the illumination is normal even though there has been refraction.
- Thus, the shadow effect depends not on the absolute deflection but on the relative deflection of the light rays, that is, on the rate at which they converge or diverge on coming out of the test-section.

Wind Tunnel Basics

- A shadowgraph consists of a light source, a collimating lens, and viewing screen, as shown in Figure.
- Let us assume that the test-section has stagnant air in it and that the illumination on the screen is of uniform intensity.
- When flow takes place through the test-section the light beam will be refracted wherever there is a density gradient.
- However, if the density gradient everywhere in the test-section is constant, all light rays would deflect by the same amount, and there would be no change in the illumination of the picture on the screen.
- Only when there is a gradient in density gradient will there be a tendency for light rays to converge or diverge.

Wind Tunnel Basics

- For a two-dimensional flow the increase of light intensity can be expressed as

$$\Delta I = k \left(\frac{\partial^2 \rho}{\partial x^2} + \frac{\partial^2 \rho}{\partial y^2} \right)$$

- where k is a constant and x and y are the coordinates in a plane normal to the light path.
- Therefore, the shadowgraph is best suited only for flow fields with rapidly varying density gradients.
- A typical shadowgraph of a highly underexpanded circular sonic jet is shown in Figure.
- Because the jet is underexpanded, the waves present in the field would be strong enough to result in a large density gradient across them.

A Mach disk (also called a Mach disc or normal shock disk) is a strong, stationary normal shock wave that forms in supersonic jets when the pressure inside the jet is much higher than the surrounding ambient pressure. It is commonly observed in under-expanded supersonic jets issuing from nozzles, such as in rocket exhausts, high-speed wind tunnels, and supersonic engine nozzles. When a supersonic flow exits a nozzle into a lower-pressure environment:

- Jet Expansion: The gas initially expands beyond the nozzle, forming expansion fans.
- Over-Expansion & Compression: The jet tries to adjust to the ambient pressure but overshoots, creating oblique shock waves and compression regions.
- Mach Disk Formation: As these waves reflect and interact near the centerline, a strong normal shock wave forms perpendicular to the flow—the Mach disk.
- Downstream Flow: After passing through the Mach disk, the flow slows to subsonic or transonic speeds, with high pressure and temperature increases.

Mach disk

Structure of a Typical Supersonic Jet with a Mach Disk

- Expansion Fans: Near the nozzle exit, allowing flow to expand.
- Oblique Shocks: Angle inward toward the centerline to compress the flow.
- Mach Disk: Central, circular normal shock in the jet core.
- Barrel Shock (or Shock Cell): Enveloping curved shock system surrounding the jet.
- Slip Lines: Shear layers emanating from the edges of the Mach disk.

Shock Cell

A shock cell (also called a shock diamond or pressure cell) is a repeating pattern of alternating shock waves and expansion fans that forms in supersonic jet flows due to pressure mismatches between the jet and the surrounding environment. These cells appear as a series of bright and dark regions in optical flow visualizations and are especially prominent in under-expanded jets from rocket engines, afterburners, and supersonic nozzles.

Shock cells form when there is a difference between the nozzle exit pressure and the ambient pressure:

Under-Expanded Jet (Nozzle Pressure > Ambient Pressure):

- The jet flow expands beyond the nozzle exit.
- Expansion fans form, lowering the pressure inside the jet.
- This over-expansion leads to compression shocks to re-compress the flow.

Over-Expanded Jet (Nozzle Pressure < Ambient Pressure):

- Compression shocks form first to increase the jet pressure.
- Expansion waves follow to re-expand the flow.

Periodic Interaction:

- The expansion and compression process repeats downstream, forming shock cells—a series of alternating compression and expansion regions along the jet axis.

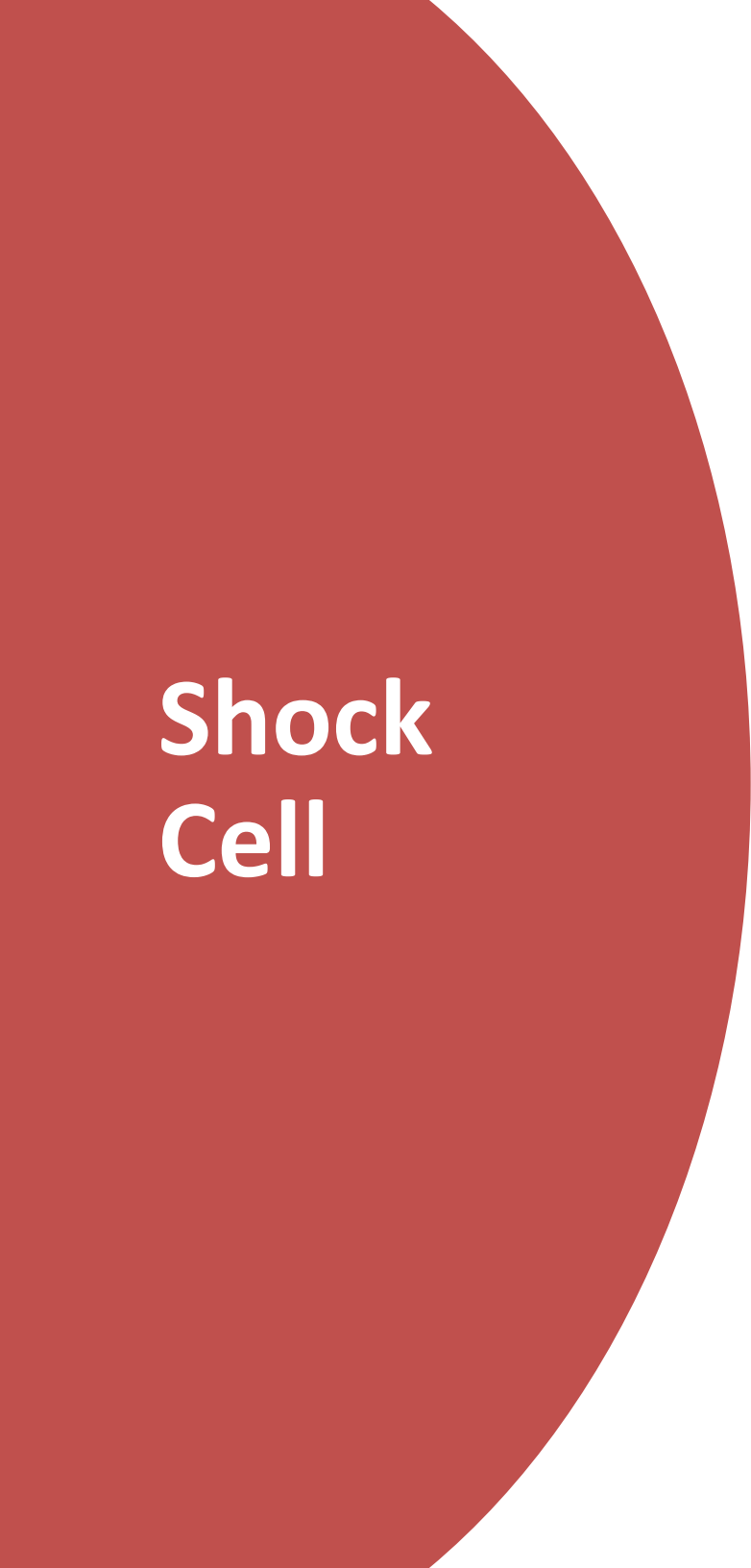
Shock Cell

Feature	Description
Shape	Conical or diamond-shaped shock/expansion patterns.
Structure	Alternating compression (shock) and expansion (fan) zones.
Flow Speed	Supersonic throughout the shock cell region (except across Mach disks, if present).
Length	Depends on nozzle pressure ratio, nozzle geometry, and ambient conditions.
Pressure Oscillation	Causes periodic pressure variations along the jet axis.

Shock Cell

Shock cells often resemble diamond-like patterns seen in:

- Schlieren photography
- Shadowgraph techniques
- Infrared imaging
- Visible light photography (for high-temperature, luminous jets, e.g., rocket plumes)



Shock Cell

Common Flow Features in Shock Cell Regions

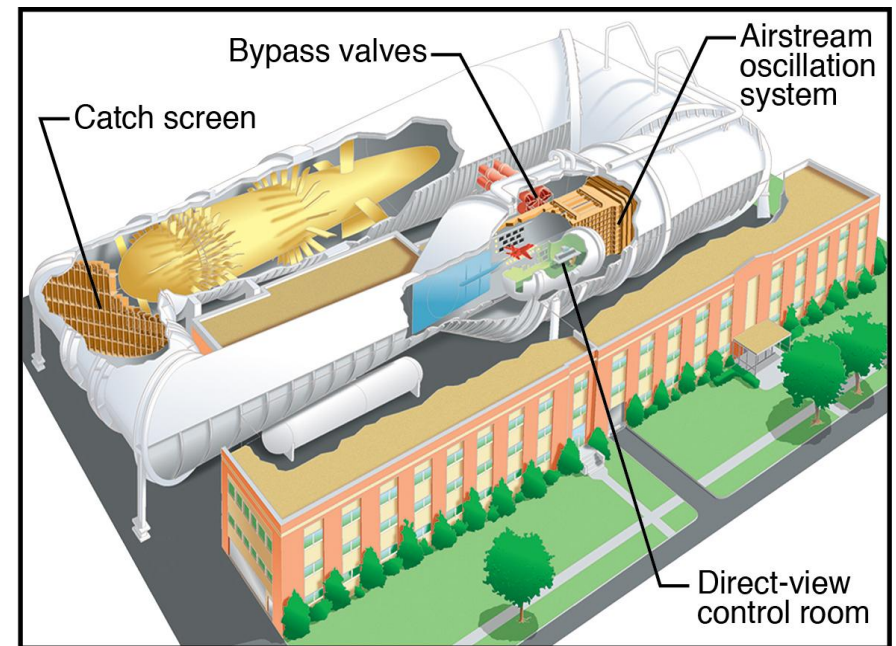
Barrel Shock: Curved oblique shock around the jet boundary.

Shear Layers: High-speed shear flow surrounding the jet.

Mixing Zones: Regions where jet flow interacts with surrounding air.

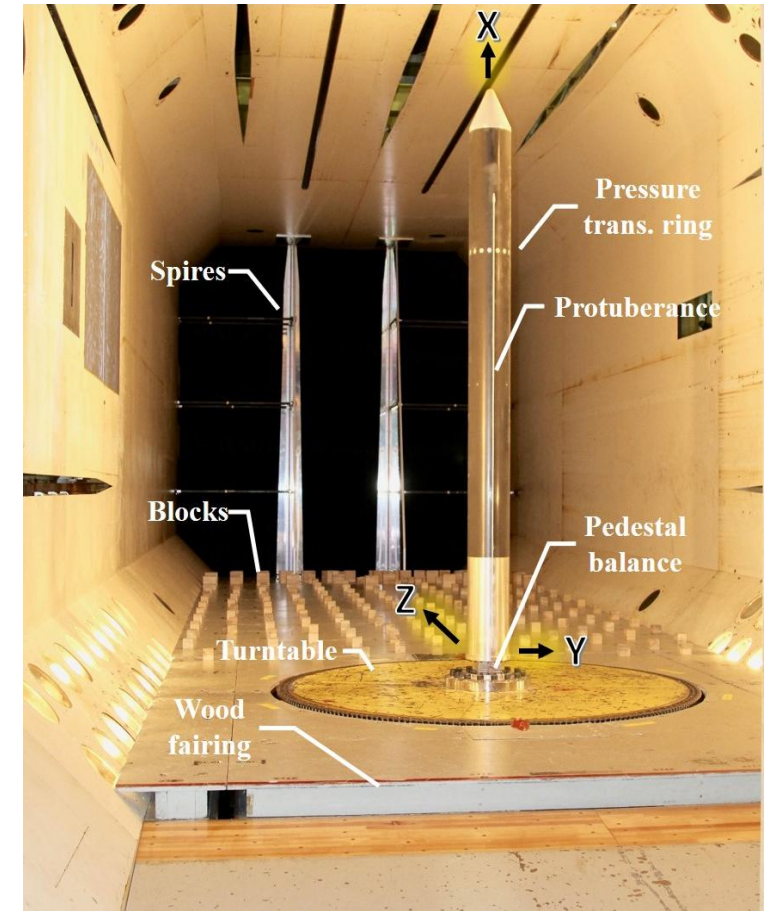
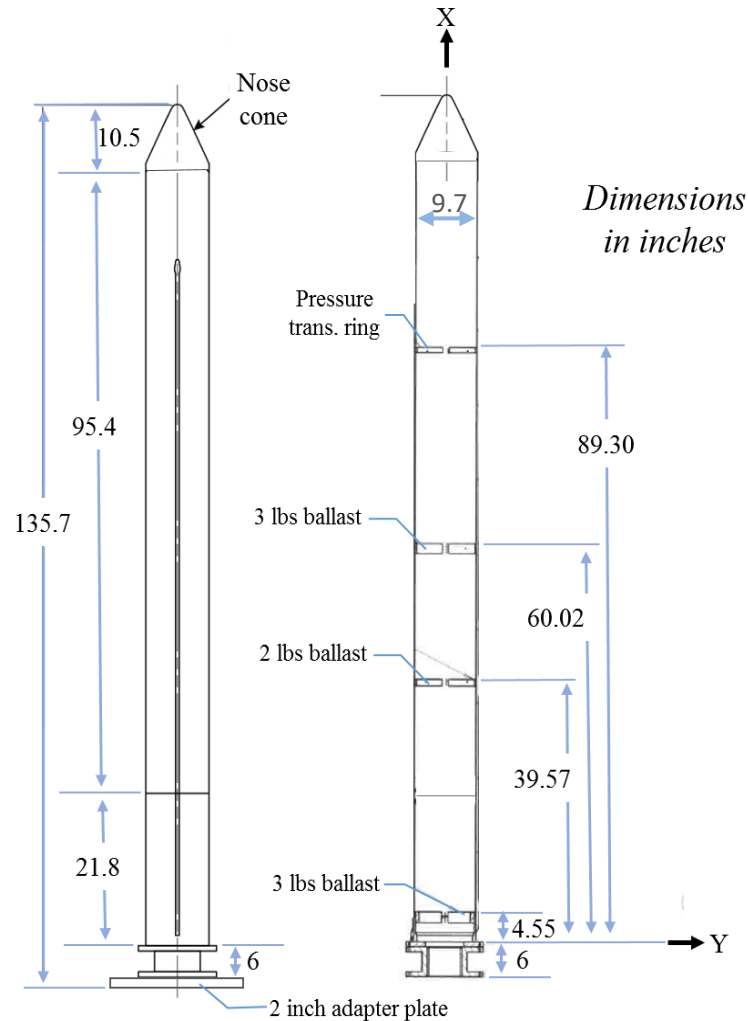
Wind Tunnels

- Support ground wind loads (GWL) analysis/testing of launch vehicles
 - Typically, primary interest is response due to vortex shedding
 - Could result in nearly sinusoidal lift/drag forces
 - Response can be resonant or nonresonant
- Current objective:
Define methodology for model-scale to full-scale mapping of winds and loads
- NASA Langley Transonic Dynamics Tunnel (TDT)
 - Unique aeroelastic test facility
 - Used extensively in previous GWL problems
 - Recently developed atmospheric boundary layer (ABL) simulation



Experimental Setup - Research Model Description

- Example model with basic geometry
- Instrumentation
 - Pedestal balance
 - Unsteady pressures
 - Accelerometers



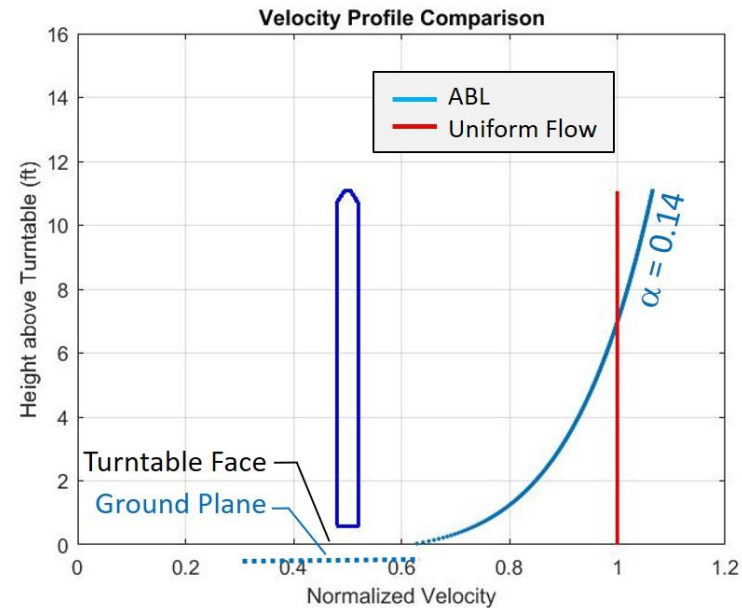
View in TDT, looking upstream

Wind Speed Mapping Methodology

- Six features to consider: *profile, representative height, turbulence spectra, duration of measurement, anemometer performance, and lateral location of instrumentation*

$$V = V_{Ref} * \left(\frac{z}{z_{Ref}} \right)^\alpha$$

where, V = local speed at elevation z , and V_{Ref} = reference speed at elevation z_{Ref}

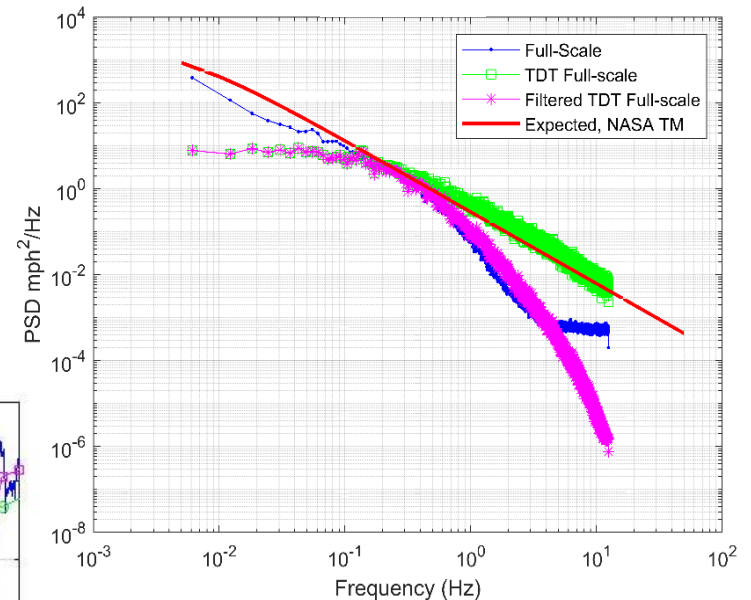
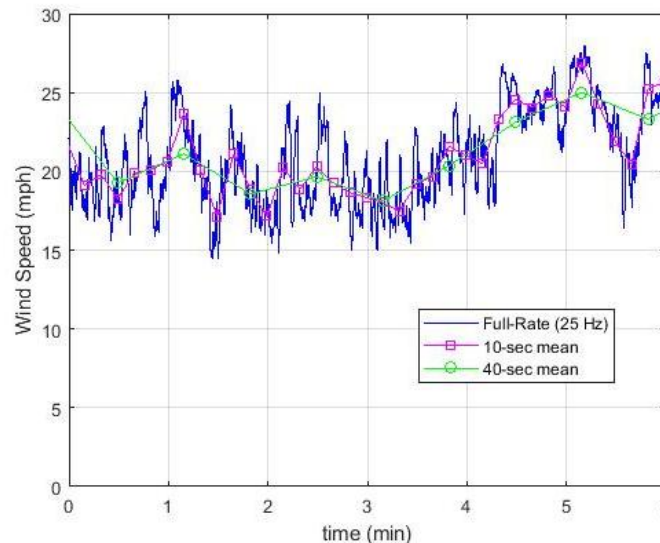


Example velocity profile comparison, courtesy of [7]

[7] Ivanco, T. G.; Keller, D. F.; Pinkerton, J. L.; "Investigation of Atmospheric Boundary-Layer Effects on Launch-Vehicle Ground Wind Loads," IEEE/AIAA Aerospace Conference, Big Sky Montana, March 2020.

Wind Speed Mapping Methodology

- Effect of anemometer performance
 - Not fast-response
 - Filtered TDT data to mimic performance
 - 10% difference in peak velocity
(21% difference in peak Q)
 - 18% change in standard deviation
- Effect of sample length



Comparison of Turbulence Spectra

Component Load Mapping Methodology

- Conversion of Velocity and Loads

- Velocity mapping determined by reduced frequency (κ), $\kappa = \frac{fD}{V}$

$$\frac{V_{FS}}{V_{MS}} = \frac{f_{FS}}{f_{MS}} \frac{D_{FS}}{D_{MS}}$$

where V is velocity, f is frequency, D is reference diameter, and subscripts FS and MS denote full- and model-scale, respectively

- Loads reduced into nondimensional coefficients, then converted to full-scale

$$C_{BM} = \frac{BM}{QDHL}$$

where BM is bending moment, Q is dynamic pressure, D is diameter, H is height, and L is reference length

Component Load Mapping Methodology

- Corrections for damping
 - Band-pass filters applied to isolate modes
 - Scale factors applied to correct for difference between model and expected full-scale damping (by mode)
 - Two correction factors depending upon direction of damping change:

$$\zeta_{cor} = \sqrt{\frac{\zeta_{measured}}{\zeta_{expected}}} \quad \text{or} \quad \zeta_{cor} = \left(\frac{\zeta_{measured}}{\zeta_{expected}} \right)$$

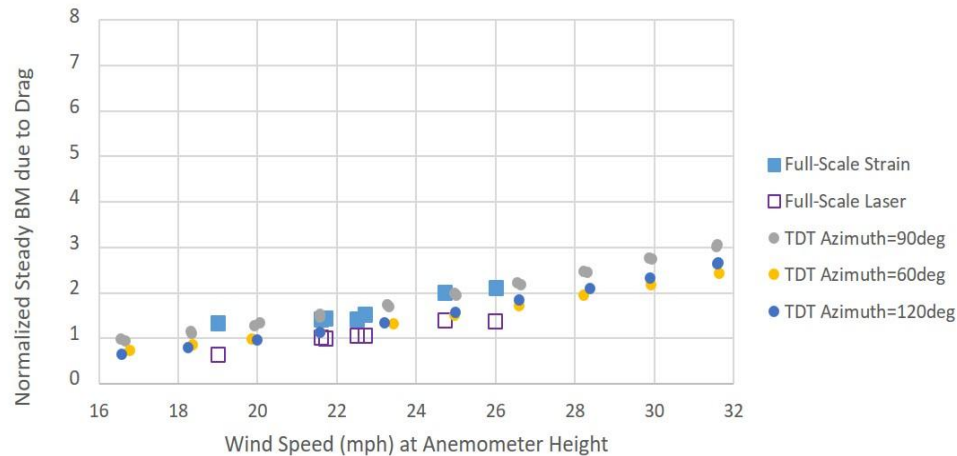
- Correction for mass offset
 - Displaced mass from wind-deflection adds to bending moment
 - Effect is different between model-scale and full-scale
 - On the order of 50% increase in loads for some cases
 - Affects 1st bending modes only

$$BM_{\zeta_{cor}+LF} = BM_{m1} * \zeta_{cor_{m1}} * massLF + BM_{m2} * \zeta_{cor_{m2}} + BM_{mean} * massLF$$

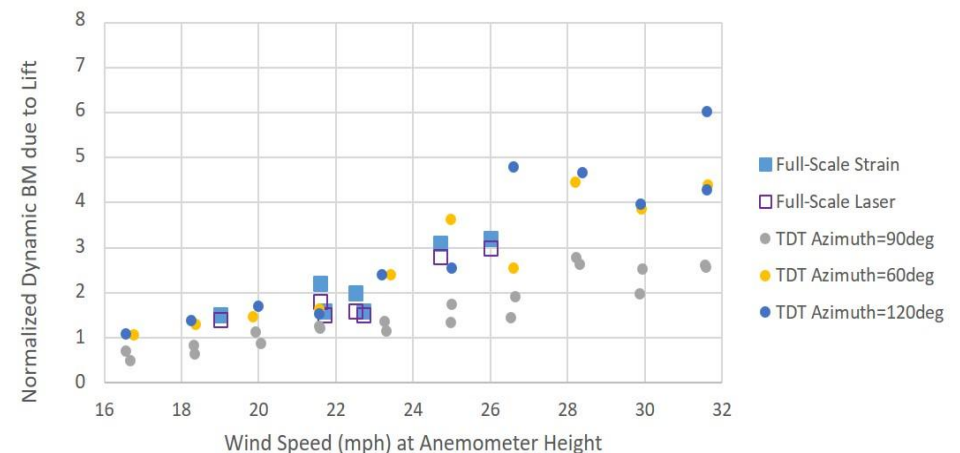
Comparison Between Wind-Tunnel and Full-Scale Loads

- Full-scale event of interest acquired
 - Detailed wind measurements
 - Correlated load time histories
 - Vehicle exposed to high winds for hours
- Aeroelastically-scaled wind-tunnel model tested in ABL to investigate and compare

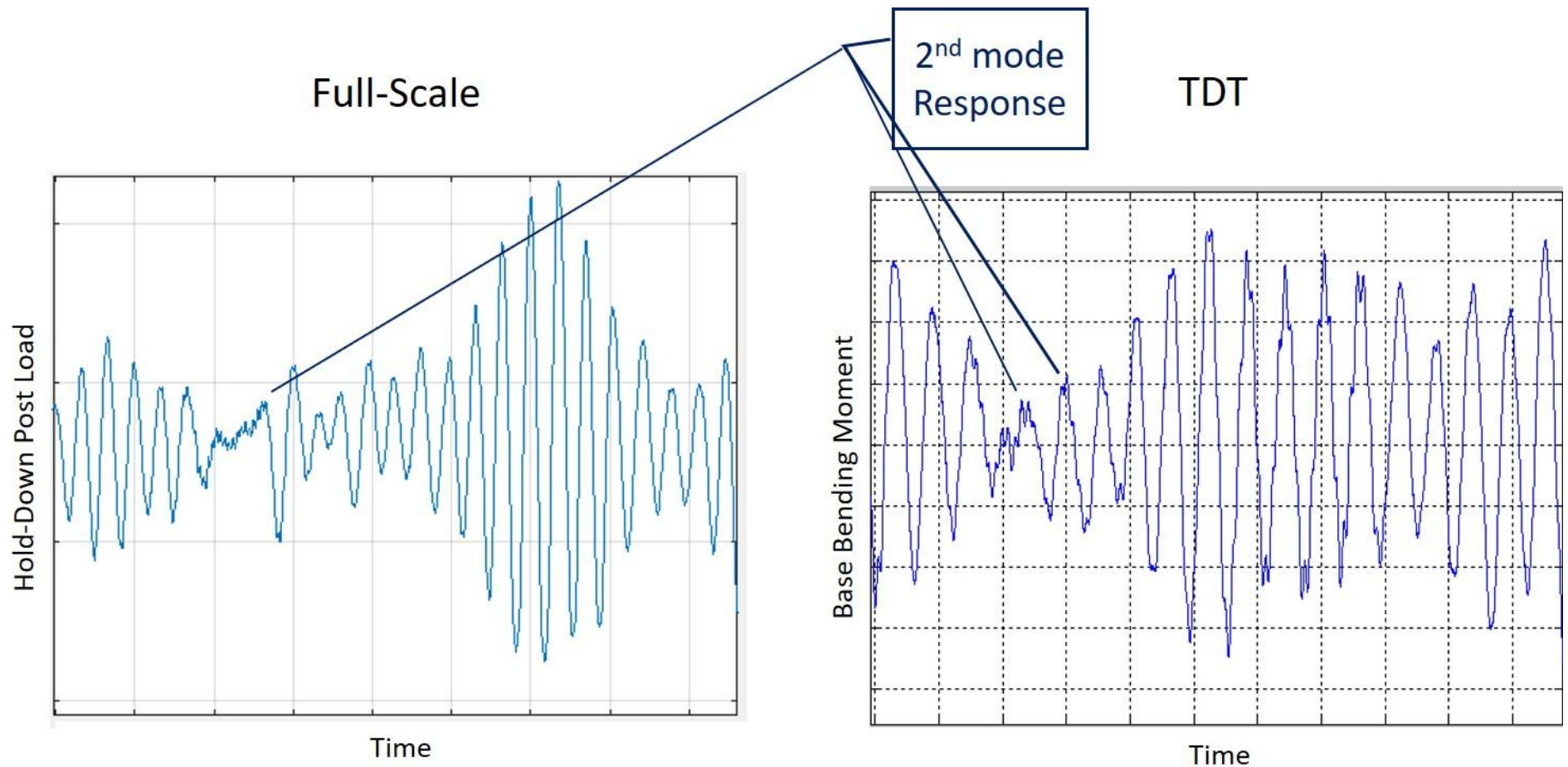
Mean Drag Comparison



Dynamic Lift Comparison



Comparison Between Wind-Tunnel and Full-Scale Loads



- Qualitative comparison of mode dynamics

Ares I-X launch vehicle buffet

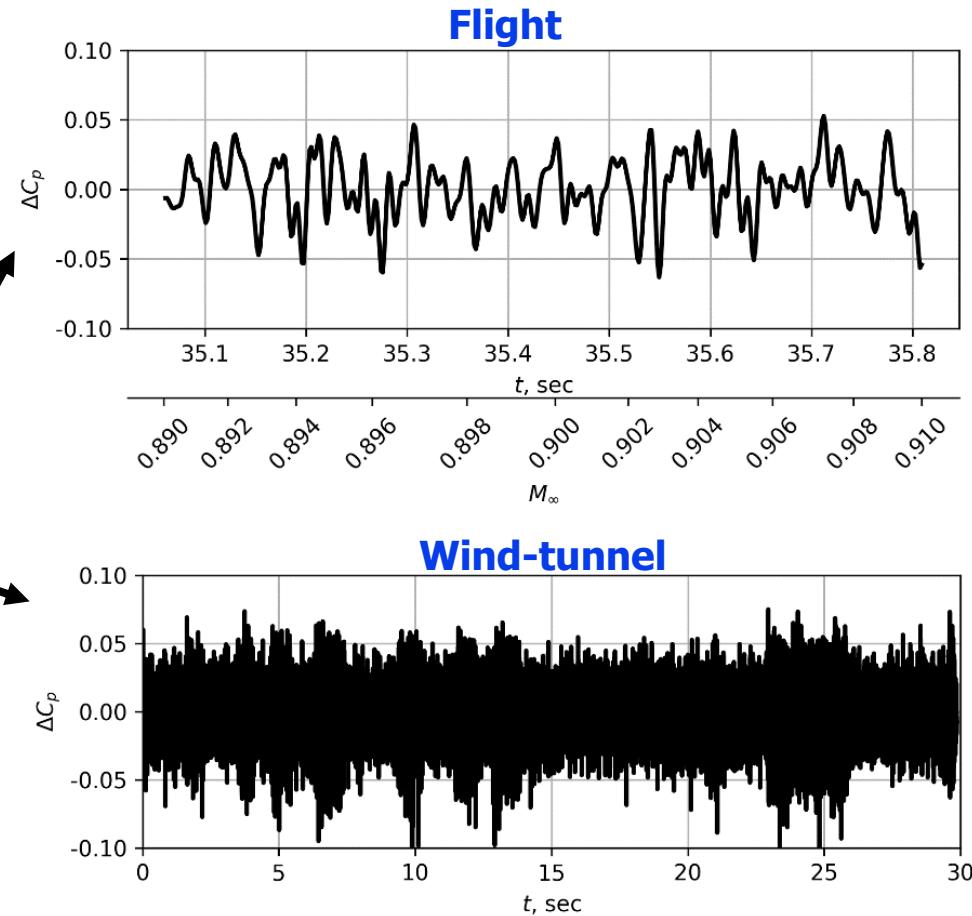
- Launch vehicle buffet
 - Aerodynamic loads caused by unsteady pressure field during ascent that may excite vehicle structural modes
 - Buffet environments traditionally modeled with buffet forcing functions based on wind-tunnel test data
- Ares I-X
 - Wind-tunnel test (2007)
 - NASA Langley Research Center Transonic Dynamics Tunnel
 - 3.5-percent scale model
 - 256 unsteady pressure transducers
 - Data acquired for ~30 sec duration at 12,000 samples/sec for each condition
 - Flight test (2009)
 - 243 unsteady pressure transducers
 - Data acquired at 651 samples/sec during flight
- Current study presents comparative analysis of wind-tunnel and flight data to assess and improve preflight predictions

Ares I-X



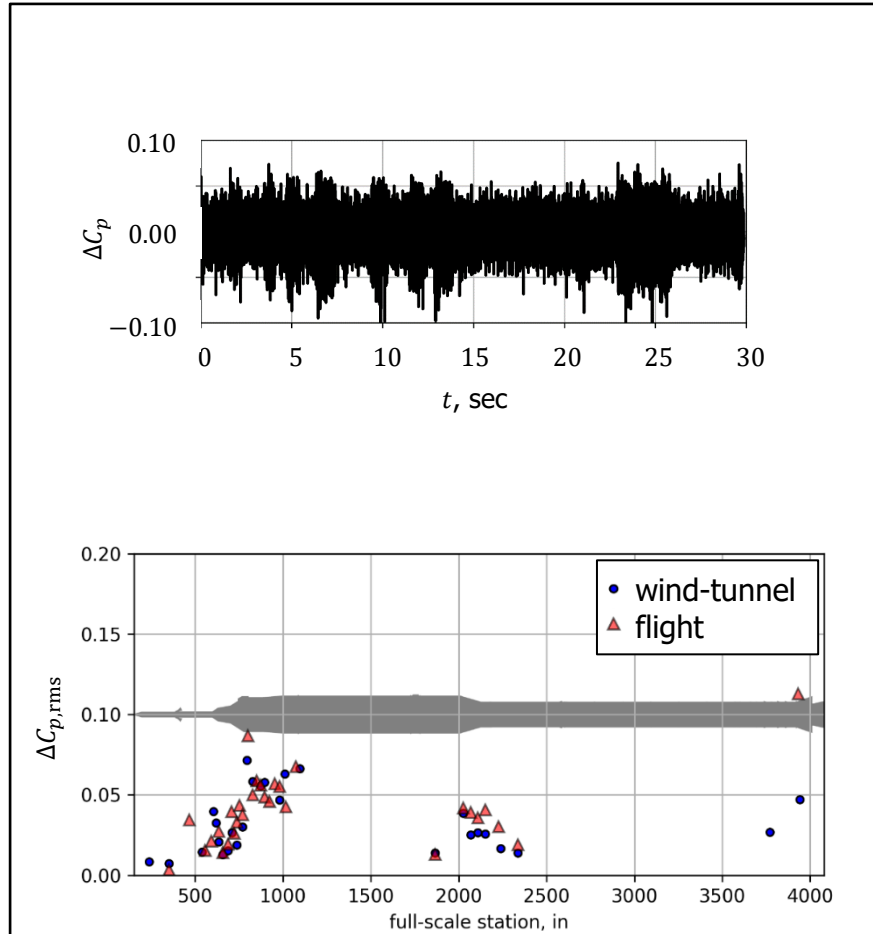
Comparing wind-tunnel and flight data

- Trend removal for flight transducers
- Scaling based on:
 - Reduced frequency
 - Dynamic pressure
- Constant wind-tunnel versus variable flight conditions (attitude, flight parameters)
 - Flight data subsets based on M_∞ to generate approximately constant condition windows
 - Full record of wind-tunnel data significantly longer than comparison flight windows
 - Flight-comparable realizations can be generated from full wind-tunnel record using corresponding model-scale time durations

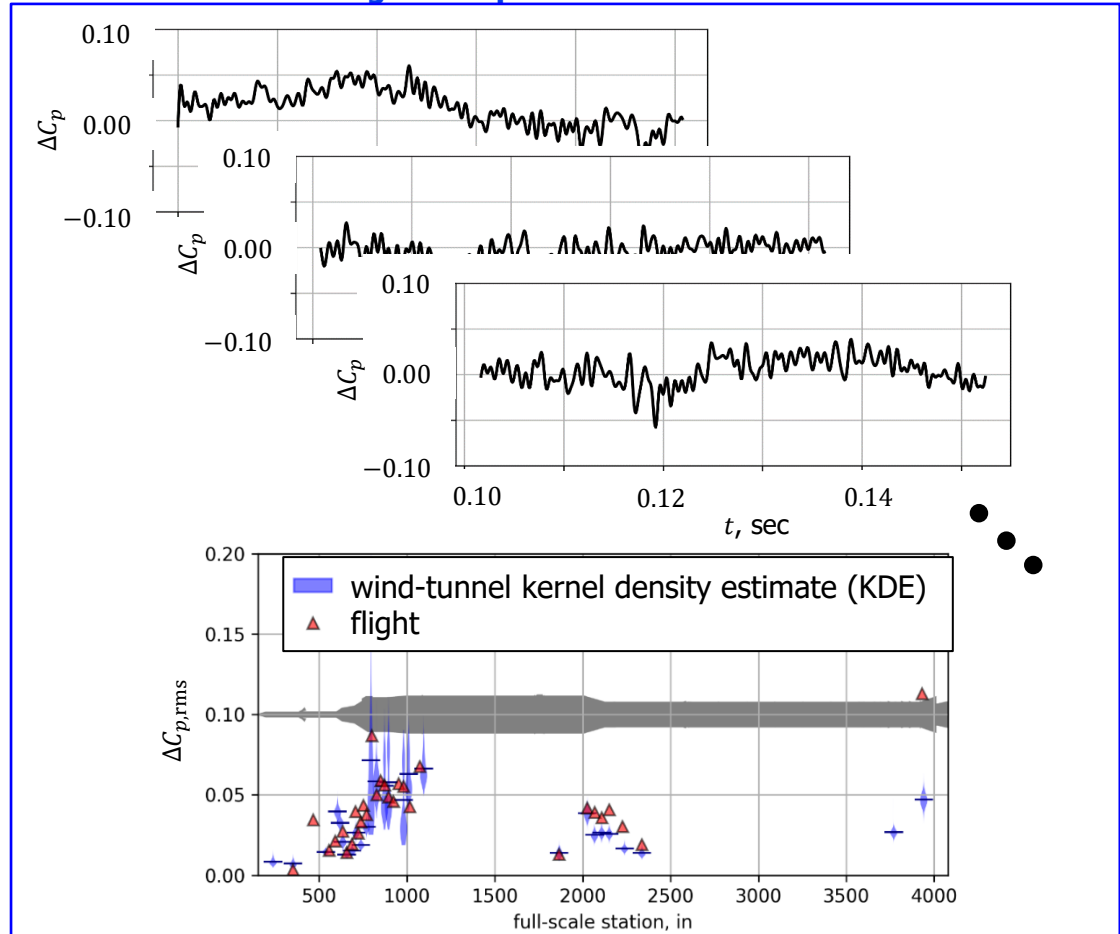


Comparing wind-tunnel and flight data

Full record



Flight-comparable realizations



Ludwig tube

Main Components

High-Pressure Tube (Driver Section):

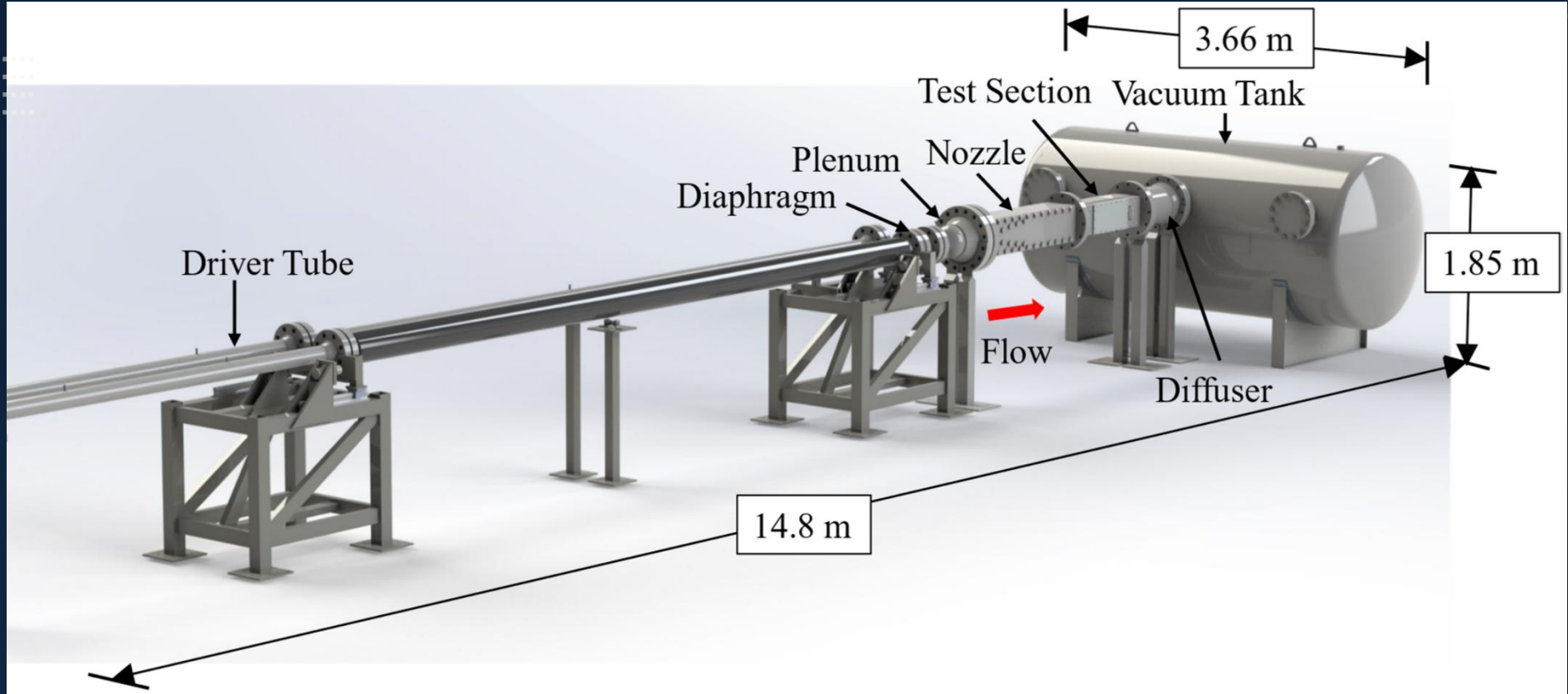
- A long tube filled with compressed gas, usually air.
- Acts as the energy storage section.
- Diaphragm or Fast-Acting Valve:
- Separates the high-pressure tube from the test section.
- Rupture or quick opening initiates the flow.

Nozzle:

- Convergent-divergent nozzle shapes the flow to achieve the desired Mach number (supersonic or hypersonic).

Test Section:

- Where models are placed and flow measurements or visualizations are performed.
- Provides a short-duration but steady and uniform flow.
- Dump Tank / Vacuum Chamber:
- Located downstream of the test section to absorb the gas flow.
- Ensures proper pressure drop to maintain supersonic/hypersonic flow.



Ludwieg Tubes

A Ludwieg tube is a type of intermittent supersonic/hypersonic wind tunnel used for aerodynamic testing and fundamental research in compressible flows. It is renowned for its ability to produce high-quality, steady flow with relatively simple construction, making it an essential tool in hypersonic aerodynamics, shock wave studies, and boundary layer transition research. The Ludwieg tube operates based on the expansion wave mechanism in a long tube filled with high-pressure gas. The flow is generated by the sudden removal of a diaphragm or rapid opening of a fast-acting valve, initiating an expansion process that drives the test section flow.

Ludwig tube

Key Features

Short Test Duration: Typically, a few milliseconds to a few seconds, depending on tube length and flow conditions.

Steady Flow: The test section experiences a nearly constant flow during the run time.

Adjustable Mach Number: By changing nozzle configurations, a wide range of Mach numbers (up to **Mach 10+**) can be achieved.

High-Quality Flow: Very low turbulence and well-defined boundary conditions.

Comparisons

Facility Type	Operation	Flow Time	Complexity	Typical Uses
Ludwig Tube	Intermittent	Short (ms-s)	Simple	Boundary layers, flow visualization
Shock Tunnel	Intermittent	Very short (μ s-ms)	Moderate/High	High-enthalpy flows, material testing
Continuous Tunnel	Continuous	Unlimited	High	Large-scale aerodynamic tests

Hot-Shot Tunnel

The hot-shot tunnel (also known as a hot-shot wind tunnel or hot gas gun tunnel) is a type of high-enthalpy, high-speed, intermittent wind tunnel designed to simulate extreme flight conditions such as hypersonic speeds and high-temperature effects. It is widely used for aerothermodynamic testing of hypersonic vehicles, re-entry bodies, and thermal protection systems.

How It Works:

Driver Section Heating:

- A lightweight piston (often made of a material like plastic or metal) is accelerated by high-pressure gas or gunpowder charges down a launch tube.
- The piston compresses and heats the driver gas (often nitrogen, air, or helium) to extremely high pressures and temperatures.

Diaphragm Rupture:

- A diaphragm separates the hot, high-pressure driver gas from the low-pressure test section.
- The diaphragm ruptures once the pressure reaches a critical level, allowing the heated gas to expand rapidly.

Nozzle Acceleration:

- The hot gas passes through a convergent-divergent nozzle, accelerating to hypersonic speeds (Mach 5 to Mach 20 or higher).

Test Section Flow:

- The flow passes over the test model, simulating aerodynamic forces and thermal loads similar to real high-speed flight conditions.

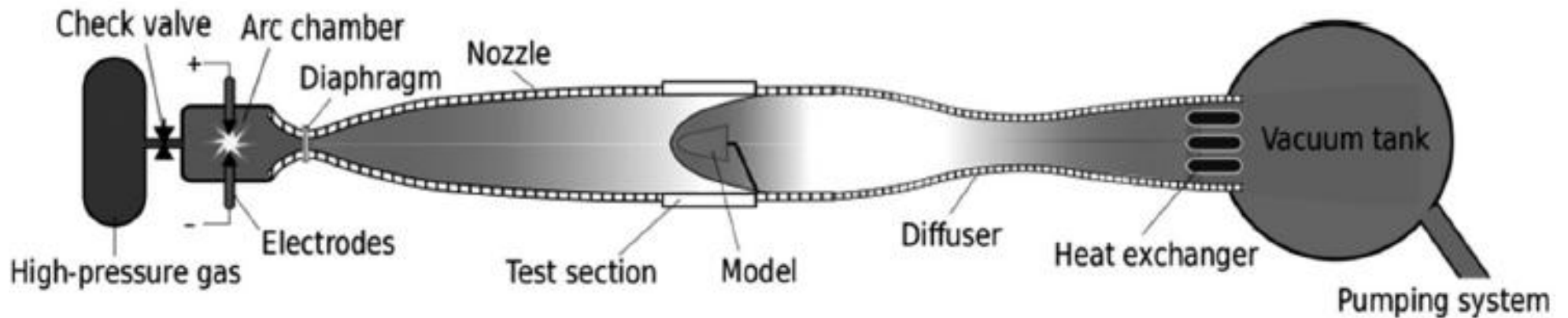
Flow Termination:

- The flow duration is short (milliseconds to a few seconds), after which the test ends.

Hot-Shot Tunnel Components

Component	Function
Launch Tube	Accelerates the piston using high-pressure gas or explosives.
Piston	Compresses and heats the driver gas to generate high enthalpy.
Driver Gas Chamber	Contains the heated driver gas before diaphragm rupture.
Diaphragm	Separates driver gas from test gas; ruptures to initiate flow.
Nozzle	Accelerates gas to required Mach number.
Test Section	Contains the model under investigation, where measurements are taken.
Dump Tank	Absorbs exhausted flow after the test section.

Hot-shot tunnel



Hot-Shot Tunnel Components

Component	Description
Compressor/Fan	Drives airflow through the tunnel; capable of operating continuously.
Settling Chamber	Smoothens airflow, reducing turbulence and ensuring uniform flow into the test section.
Contraction Section	Accelerates the airflow into the test section while minimizing flow separation.
Test Section	The working area where models are placed for aerodynamic testing; flow is steady and controlled here.
Diffuser	Slows down airflow after the test section to recover pressure and direct flow back toward the compressor.
Heat Exchanger (optional)	Cools the air to manage temperature rise in closed-loop tunnels.

Continuous Tunnel

- A continuous tunnel (also called a continuous-flow wind tunnel) is a type of wind tunnel that operates with continuous, steady airflow for an unlimited duration (theoretically), allowing for long-duration aerodynamic testing. These tunnels are widely used in aerodynamics, aerospace engineering, automotive industries, and hypersonic research for studying steady-state flow phenomena over models or test objects. In a continuous tunnel, air is circulated continuously through the tunnel loop by mechanical means such as compressors, fans, or pumps. The system allows for the constant supply and removal of airflow at a controlled speed and pressure.

Comparisons

Feature	Continuous Tunnel	Blowdown Tunnel	Hot-Shot Tunnel
Flow Duration	Continuous (unlimited)	Limited (seconds to minutes)	Very Short (milliseconds)
Flow Quality	High, stable	High (short time)	High (short time, high temperature)
Speed Range	Subsonic to Hypersonic (power-limited)	Subsonic to Hypersonic	Hypersonic (high enthalpy)
Typical Uses	Steady-state aerodynamics, long-term tests	Transient aerodynamic testing	High-temperature hypersonics

Free Piston Shock Tunnels

A free piston shock tunnel is a specialized type of hypersonic wind tunnel that generates high-speed, high-enthalpy, and short-duration test flows by using the motion of a free-flying piston to compress and heat gas before it is expanded through a nozzle into a test section. This tunnel type is particularly suited for hypersonic and hypervelocity testing, where high-temperature effects such as air dissociation and chemical reactions need to be simulated realistically. The free piston shock tunnel works in multiple stages:

Piston Acceleration:

- A piston (not mechanically connected to a driver) is accelerated by high-pressure gas in a launch tube (driver section).
- The moving piston compresses the driver gas behind it to very high pressures and temperatures.

Shock Generation:

- The highly compressed driver gas ruptures a diaphragm, sending a strong shock wave into a separate shock tube filled with a test gas (usually air or nitrogen).

Gas Heating:

- As the shock travels through the test gas, it heats and compresses it to high enthalpy conditions (simulating hypersonic flight environments).

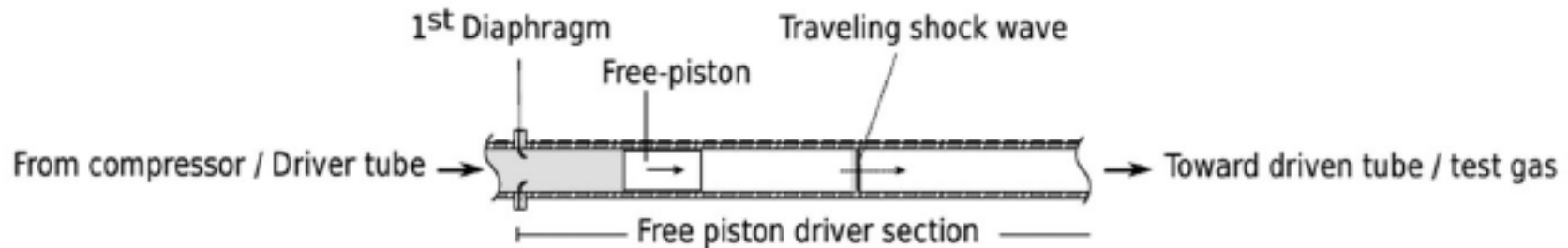
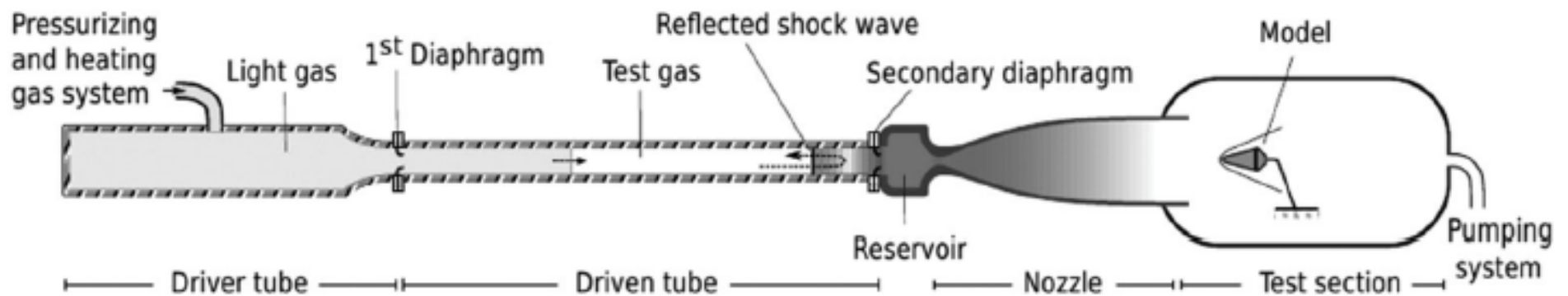
Expansion and Test Flow:

- The shocked and compressed test gas passes through a nozzle, accelerating to the desired hypersonic speed before entering the test section.
- The flow is steady for a very short duration (typically milliseconds to a few tens of milliseconds), during which measurements are taken.

Free Piston Shock Tunnel Components

Component	Description
Driver Tube	Contains the piston and initial high-pressure gas for piston acceleration.
Piston	Free-moving object that compresses driver gas to very high pressures.
Shock Tube	Contains the test gas and receives the shock wave after diaphragm rupture.
Diaphragms	Separate different sections; rupture at controlled pressures to initiate flow processes.
Nozzle	Accelerates the test gas to hypersonic speeds.
Test Section	Contains the experimental model and measurement equipment.
Dump Tank	Collects exhausted gases after the test run.

Free Piston Shock Tunnels



Arc Jet Facility

An Arc Jet Facility is a specialized high-temperature wind tunnel designed to simulate the extreme thermal environments encountered during hypersonic flight, such as spacecraft atmospheric re-entry or high-speed missile flight. It is primarily used to test thermal protection systems (TPS) and materials under intense heat loads, replicating the aerothermal heating caused by hypersonic speeds.

- Arc jet facilities use an electric arc discharge to heat a working gas (typically air or nitrogen) to very high temperatures. The heated gas is then expanded through a nozzle to generate a high-velocity, high-temperature flow over the test article.

Operational Steps:

Electric Arc Generation:

- An electrical arc (like in welding) is created between two electrodes.
- This arc heats the working gas to extremely high temperatures—thousands of Kelvins.

Gas Heating and Acceleration:

- The gas, now in a partially ionized plasma state, flows through the arc region and absorbs energy.
- It is then expanded through a converging-diverging nozzle, converting thermal energy into kinetic energy, simulating hypersonic flow.

Test Section Exposure:

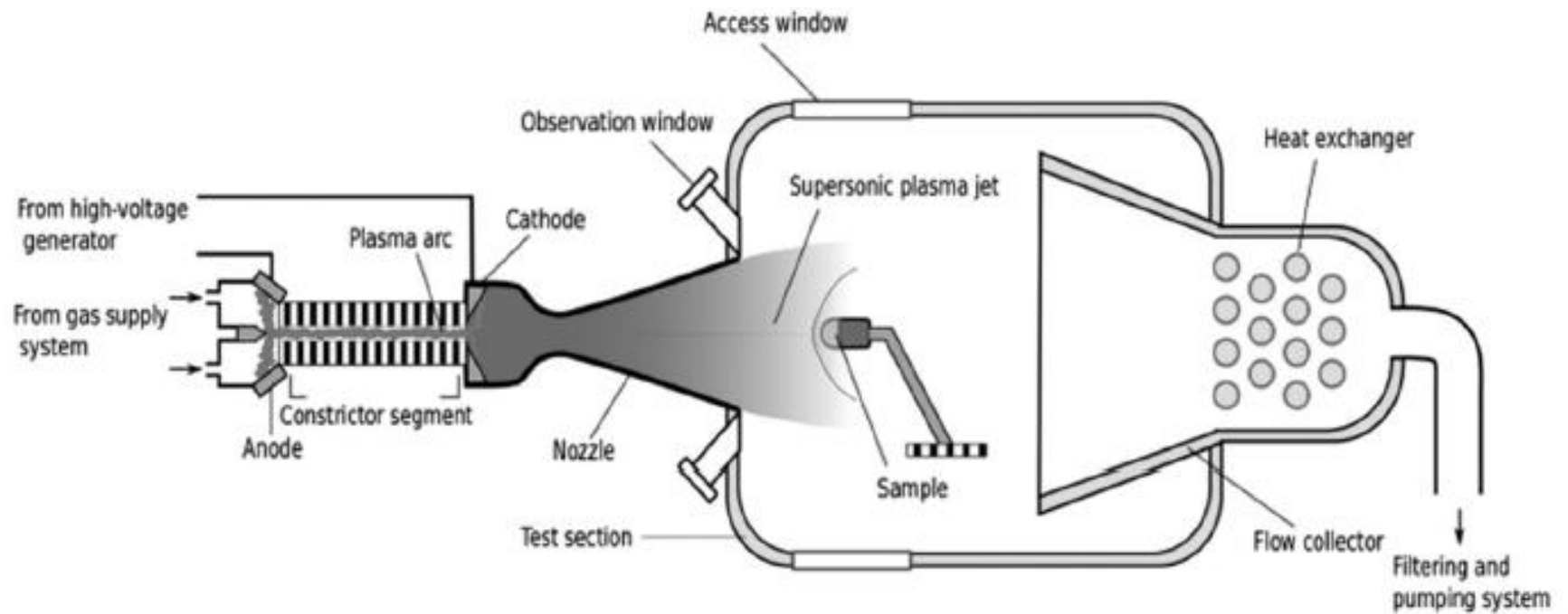
- The hot, high-speed gas flows over the test specimen—typically heat shield tiles, coatings, or other TPS materials.
- Measurements of heat flux, surface temperature, ablation, and material response are taken.



Arc Jet Facility Components

Component	Description
Power Supply	Provides high-voltage electrical energy to generate the arc.
Electrodes	Conductive elements between which the arc is sustained.
Arc Chamber	Region where gas is heated to extremely high temperatures.
Nozzle	Accelerates gas to high velocities, producing a hypersonic stream.
Test Section	Contains material samples for thermal testing.
Cooling Systems	Used to manage the heat load on tunnel components and electrodes.
Diagnostics	Includes sensors for heat flux, thermocouples, pressure gauges, and optical diagnostics.

Arc Jet Facility



Arc jet facilities

Arc jet facilities are essential for testing thermal protection systems (TPS) and studying high-temperature gas flows under hypersonic conditions. To extract valuable, accurate data during tests, a variety of diagnostic techniques are employed. These diagnostics are crucial for assessing material performance, heat transfer, aerothermal environment, and plasma characteristics.

Diagnostic Type	Techniques Used	Purpose
Temperature	Thermocouples, IR Pyrometry	Surface temperature mapping
Heat Flux	Heat Flux Gauges, Inverse Heat Conduction	Surface heat transfer rate
Ablation/Recession	Profilometry, Laser Triangulation	Surface material loss and deformation
Flow Properties	Spectroscopy (OES, LIF, Raman), Laser Absorption	Gas temperature, species concentration, velocity
Pressure	Pressure Transducers	Static and stagnation pressure measurements
Imaging	High-Speed Video, Infrared Cameras	Visual monitoring of flow and material response
Material Analysis	SEM, EDX, XRD (Post-Test)	Chemical and microstructural changes

Ballistic Range

- Ballistic range (also called a ballistic testing range or ballistic range facility) is an experimental test facility designed to study the aerodynamic behavior, impact physics, and flight characteristics of projectiles or models that travel freely through a controlled test environment after being launched at high speeds. It is commonly used in aerospace engineering, defense research, and hypersonic studies.
- Unlike wind tunnels, where the airflow moves around a stationary model, in a ballistic range the model or projectile itself moves through the test section.

Ballistic Range Components

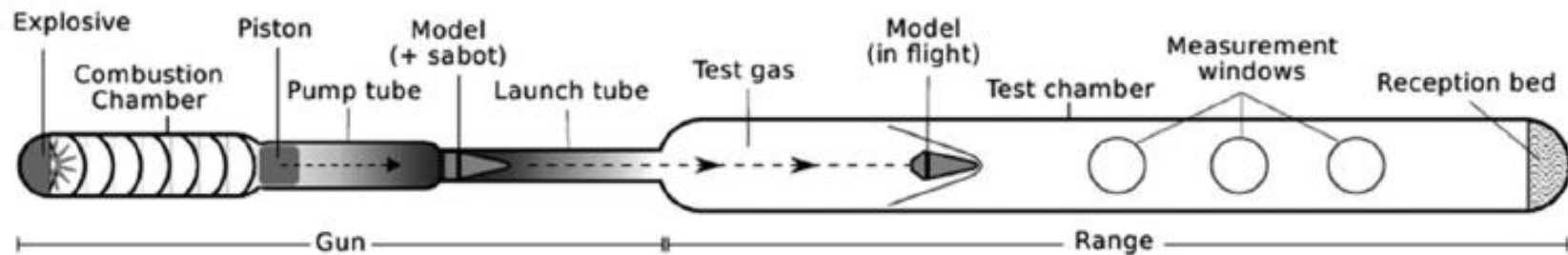
Component	Description
Launcher	Device that accelerates the projectile (gas gun, powder gun, or other).
Launch Tube	The tube through which the projectile is initially accelerated.
Test Chamber/Flight Path	Long, often evacuated, section where the projectile flies.
Diagnostics Section	Equipped with high-speed cameras, pressure transducers, laser systems, etc.
Target or Catcher	Stops or recovers the projectile after testing.
Vacuum Pumps (optional)	Used if testing in low-pressure or vacuum environments.

Ballistic Range

Types of Ballistic Ranges

- Single-Stage Gas Gun: Uses compressed gas to accelerate projectiles.
- Two-Stage Light-Gas Gun: More powerful, often used for hypervelocity impacts (up to 10 km/s or more).
- Powder Gun: Uses explosive charges for high-velocity shots.
- Electromagnetic Launchers (Railguns or Coilguns): Used for high-speed and specialized applications.

Ballistic Range



Holloman High-Speed Test Track (HHSTT)

The **Holloman High-Speed Test Track (HHSTT)** is a world-renowned ground-based test facility located at **Holloman Air Force Base** in **New Mexico, USA**. Operated by the **U.S. Air Force's 846th Test Squadron**, it is the **longest and fastest test track** in the world, designed to conduct a wide variety of high-speed dynamic tests involving **aerospace vehicles, weapons systems, materials, and subsystems** under precisely controlled conditions.

Feature	Description
Track Length	Over 10 miles (16 kilometers) , making it the longest track globally.
Maximum Speed	Speeds exceeding Mach 8 have been achieved.
Propulsion Methods	Rocket sleds (solid fuel, liquid fuel) or gas propulsion systems.
Precision Control	High-precision instrumentation and synchronization with test equipment.
Environment	Ground-based, atmospheric conditions (can be customized for some tests).

4T Testing

4T Testing (Trajectory, Test, Target, and Time)refers to a specialized test methodology used primarily in aerospace and defense industries to evaluate the performance and survivability of systems under extreme dynamic conditions. This type of testing focuses on the dynamic response and interactions of projectiles, vehicles, or other objects during high-speed, time-critical events, often related to impact, penetration, or terminal phase testing of munitions and defense systems.

Purpose of 4T Testing

- Evaluate impact behavior, penetration mechanics, and aerodynamic stability of projectiles or components.
- Analyze terminal effects such as fragmentation, penetration, or structural damage.
- Study free-flight characteristics such as stability and dynamic response.
- Validate performance of defensive systems, armor, or protective materials under high-speed impact conditions.

4T Testing

Typical 4T Test Setup

- **Launch System:**

The test object is launched using a **gun, rocket sled, ballistic range, or gas launcher** to achieve the desired **trajectory** and **velocity**.

- **Test Flight:**

The object follows its intended flight path toward a **target** under precisely monitored conditions.

- **Impact or Interaction:**

The object strikes or interacts with the target material or structure at a pre-defined point and speed.

- **Measurement & Data Collection:**

High-speed sensors, cameras, and telemetry systems capture data such as:

- Impact forces
- Penetration depth
- Fragmentation patterns
- Velocity and acceleration
- Surface temperatures and material response

16T Testing

16T Testing (Trajectory, Test, Target, Time, Temperature, Turbulence, Transition, Thrust, Torque, Thermodynamics, Telemetry, Tracking, Tactics, Threat, Terrain, and Technology) refers to a specialized and comprehensive experimental testing methodology primarily used in aerospace, defense, and hypersonic systems development. This expanded testing concept significantly broadens the 4T Testing framework (Trajectory, Test, Target, Time) to include 12 additional parameters, enabling a holistic evaluation of complex aerospace systems under realistic operational conditions. Purpose of 16T Testing

- Integrated Systems Testing: Evaluates multiple aspects of complex weapon systems, hypersonic vehicles, or aerospace platforms in a single test campaign.
- Mission-Relevant Data Collection: Simulates real-world operational environments, incorporating aerodynamic, thermal, mechanical, and tactical parameters.
- Advanced Hypersonic Research: Supports research and development of hypersonic vehicles where interactions among aerodynamic heating, structural loads, stability, and propulsion are critical.

16T Testing

Component	Description
Trajectory	The flight path or motion of the test object.
Test	The specific experiment or operational scenario being evaluated.
Target	The object or location being engaged, impacted, or analyzed.
Time	The duration and timing of the test event.
Temperature	Thermal conditions affecting the system, including heat loads and material temperatures.
Turbulence	The level of flow disturbance and its effect on flight performance and stability.
Transition	Laminar-to-turbulent flow changes, especially critical in hypersonic regimes.
Thrust	Propulsion performance and force generation during the test.
Torque	Rotational forces acting on the system or components.
Thermodynamics	Energy transfer, heating, and cooling processes affecting system performance.
Telemetry	Real-time data acquisition and transmission during the test.
Tracking	Monitoring the position, orientation, and velocity of the test object throughout the trajectory.
Tactics	The operational strategy or engagement scenario being simulated in the test.
Threat	Simulation of enemy systems, defensive countermeasures, or hazardous environments.
Terrain	Environmental or geographic conditions that influence test results or operational effectiveness.
Technology	Novel systems, subsystems, or innovations under test for validation and analysis.

16S Testing

16S Testing refers to a specialized, comprehensive testing methodology focused on assessing the structural, stress, strain, and survivability aspects of aerospace and defense systems under extreme conditions. While less widely documented than methods like 4T or 16T testing, "16S" typically refers to "Sixteen Structural Stress and Survivability Scenarios" or "Sixteen Structural States", covering multiple physical and mechanical response factors.

Purpose of 16S Testing

- Comprehensive Structural Qualification: Ensures systems can withstand combined mechanical, thermal, and aerodynamic loads.
- Survivability Assessment: Determines whether a structure can remain operational after experiencing multiple stress types, including damage and degradation.
- Life-Cycle Durability: Predicts how long systems can survive under extreme conditions such as hypersonic flight, launch loads, or re-entry.
- Certification & Risk Mitigation: Validates designs for operational certification and safety.

16S Testing – Likely Components

Category	Typical Parameters Tested
1. Static Stress	Quasi-static load-bearing capability under high-pressure or axial loads.
2. Dynamic Stress	Response to fluctuating or oscillatory forces.
3. Strain Behavior	Deformation characteristics under various loads.
4. Thermal Stress	Expansion, contraction, and material response under high heat loads.
5. Fatigue Life	Long-term cyclic loading and material durability.
6. Shock Load Response	Behavior under sudden impacts or explosive forces.
7. Vibration	Structural resonance and vibratory endurance.
8. Acoustic Loads	Effects of high sound pressure levels, common in rocket or engine testing.
9. Buckling	Stability under compression or bending forces.
10. Creep	Slow deformation under sustained high temperature or load.
11. Fracture Mechanics	Crack initiation and growth under stress.
12. Impact Resistance	Response to high-speed impacts (e.g., debris, projectiles).
13. Thermal Fatigue	Damage from repeated thermal cycling.
14. Pressure Cycling	Stress response to repeated pressurization and depressurization.
15. Residual Stress	Locked-in stresses from manufacturing or assembly processes.
16. Survivability	System's ability to remain functional after multiple damage mechanisms.

Arc Jet Testing

Arc Jet Testing is an advanced experimental technique used to simulate the extreme thermal environments experienced by vehicles during hypersonic flight and atmospheric re-entry. This type of testing is essential for evaluating thermal protection systems (TPS), heat shield materials, and other aerospace components exposed to intense aerodynamic heating.

Arc Jet testing generates high-temperature, high-enthalpy gas flows by using an electric arc to heat gas to plasma conditions, then accelerates this hot gas through a nozzle to flow over the test specimen, replicating the severe thermal conditions of high-speed flight. Test Process

- **Setup:** Test article is mounted in the test section.
- **Arc Initiation:** Electrical power generates the arc, heating the working gas.
- **Gas Expansion:** Heated gas is expanded through the nozzle to achieve desired flow conditions.
- **Testing:** Test article is exposed to the hot gas stream for a predetermined duration (seconds to minutes).
- **Data Collection:** Temperature, heat flux, material erosion, and flow parameters are recorded.

Arc Jet Testing

Component	Description
Power Supply	High-voltage source for maintaining the electric arc (can be several megawatts).
Electrodes	Create and sustain the electric arc to heat the gas.
Arc Heater/Plasma Generator	Chamber where gas is heated to plasma conditions.
Nozzle	Accelerates the heated gas to supersonic or hypersonic speeds.
Test Chamber	Contains the test sample and diagnostic equipment.
Cooling Systems	Maintain safe temperatures in facility hardware.
Instrumentation	Sensors to monitor heat flux, surface temperatures, gas properties, etc.

Heat Flux Testing

Heat Flux Testing is an experimental method used to measure the rate of thermal energy transfer (heat flux) per unit area on a surface exposed to heating. In aerospace, defense, and thermal protection research, it is critical for evaluating how materials and systems respond to high thermal loads in environments such as:

- Hypersonic flight
- Atmospheric re-entry
- Rocket propulsion systems
- Arc Jet testing
- Plasma flow environments

Heat flux is usually expressed in units of W/m^2 (watts per square meter) and is a crucial parameter for verifying thermal protection systems (TPS), insulation materials, and structural components. The purpose of Heat Flux Testing

- Determine thermal loads experienced by a surface.
- Evaluate thermal protection system performance.
- Validate computational thermal models.
- Design and optimize cooling systems or thermal barriers.
- Study ablation and material erosion under high heat conditions.

Type	Working Principle	Application
Gardon Gauge	Measures temperature difference across a thin metallic foil.	High heat flux environments (e.g., Arc Jet, rocket nozzles)
Schmidt-Boelter Gauge	Measures temperature difference across a thermopile sensor.	Moderate heat flux environments (e.g., wind tunnels)
Slug Calorimeter	Measures temperature rise in a known mass to calculate heat flux.	Transient, high-intensity testing
Thin-Film Heat Flux Sensors	Uses temperature-sensitive films for high-speed response.	High-speed testing, complex geometries

Heat Flux Testing – Common Sensors

Hot-Fire Testing

Hot-Fire Testing is a crucial experimental procedure used to evaluate rocket engines, propulsion systems, and associated components by operating them under real firing conditions. This testing involves igniting and running the engine (or propulsion component) while measuring its thrust, combustion stability, thermal performance, propellant flow, and structural integrity. Typical Hot-Fire Test Process

Test Preparation:

- Engine or component mounted securely on a test stand.
- Instrumentation installed (pressure sensors, temperature gauges, accelerometers, etc.).
- Propellant supply lines connected and pressurized.

Countdown & Safety Checks:

- Systematic checks of all systems (power, hydraulics, pneumatics, propellants).
- Safety protocols established to mitigate hazards.

Ignition and Operation:

- Ignition system activates and initiates combustion.
- Engine is throttled as required, simulating mission conditions.

Data Acquisition:

- Continuous monitoring of thrust, temperatures, pressures, flow rates, and vibrations.
- Shutdown and Post-Test Review:
 - Propellant flow is terminated, engine safely shut down.
 - Data reviewed for anomalies or unexpected behaviors.
 - Post-test inspections conducted on hardware for erosion, thermal damage, or mechanical failures.

Hot-Fire Testing - Parameters

Parameter	Purpose
Thrust	Measure of engine's output force.
Specific Impulse (Isp)	Indicator of engine efficiency in using propellant.
Chamber Pressure	Critical for combustion performance and stability.
Injector & Nozzle Temperatures	Ensure structural safety and thermal limits.
Propellant Mass Flow Rates	Evaluate flow system performance and combustion efficiency.
Combustion Stability Metrics	Detect high-frequency instabilities or vibrations.
Vibration & Loads	Assess dynamic structural responses.

Plasma Wind Tunnel Testing

Plasma Wind Tunnel Testing is an advanced experimental technique used to simulate the high-temperature, high-enthalpy flow conditions encountered by vehicles during hypersonic flight or atmospheric re-entry. Unlike conventional wind tunnels, plasma wind tunnels create a plasma—an ionized gas state—by electrically heating the gas to extremely high temperatures, allowing realistic testing of thermal protection systems (TPS), aerospace materials, and aerothermodynamic behaviors.

Plasma Wind Tunnel Testing - Types

Heating Method

Description

Arc Heating

Uses direct-current electric arcs between electrodes (similar to Arc Jets).

Induction Plasma Heating

Uses electromagnetic induction to heat gases in a contactless process.

Microwave Plasma Heating

Uses high-power microwaves to ionize and heat gases.

Plasma Wind Tunnel Testing - diagnostics

Diagnostic Type	Purpose
Heat Flux Sensors	Measure thermal loads on test surfaces.
Infrared Thermography	Visualize surface temperature distributions.
Spectroscopy (OES, LIF, etc.)	Identify plasma species, temperatures, and ionization states.
High-Speed Cameras	Capture real-time material response and ablation phenomena.
Thermocouples & Embedded Sensors	Record internal temperature and thermal gradients.
Mass Spectrometry	Analyze exhaust gas composition post-interaction.

Plasma Wind Tunnel Testing - facilities

Facility	Country	Specialization
Plasma Wind Tunnel PWK Series (DLR)	Germany	Re-entry and TPS testing under various atmospheres.
AMES Plasma Wind Tunnel (NASA)	USA	Entry vehicle TPS testing, especially for Mars/Venus missions.
LAEPT Plasma Wind Tunnel	France	Plasma-surface interaction research and TPS studies.
JAXA Plasma Wind Tunnel	Japan	Hypersonic and atmospheric re-entry testing.

Laser-Based Flow Diagnostics

Laser-Based Flow Diagnostics refers to a collection of advanced, non-intrusive experimental techniques that use laser light to measure and visualize fluid flow properties in aerospace, hypersonic, and thermal systems. Laser diagnostics are critical for studying complex flow phenomena such as:

- Shock waves
- Boundary layers
- Mixing and combustion
- Plasma flows

Laser-Based Flow - PIV

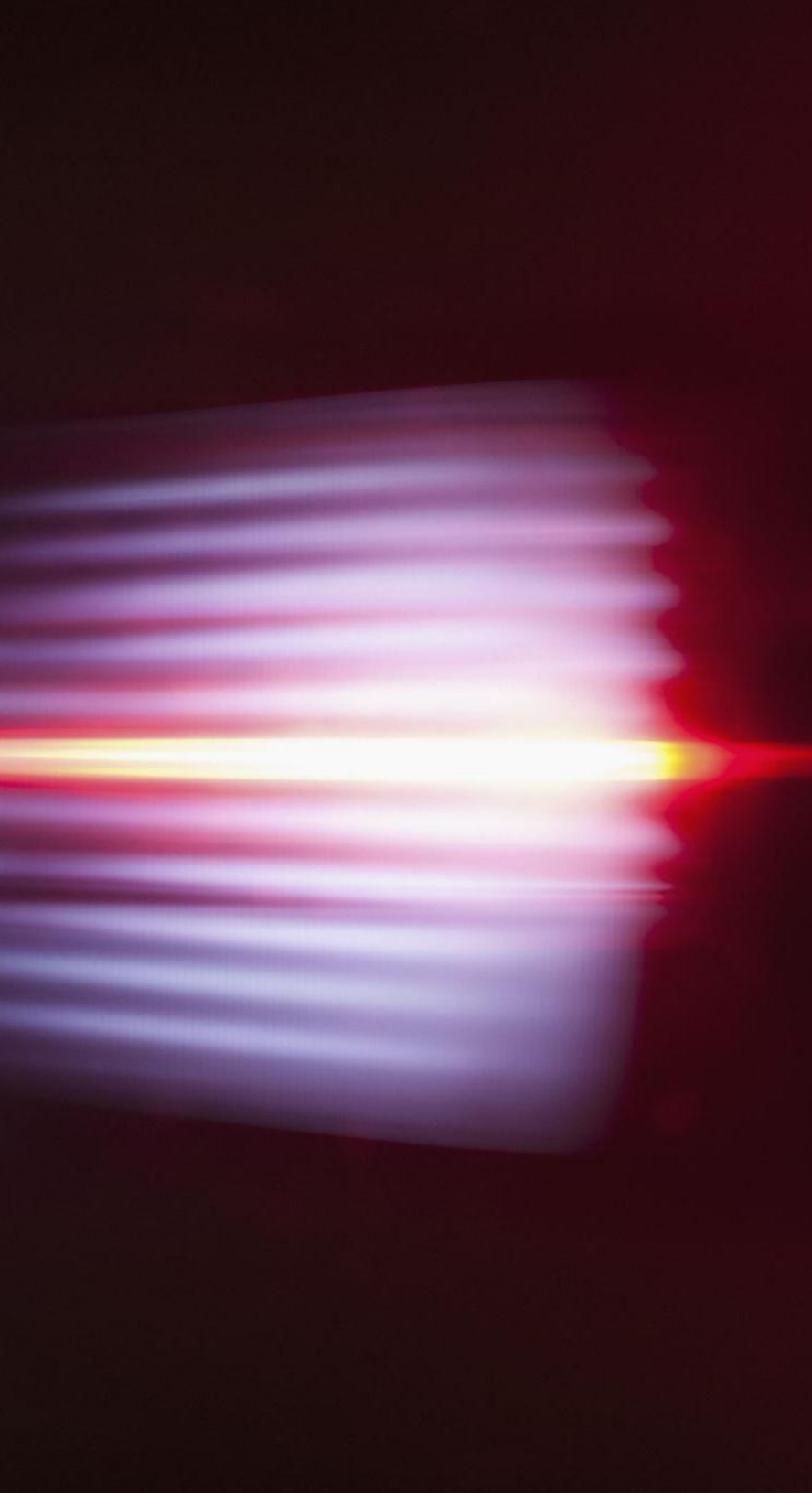
Particle Image Velocimetry (PIV) is used to measure velocity fields by tracking particles seeded into the flow.

The process is:

- Flow is seeded with fine particles.
- A laser sheet illuminates the flow; particles scatter light.
- High-speed cameras capture successive images.
- Particle displacements between images are analyzed to compute velocity vectors.

It is applied to

- Boundary layer studies.
- Vortex dynamics.
- Shock-induced flow separation.



Laser-Based Flow - LDV

Laser Doppler Velocimetry (LDV) / Laser Doppler Anemometry (LDA) is used to measure pointwise velocity using the Doppler shift of scattered laser light.

The process is:

- Two laser beams intersect at a focal point, creating an interference pattern.
- Particles crossing the point scatter light with a Doppler frequency shift.
- The frequency shift relates to the particle velocity.

Laser-Based Flow - PLIF

Planar Laser-Induced Fluorescence (PLIF) is used to measure species concentration, temperature, and density.

The basic process is

- A laser excites specific gas species.
- The gas fluoresces (emits light) at a specific wavelength.
- The fluorescence is captured to map species concentration or temperature.