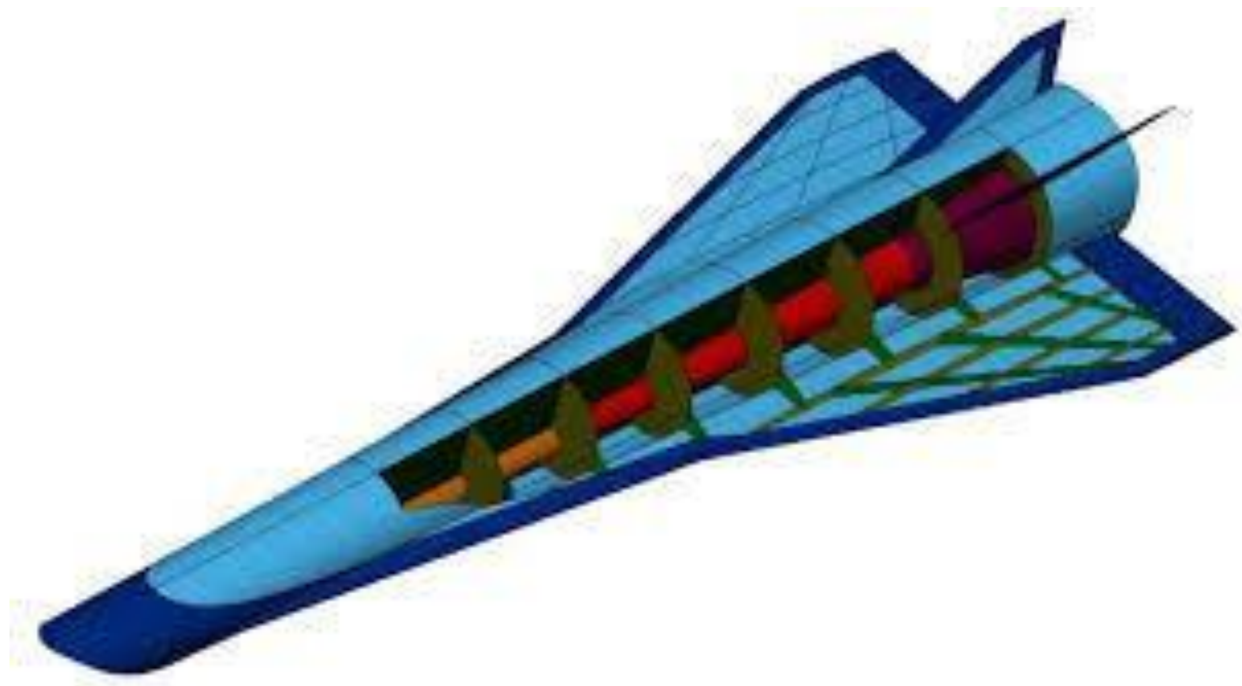
Deeper into Aerospace – Hypersonic

Engineering



Dr. Chuck Easttom, M.Ed, MSDS, MBA, MSSE, Ph.D.2, D.Sc.

Part I

Mathematics

Heat Transfer Modes

In hypersonic flight , heat transfer becomes a critical design challenge, especially due to the extreme thermal loads on the vehicle surface. Understanding the different heat transfer modes is essential for designing thermal protection systems (TPS) and ensuring structural integrity.

Mode	Mechanism Heat	Dominant Where
Conduction	transfer through solid vehicle materials	Inside the vehicle structure and TPS layers Outer surface (boundary layer
Convection	Heat transfer between hot gases and surface	interactions) From both shock layer
Radiation	Emission of energy via electromagnetic waves	gases and hot surfaces

Convective Heat Transfer

This is the most dominant form of heat transfer mode. Hot gas (air or plasma) flows over the vehicle. Energy is transferred from gas to surface via boundary layer processes. This can be either

Laminar convection: Smooth boundary layer, lower heat flux.

or

Turbulent convection: Chaotic motion → much higher heat transfer (up to 5–10×).

Convective Heat Transfer

Heat Flux Equation (Stagnation Point – Fay–Riddell Approximation):

$$q_s = 0.763 \cdot \left(\frac{\rho_e \mu_e}{R_n} \right)^{0.5} \cdot h_{e,w}$$

Where: qs: Heat flux at stagnation point (W/m²),

ρe, μe: Density and viscosity of gas at boundary edge,

Rn: Nose

he,w: Enthalpy difference between boundary layer edge and wall.

radius,

Conductive Heat Transfer

Heat absorbed at the surface travels inward through structural materials. Governed by Fourier's Law:

$$Q=-k \quad \frac{ⅆ}{ⅆ}$$

Where q: Heat flux (W/m²),

k: Thermal conductivity (W/m·K),

$ⅆT\ ⅆx$

—: Temperature gradient.

D’Alembert’s paradox

D'Alembert's paradox, also known as the hydrodynamic paradox, states that in ideal fluid flow (incompressible and inviscid), a body moving at a constant speed through a fluid experiences no drag force. This contradicts real-world observations where objects moving through fluids, like air or water, do experience drag, especially at higher speeds

D'Alembert's paradox

D'Alembert's paradox, formulated by the French mathematician Jean le Rond d'Alembert in the 18th century,canbesummarizedasfollows:"Inaninviscid,incompressible,andsteadyflowofafluidarounda

solid body, the net drag force exerted on the body is zero." Using the Euler equations for an ideal fluid

(which neglect viscosity), one can compute the pressure distribution around a body like a cylinder or sphere. If the flow is symmetric (as it is in ideal conditions), the pressure forces on the front and rear of the object cancel out.

The total drag force FDFD from the pressure distribution is:

$$F_D = \int_{\text{surface}} p\,\mathbf{n} \cdot \mathbf{i}\, dA = 0$$

where:

p is pressure,

n is the normal to the surface, i is the direction of motion. So, according to this theory, there is no net force resisting the motion of the object. In real life, objects like airplanes, cars, and balls clearly experience drag. The paradox arises because ideal fluid theory ignores viscosity. In reality, viscous effects lead to boundary layer formation and flow separation, especially

behindobjects—causingpressuredrag.Turbulentwakesandvortices are not captured by ideal flow theory.

Aeroacoustics

Aeroacoustics is the study of sound generation, propagation, and interaction in afluid flow,especially airflow.Itcombinesprinciples from aerodynamics and acoustics to understand how unsteady fluid motion produces noise

Aeroacoustics – Physical Origins

A. Turbulence-Induced Noise

- Fluctuations in velocity and pressure within a turbulent flow produce broadband noise.
- Common in jet engines and aircraft wakes.

B. Shear Layer Instabilities

- High-speed flow over a surface (e.g., an airfoil or cavity) creates shear layers that roll into vortices and radiate sound.

C. Shock-Associated Noise

- In supersonic and hypersonic flows, shock waves interact with turbulence or surfaces, generating strong acoustic emissions.

D. Vortex-Surface Interaction

- A vortex striking a surface or an edge (like a flap or strut) produces tonal noise — common in landing gear and flap side eges.

- **E. Blade Passing and Rotational Effects** In fans,
- propellers, and rotors, noise is generated by:
    - Blade passing frequency (BPF): tonal noise,
    - Wake interaction and blade-vortex interactions.

Aeroacoustics -Lighthill's Acoustic Analogy

Sir Michael James Lighthill (23 January 1924 – 17 July 1998) was a British applied mathematician, known for his pioneering work in the field of aeroacoustics. The Lighthill analogy considers a free flow, as for example with an engine jet. The nonstationary fluctuations of the stream are represented by a distribution of quadrupole sources in the same volume.

James Lighthill developed the foundational framework for aeroacoustics by rewriting the **Navier–Stokes equations** to isolate sound-producing terms:

$$\frac{\partial^2 \rho'}{\partial t^2} - c_0^2 \nabla^2 \rho' = \nabla \cdot \nabla \cdot \mathbf{T}$$

Where:

- ρ': Acoustic density perturbation,
- c0: Speed of sound,
- T: Lighthill's stress tensor (source of sound).
- This shows that **aerodynamic sound** is produced by **unsteady stress distributions**, especially from turbulence.

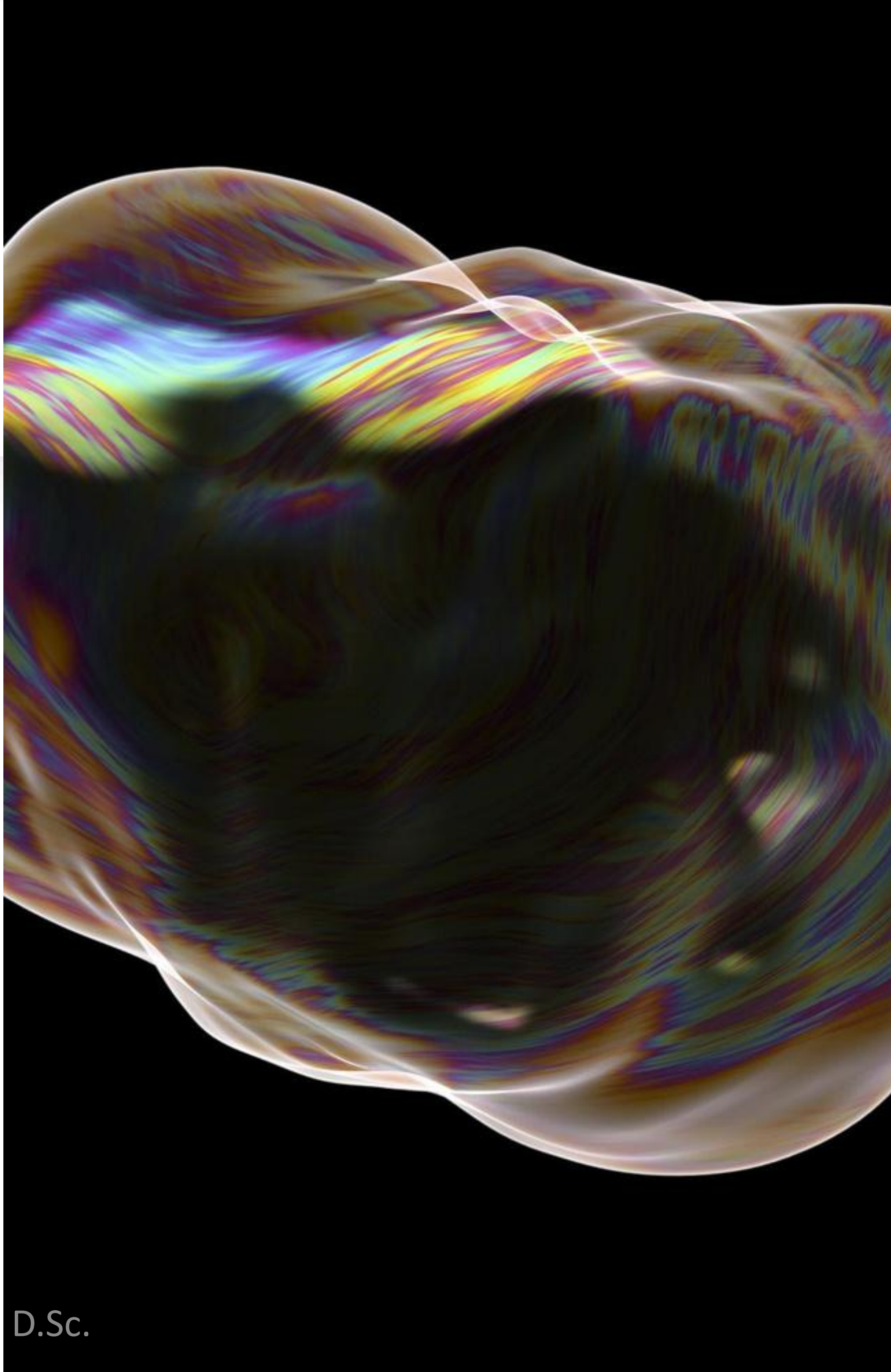
Types of Aeroacoustic Noise

Noise Type	Description	Example
Broadband	Continuous noise over a wide frequency range	Jet exhaust, turbulent wake
Tonal	Discrete frequencies (tones) due to periodic events	Blade passing, cavity resonance
Impulse	Sharp spikes in sound pressure (short duration)	Sonic boom, vortex shedding

Hypersonic Aeroacoustics

At hypersonic speeds (Mach > 5), aeroacoustics includes unique features:

- **Shock-turbulence interaction noise**,
- **Boundary layer noise** due to second-mode instabilities (Mack modes),
- **Sonic boom propagation** through stratified atmospheres,
- **Surface heating due to acoustic-wave amplification** (important for TPS design).



Aeroacoustic Simulation

Simulation of aeroacoustic phenomena is typically handled using:

•**Direct NumericalSimulation (DNS)**for small-scale,high-fidelity studies,

•**Large Eddy Simulation (LES)** with FW–H for practical engineering applications,

•**Hybrid RANS-CAA** methods for coupling flow field with noise prediction.

Eulerian specification of the flow field

In fluid dynamics, the Eulerian specification of the flow field describes the fluid motion by focusing on fixed points in space, rather than tracking individual fluid particles. It defines fluid properties like velocity, pressure, and density as functions of position and time, effectively providing a snapshot of the flow at each instant. The focus is on a specific location in space, and how the fluid properties change at that location over time. The fluid properties are represented as fields, meaning they are defined at every point in the flow domain. The Eulerian description doesn't track the movement of individual fluid particles; instead, it describes what happens at a given point regardless of which particle happens to be there at that moment.

Lagrangian specification of a flow

The Lagrangian specification of a flow field involves tracking the motion of individual fluid parcels over time. In essence, it's like following a specific drop of dye as it moves through a stream, noting its position and velocity at different points in time. This approach contrasts with the Eulerian specification, which focuses on fluid properties at fixed points in space. The Lagrangian method concentrates on the path and properties of specific fluid elements (like a small volume of fluid) as they move through space and time. By tracking the position of a fluid parcel over time, you generate a pathline, which represents the trajectory of that specific parcel.

Jet Interaction (JI) effects

Jet Interaction (JI) effects refer to the complex **aerodynamic and fluid dynamic phenomena** that occur when **propulsive jets interact with nearby structures, external flowfields, or surfaces**. This interaction can cause **pressure perturbations, shock formations, flow separation**, and **structural loading** that affect **vehicle performance, stability, and control**.

Interaction Type **Jet–**	Description Exhaust plume impinges on a
Surface Interaction	body (e.g., fins, wings, or base surfaces)
Jet–Jet Interaction	Multiple jets influence each other (e.g., RCS thrusters)
Jet–External Flow Interaction	Jet interacts with external high-speed or hypersonic freestream flow
Jet–Shock Interaction	Jet intersects with shock waves (common in supersonic/hypersonic regimes)

Jet Interaction (JI) effects

A. Shock Formation and Reflection •Jets in supersonic flow produce expansion fans and shock cells.

•Interaction with surfaces leads to shock reflection, bow shocks, and Mach disks.

B. Flow Separation and Reattachment

- The high-pressure exhaust can cause boundary layer separation on nearby surfaces.
- Can lead to unsteady loads, buffeting, and vortex shedding.

C. Plume-Induced Forces

•Jet plumes exert side forces and moments on the vehicle, influencing stability and control.

•Especially important in reaction control system (RCS) applications.

D. Base Pressure Effects

- Jet interaction near the aft of a vehicle can drastically alter base pressure and cause drag fluctuations.

Jet Interaction (JI) effects- Parameters

Parameter **Jet**	Impact on Jet Interaction Supersonic
Mach number	jets cause shocks and expansion
Ambient flow speed	Higher freestream velocity → stronger interaction
Nozzle geometry	Affects exhaust spread and directionality
Jet-to-freestream pressure ratio (Pj/Pa)	Governs jet expansion/compression characteristics
Standoff distance	Closer surfaces amplify interaction effects

Deployed Aero Drag Reduction Approaches

Natural [pressure gradient] Laminar Flow Riblets Reduced roughness Flow separation control, passive/active/fairings Vortex generators Passive porous surfaces for shock-boundary layer interaction Suction laminar flow control

Passive

Passive devices are fixed or non-powered structures that improve aerodynamic or thermodynamic performance without any external energy input or moving parts.

Passive Device	Function Control flow separation and
Vortex generators	delay boundary layer detachment
Riblets	Reduce skin friction drag by modifyingnear-wallturbulence Improve lift on trailing edges of wings
Gurney flaps	Protect spacecraft from high reentry temperatures
Passive cooling tiles	
Aerodynamic fins/strakes	Stabilize or guide flight dynamics

Vortex Generators

Vortex Generators (VGs) are small aerodynamic devices, typically shaped like vanes or fins, that are mounted on a surface (usually wings, fuselages, or control surfaces) to generate controlled vortices in the boundary layer. Their primary purpose is to delay flow separation, enhance lift, and improve control effectiveness, especially in high angles of attack or adverse pressure gradients.

In fluid flow over a surface:

- The boundary layer — the thin layer of air near the surface — tends to separate when encountering adverse pressure gradients (such as behind a curved surface).
- Separation reduces lift and increases drag or loss of control.

Vortex generators help by: • Creating streamwise vortices that mix high-energy air from the freestream into the low-momentum boundary layer.

- This energizes the boundary layer, making it more resistant to separation.

Vortex Generators - Characteristics

Parameter	Typical Range ~20–80% of boundary
Height	layer thickness
Shape	Delta wing, rectangular vane, ramp, or wedge
Orientation	Often canted at ~15–20° to freestream
Material	Aluminum, composite, plastic, or adhesive tape

Vortex Generators -Applications

Application Area	**Purpose/Benefit** Delay stall, enhance lift at high angles
Aircraft wings **Control surfaces**	of attack Improve responsiveness of rudders, elevators, ailerons
Engine nacelles	
Helicopter rotors	Prevent flow separation around engine inlets
Missiles and UAVs	Stabilize flow over rotor blades Improve aerodynamic stability and maneuverability

Types of Vortex Generators

Type	Description
Delta-shaped	Common in aerospace; pointed upstream
Rectangular vane	Simplified flat fin structures
Sawtooth/ramped	Low-profile; used in supersonic/hypersonic flows
Micro VGs	Very small, often embedded or painted-on
Active VGs	Can retract or rotate (rare, complex systems)

Suction laminar flow Control

Suction Laminar Flow Control is a boundary layer flow control method that uses low-level suction through a porous or slotted surface to remove low-energy fluid near the wall, thereby maintaining laminar flow over a longer portion of an aerodynamic surface. The goal is to delay the transition from laminar toturbulent flow, which reduces skin friction drag and improves aerodynamic efficiency.

In high Reynolds number flows (like on aircraft wings or fuselages), the laminar boundary layer eventually transitions to turbulence, causing:

- A 3–5× increase in skin friction,
- Increased fuel consumption and drag,
- More heating in high-speed flight.

By removing a small portion of the near-wall boundary layer fluid, Suction Laminar Flow Control:

- Stabilizes the laminar layer,
- Prevents or delays instabilities like Tollmien–Schlichting waves and crossflow vortices,
- Maintains laminar flow over larger areas of the surface.

Suction Laminar Flow Control

Key Components:

- Porous surface or slotted panels,
- Suction system (pumps or low-pressure chamber) underneath
- the surface,

  Flow control sensors and feedback (in active systems).

Mechanism: • Suction gently removes slow-moving fluid from the boundary
  layer.

- This reduces boundary layer thickness and disturbance amplitude.
- Result: Increased stability of the laminar boundary layer.

Suction Laminar Flow Control

Parameter **Suction**	Design Role
distribution	Must match disturbance growth regions (often nonlinear)
Porous material	Needs to resist clogging, erosion, contamination
Suction rate	Typically < 0.5% of boundary layer mass flow
Structural integration	Avoids weight or stiffness penalties
Maintenance	Mustprevent clogging, especially in dusty environments

Laminar Flow Control (LFC) Methods

Method	Power Input	Complexity	Effectiveness	Robustness
Natural Laminar Flow (NLF)	None	Low	Moderate	High
Suction LFC (SLFC)	Yes	Moderate	High	Medium
Active LFC (e.g., plasma)	High	High	Potentially very high	Low

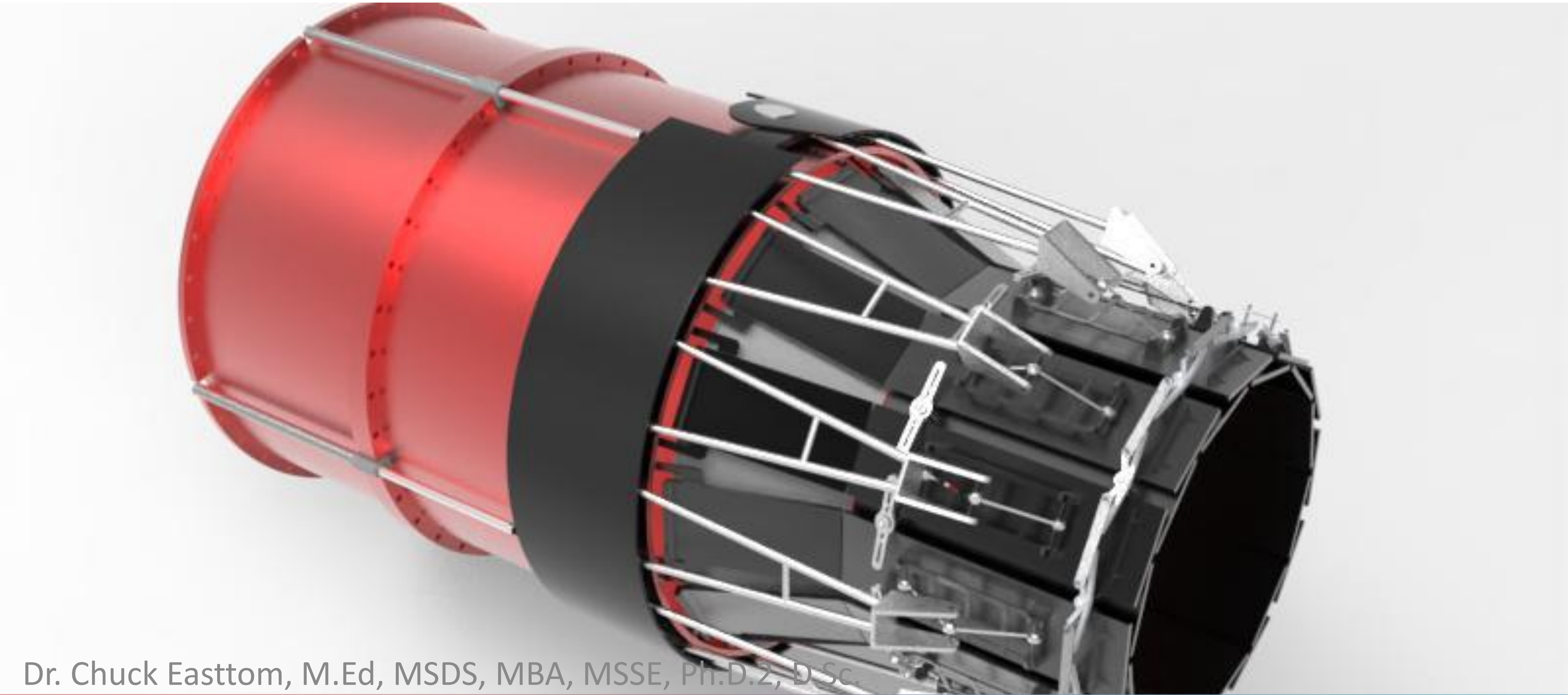
Active

Active devices require external power or control input and often include moving parts, sensors, or actuators to dynamically respond to changing flight conditions.

Active Device **Thrust**	Function Change exhaust direction
vectoring nozzles Active	to steer the vehicle
flow control (blowing/suction)	Modify boundary layer or delay separation
Adaptive wings/flaps	Morph shape for optimal aerodynamic response
Reaction control systems (RCS)	Use gas jets for space attitude control
Active cooling systems	Use coolant circulation in TPS or engines

Thrust vectoring nozzles

Thrust vectoring nozzles are propulsion nozzle systems designed to change the direction of the engine exhaust to produce steering or control forces. By deflecting the exhaust jet away from the centerline, these nozzles generate torque or side forces that help control the pitch, yaw, or roll of the vehicle. Thrust vectoring allows for control without relying solely on aerodynamic surfaces, especially in low-speed or high- angle-of-attack conditions.



Thrust vectoring nozzles - Mechanical Deflection (Movable Nozzles)

Type **2D**	Description
Nozzle	Moves in pitch and/or yaw axes; rectangular shape
3D Nozzle (Swivel/Pivot)	Deflects in all directions (e.g., F-22 Raptor nozzles)
Rotating Nozzle	Nozzlerotates completely (used in some VTOL aircraft)

Thrust vectoring nozzles – Fluidic Thrust Vectoring

Uses secondary fluid jets (blowing or suction) along the nozzle wall to steer the main jet without moving parts.

Simpler mechanically, but requires complex fluid control.

Thrust vectoring nozzles -Jet Tab or Vanes

Mechanical deflectors placed inside or at the exit of the nozzle to redirect exhaust.

Common in solid rocket motors or tactical missiles.

Reaction Control System (RCS)

A Reaction Control System (RCS) is a thruster-based control system used to manage the attitude (orientation) and sometimes translation (position) of a vehicle in space or near-space environments. It operates by expelling mass (propellant) in a specific direction, generating thrust via Newton's Third Law: "For every action, there is an equal and opposite reaction." RCS is essential where aerodynamic control surfaces are ineffective or absent, such as in vacuum, at high altitudes, or during space maneuvers.

An RCS consists of multiple small thrusters placed around the spacecraft. Each thruster can be fired independently or in combinations to produce:

- Torque for rotational control,
- Linear thrust for position adjustment.

The placement of thrusters is designed to provide 3-axis control (pitch, yaw, and roll) as well as 6 degrees of freedom in maneuverable systems (adding surge, heave, and sway translations).

Reaction Control System (RCS) - Function

Function **Attitude control**	Description Pitch, yaw, and roll
Translational maneuvers	adjustment Small orbital changes
	or docking adjustments
Stabilization	Dampeningunwantedrotations or oscillations
Desaturation	Removingangularmomentum from reaction wheels (in satellites)
Back-up control	Emergency backup for primary flight control systems

Reaction Control System

Propulsion Type	Description	Example Application
Cold gas thrusters	Simple, non-reactive; gas expelled from a tank	CubeSats, small satellites
Monopropellant	Single fluid (e.g., hydrazine) decomposed by catalyst	Space Shuttle RCS
Bipropellant	Fuel + oxidizer; higher thrust and efficiency	Large spacecraft, Mars landers
Electric propulsion	Usesionorplasma(low thrust, high efficiency)	Station-keeping, long-duration probes

Fairings

Fairings are aerodynamic covers used to reduce drag, protect internal components, and smooth out airflow around joints, protuberances, or discontinuities on a vehicle.

Fairing Type	Function
Payload fairing (rocket)	Protects satellite or cargo during ascent through the atmosphere
Wing-body fairing	Smooths airflow atthe wing–fuselage junction
Landing gear fairing (spats)	Reduces drag around wheels when retracted or exposed
Sensor/equipment fairings	Covers protruding sensors, antennas, etc.
Engine nacelle fairing	Reduces nacelle drag and helps with cooling flow control

Other Flow Control Approaches

Trapped vortex diffuser

Circulation control

Pneumatic vortex control

Turbulent drag reduction [TDR] via slot injection

Low profile vortex generators

Pneumatic/ actuated strake vortex control

Active mixing control
Spanwise blowing for vortex lift

Phase locked active wave cancellation

Microbubble drag reduction

Transverse wall motion/ oscillation for turbulent drag reduction

Jet vortex generators

Wing tip treatments [various]

Mission adaptive /morphing wing

Thrust vectoring for control
Vortex flap

Polymer drag reduction
MHD control

Owl-comb leading edge vortex generators

Plasma drag reduction and flow Separation Control

Options – Drag Due To Lift Reduction

Aspect Ratio [increase]

Loading [eliptic, generally]
Leading edge bumps
Serrated trailing edges
Tip turbines Winglets
Vortex diffuser vane
Tip sails

Ring wing Joined wings/ tails Wing tip engines Sweptback tapered tips Porous tips Tip blowing Rotating tip cylinder Oscillatory Span Load Bi-plane

Basic Approaches: Turbulent Drag Reduction

Reduce roughness Reduce wetted area Reduce fluid viscosity near the wall Reduce fluid density near the wall [wall heating] Reduce longitudinal mean velocity in wall vicinity [mass injection] Reduce turbulence activity

Transport Based Transition Modeling

Reynolds-Averaged Navier-Stokes (RANS) Computational Fluid Dynamics calculations can include transition prediction via additional transport equations that calculate intermittency, γ, that modifies the source terms in the RANS equation(s):

$$\frac{\partial(\rho k)}{\partial t} \frac{\partial(\rho ujk)+}{\partial x_j} = \gamma P_k - \gamma_{lm} E k + \Pi cc + \frac{1}{Re} \frac{}{\partial xj} \left[(\mu + \sigma k \mu t) \frac{\partial k}{\partial x} \right]$$

Accurate calculation of γ relies on the prediction of transition onset by relevant mechanisms

Most commonly-used transition models are intended for low-subsonic to transonic Mach numbers

Additional transport quantities are usually modeled as well, which are used to calculate the production of γ

Currently, there is no thoroughly-vetted, widely-implemented transport model for the prediction of transition at hypersonic Mach numbers

SST-γ model of Liu et al. (2022)

- A single auxiliary transport equation is added
  - Hypersonic analogue of Menter's γ model
- Production is triggered when local vorticity Reynolds number exceeds a threshold
- Effects of pressure gradient, nose radius, and surface temperature are modeled empirically via $f(Me,Te)$ and $R_{\theta,c}$
- Transition mechanisms involving 1st– and 2nd–mode instabilities are grouped together in streamwise onset function
- Streamwise and crossflow modes are competitive

$$\frac{\partial(\rho\gamma)}{\partial t} + \frac{\partial(\rho u_j\gamma)}{\partial x_j} = P_\gamma - E_\gamma + \frac{1}{Re}\frac{\partial}{\partial x_j}\left[(\mu+\mu_t)\frac{\partial\gamma}{\partial x}\right]$$

$$P_\gamma = C_1\,\rho\,F_{onset}\,\gamma(1-\gamma)$$

$$F_{onset} = f*(F_{onset,s}, F_{onset,cf})$$

$$F_{onset,s} = \frac{Re}{f(Me,Te)\,Re_{\theta,c}}$$

$$F_{onset,cf} = \frac{\Delta H_{cf}\,Re_V}{f(M_e,Te)\,C_{cf,crit}}$$

SST-γ-νL model of Qiao et al. (2021)

- Two auxiliary transport equations are added
  - Extensionofthe early work by Warrenand Hassan (1998), Papp and Dash (2002)
- Production of γ is triggered when ν_L exceeds a threshold
- Transport of νL models the impact of bluntness, pressure gradient, and surface (& freestream) temperature
- Transition mechanisms dominated by 1st , 2nd, and crossflow modes are treated separately
  - τL constituents are calculated individually
- All modes contribute additively to the production of νL.

$$\frac{\partial(\rho\gamma)}{\partial t}+\frac{\partial(\rho u_j\gamma)}{\partial x_j}=P\gamma-E\gamma+\frac{1}{Re}\frac{}{\partial xj}\left[(\mu+\mu t)\frac{\partial\gamma}{\partial x_j}\right]$$

$$P\gamma=\rho C1F_{onset}(1-\gamma)-\ln(1-\gamma)^{\frac{1}{3}}S$$

$$F_{onset}={}^{*}\left(\frac{\nu}{\nu}\right)$$

$$\frac{\partial(\rho\nu L)}{\partial t}+\frac{\partial(\rho u_j\nu L)}{\partial x_j}=P\nu_L-E\nu+_L\frac{1}{Re}\frac{}{\partial xj}\left[\rho\sigma(\nu+\sigma\nu_L\nu_L)\frac{\partial_L}{\partial x_j}\right]1$$

$$P_{L=}C_\mu\,\rho\,\tau_L\,S^2$$

$$\tau L=\tau 1+\tau 2+\tau_{cf}$$

OVERFLOW 2.3e Parameters

OVERFLOW 2.3e is modified to include both SST-γ and SST-γ-νL models

All test cases are run with HLLE++, van Albada limiter, and SSOR

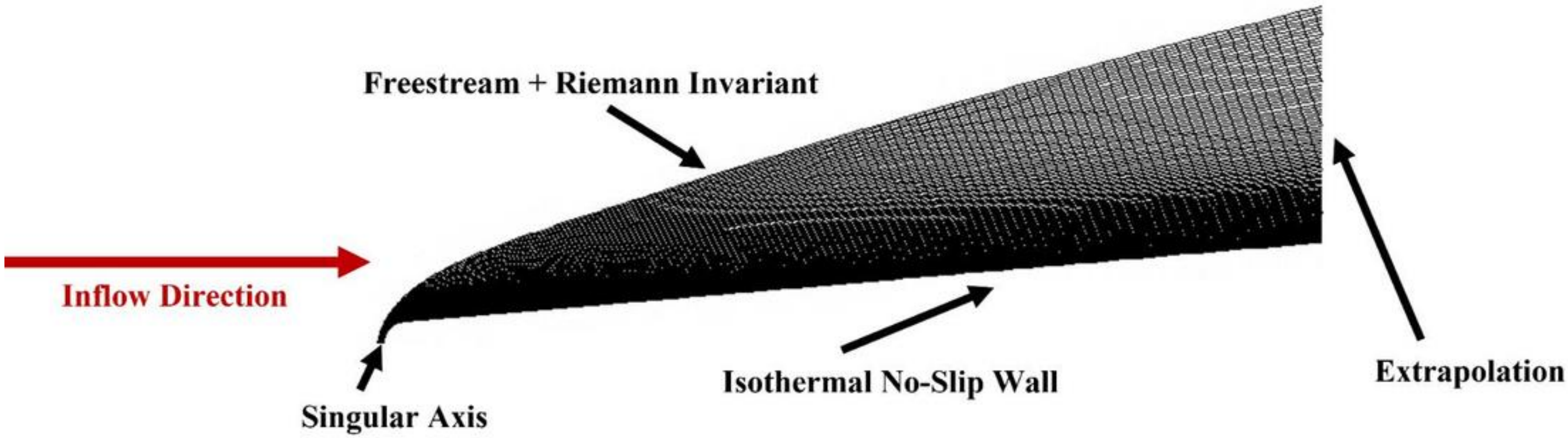
Mesh requirements estimated via grid refinement study for a single test case

Gridsused here aregenerally muchfiner than those used in Liu et al. (2022) and Qiao et al. (2021)

For γ-νL case, turbulence modeling time step has been reduced to 0.2 times the local flow time step

5 subiterations per flow time step are also used

Freestream-turbulence-sustaining terms and QCR are not used in this study



Simulation parameters

Requirements for Tu∞, **μ**T∞, and γ-νL∞ are not the same for the SST-γ and SST-γ-νL models

Values of Tu∞ reported by Liu el al. (2022) and Qiao et al. (2021) did not produce visual agreement in all cases, and freestream values were adjusted where appropriate to achieve the experimentally correct onset location

Cases use shock-aligned grids generated from laminar precursor runs to identify shock location

Riemann invariant

The Riemann invariant is a conserved quantity along specific characteristic curves in a hyperbolic PDE system, such as the Euler equations for compressible flow. It is used to simplify and solve flow problems involving shock waves, expansion fans, or nonlinear wave propagation. Riemann invariants are particularly useful for 1D isentropic, inviscid flow (e.g., flow through nozzles, around corners, or in expansion waves).

Riemann invariant

For 1D isentropic flow, the characteristic curves are:

Forward characteristic: $\frac{dx}{dt} = u + a$

Backward characteristic: $\frac{dx}{dt} = u - a$

Along these characteristics, **Riemann invariants** are constant:

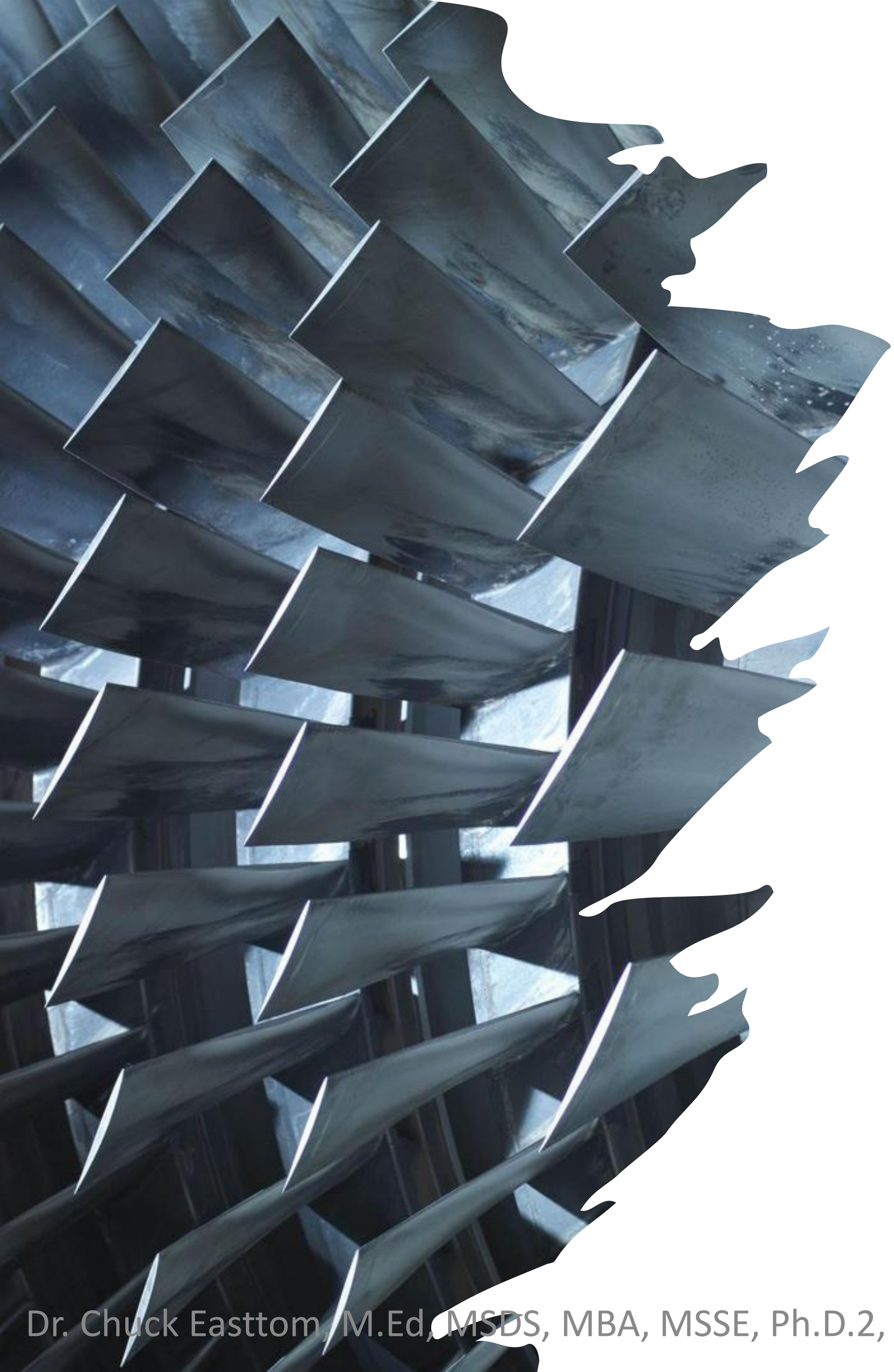
Along $\frac{dx}{dt} = u + a$:

$$R^{+} = u + \frac{2a}{\gamma - 1} = \text{constant}$$

Along $\frac{dx}{dt} = u - a$:

$$R^{-} = u - \frac{2a}{\gamma - 1} = \text{constant}$$

Where:
u: flow velocity, a: local speed of sound, γ: ratio of specific heats.



Riemann invariant

Riemann invariants are powerful tools in analytical and numerical fluid dynamics, simplifying the solution of complex hyperbolic PDEs. In aerospace, they are critical in modeling high-speed flows involving expansion waves, nozzles, and wave propagation, and serve as the foundation of modern Riemann solvers used in CFD.

Shock/Shock Interactions

Inhypersonic aerodynamics,shock/shockinteractions (SSI) refer to thephenomenon where twoormore shock waves interact with oneanother. Theseinteractions are critical in hypersonic flight due to their profound impact on pressure loads, heating rates, and structural integrity.

The key physical processes in shock-shock interactions include:

- ShockCompression:Suddenincreasesinpressure, density, and temperature across shock waves.
- Triple Point Formation: Point where three shock waves meet, generating complex flow patterns.
- Mach Stem Development: Near-vertical shock between the incident and reflected shocks, leading to high thermal loads. Slip Lines: Shear layers
- where flow properties change discontinuously downstream of the triple
  point.

Shock/Shock Interactions can result in:

- Localized Heating: Extremely high heat transfer rates at the triple point and Mach stem regions, potentially causing thermal failure. Structural Loads: High-
- pressure forces that can lead to deformation or damage of vehicle surfaces. Design Challenges:
- Requires careful design of intakes, control surfaces, and thermal protection systems for hypersonic vehicles (missiles, re-entry vehicles, etc.).

Types of Shock/Shock Interaction

s

There are several types of SSI, generally categorized by the anglesandstrengthsoftheinteractingshocks:

1.RegularReflection(RR)

- Occurs when an incident shock reflects from a surface, producing a reflected shock. Common in low-angle interactions
- where the flow can adjust smoothly.

2. Mach Reflection (MR)

- Occurs when the incident shock cannot reflect regularly due to geometric constraints or high shock strength. A Mach
- stem forms between the incident and reflected shocks, along with a triple point where the shocks meet. Produces
- high-pressure and high-temperature regions.

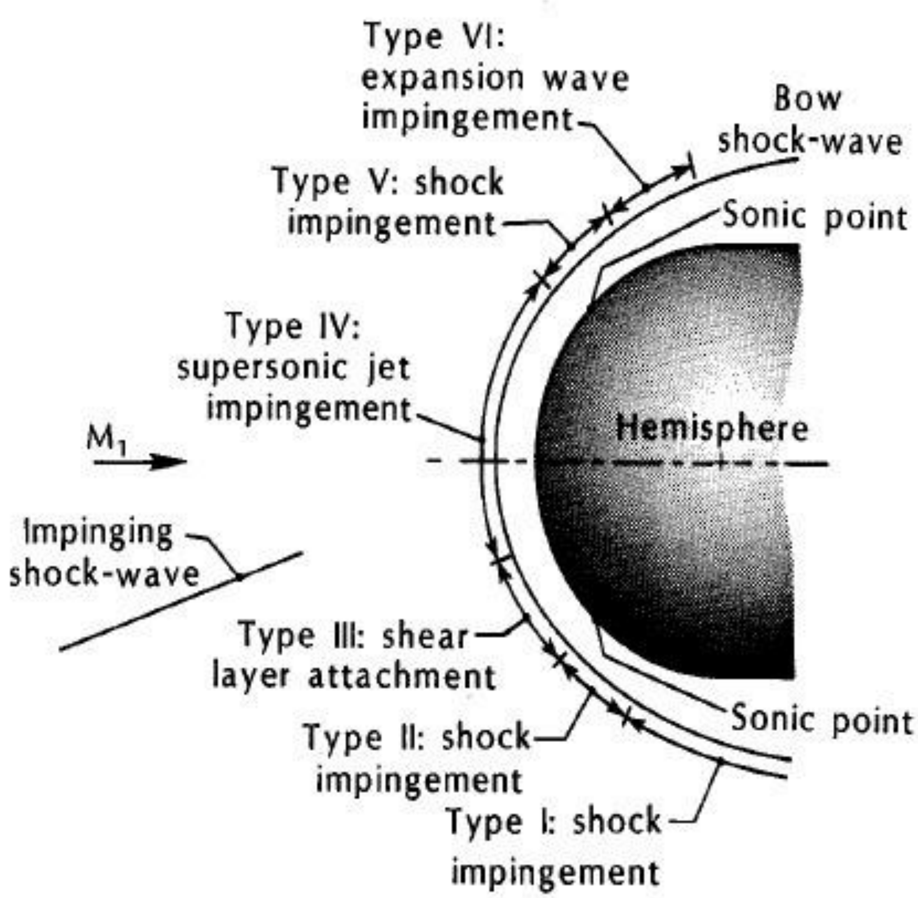
3. Edney Type Interactions

Developed by Bernard Edney, these classifications describe common SSI configurations in hypersonic flows:

- Type I: Weak interaction, with shocks merging smoothly.
- Type II: Reflection-like interaction with slight compression.
- Type III: Stronger reflection with a localized region of high
- pressure/temperature. Type IV: Severe interaction,
- producing large Mach stems and intense heating. Type V:
- Crossing shocks with minimal interaction.

Type VI: Detached shocks interacting with body-generated shocks, often near blunt bodies.

Edney’s Shock/Shock Interactions



Edney, B., “Annomalous Heat Transfer and Pressure Distributions on Blunt Bodies at Hypersonic Speeds in the Presence of an Impinging Shock,” FFA Report 115, 1968

Fatigue

Fatigue in aerospace engineering refers to the progressive and localized structural damage that

occurswhenamaterialissubjectedtorepeatedorfluctuatingstresscycles,evenifthosestressesare

well below the material's ultimate tensile strength. Fatigue can lead to sudden, catastrophic failure without significant plastic deformation or prior warning.

Aerospace engineers use fatigue design principles to ensure safe operation:
Design Strategies:

- Safe-life design: Remove part before expected fatigue failure (used in rotorcraft, some engine parts).
-
- Fail-safe design: Allow for redundancy and damage tolerance (airframe structures).
  Damage tolerance: Allows cracks to exist, but ensures they grow slowly and can be inspected.

Tools Used:

- Finite Element Analysis (FEA) with fatigue modules,
- Miner's Rule for cumulative damage estimation,
- Fracture Mechanics for crack growth prediction (Paris' Law).

Fatigue

Fatigue occurs when a material is subjected to cyclic loading—repeated application and removal of stress over time. Every time a plane takes off, lands, or encounters turbulence, its structure experiences changes in load. This repeated loading can cause microscopic cracks to form in the material. Over time, these cracks grow larger, eventually leading to failure if left unchecked. There are three main stages of fatigue:

1. Crack initiation: Tiny cracks start to form on the surface of a material, often at stress concentrators like sharp corners, holes, or surface imperfections.
2. Crack propagation: Once a crack forms, it slowly grows with each loading cycle. The rate of crack growth depends on the material, the magnitude of the stress, and the environment (e.g., corrosion).
3. Final failure: When the crack reaches a critical size, the material can no longer withstand the applied loads and suddenly fractures, leading to catastrophic failure.

In aerospace, fatigue is particularly dangerous because aircraft structures must endure millions of cycles over their operational life. Each takeoff and landing, for example, contributes to the cyclic stress on the wings and fuselage. While the stresses might be well within the material's overall strength, the repeated nature of these loads leads to fatigue failure over time.

-Peterson, Alex. Aerospace Engineering Step by Step: Fundamentals of Aircraft Design, Structures & Systems: From Theory to Practice (Step By Step Subject Guides)

Fatigue – Common Locations

Component	Reason for Fatigue Susceptibility
Wing spars and skins	Flexural loading during flight cycles
Fuselage skin near windows	Pressurization-depressurization cycles
Engine fan blades	High-frequency vibration cycles
Landing gear	High-impact, cyclical loading on takeoff/landing
Rivet holes and fasteners	Stress concentration sites

Paris' Law

Paris' Law is a widely used empirical relationship in fracture mechanics thatdescribes therate at whichafatiguecrackgrows under cyclic loading. It is a core part of damage-tolerant design and fatigue life prediction in aerospace and structural engineering.

$$\frac{da}{dN} = C\Delta K^{m}$$

Where:

$\frac{da}{dN}$:Crack growth rate per cycle (rate of increase in crack length),

a: Crack length,

N: Number of load cycles,

ΔK: Stress intensity factor range = Kmax−Kmin,

C and m: Material constants determined experimentally.

https://www.numberanalytics.com/blog/paris-law-materials-science-guide

Paris' Law

Also known as the Paris–Erdogan equation

In a 1961 paper, P. C. Paris introduced the idea that the rate of crack growth may depend on the stress intensity factor. Then in their 1963 paper, Paris and Erdogan indirectly suggested the equation with the aside remark "The authors are hesitant but cannot resist the temptation to draw the straight line slope 1/4 through the data" after reviewing data on a log-log plot of crack growth versus stress intensity range. The Paris equation was then presented with the fixed exponent of 4.

Purpose of Paris’ Law

Component	Purpose of Using Paris’ Law
Aircraft wings and fuselage	Predict crack growth due to pressurization cycles
Engine components	Monitor rotating parts for fatigue-induced cracks
Landing gear	Evaluate growth under cyclic ground loads
Spacecraft structures	Plan inspection intervals and safe mission durations

Using Paris' Law

You can integrate Paris' Law to calculate the

numberofcyclesNittakesforacracktogrow

from a0 to ac:

$$N = \int_{a_0}^{a_c} \frac{1}{C(\Delta K)^m} \, da$$

This gives a **fatigue lifeestimate** between inspectionintervals or until failure.

Miner's rule

Also known as the Palmgren-Miner rule, describes cumulative damage.

$$D = \sum_i \frac{n_i}{N_i} \leq 1$$

Where:

D: Cumulative damage,

n_i: Cycles at load level i,

Ni: Number of cycles to failure at that load,

Failure is expected when D=1

Basquin's law

Basquin’s Law is an empirical relationship that describes how thestress amplitude of a material subjected to cyclicloading relates to the number of cycles to failure in the high-cycle fatigue regime (typically N>104).

$$\sigma_a = \sigma_f'(2N)^b$$

Or alternatively:

$$\sigma_a = AN^b$$

σa: Stress amplitude (MPa),

N: Number of cycles tofailure,

σf′: Fatigue strength coefficient (material property),

b: Fatigue strength exponent (typically negative), A: Constant depending on material and conditions..

Basquin’s law and Aerospace Engineering

Component **Aircraft wings & fuselage**	Relevance of Basquin’s Law Predict fatigue life due to vibration and pressurization
Rotating shafts & turbines	Evaluate high-cycle fatigue from oscillating loads
Fasteners & joints	Estimate stress-based fatigue failure
Landing gear	High-cycle fatigue from repeated takeoff/landing

Boundary Layers

The boundary-layer concept is an excellent model for viscous effects in attached flow, but there are a variety of ways viscosity affects aerodynamics. The key viscous effect facing aerodynamicists is flow separation. Flow separation leads to additional drag on aircraft, although controlled flow separation provides a way of achieving enhanced performance in some cases. For example, the strakes on the F-16 generate vortices that enhance lift, and the leading-edge vortex on the Concorde, with the additional “vortex lift” at takeoff and landing, was responsible for making the aircraft feasible. Another important viscous effect is skin friction drag, which is a function of the boundary-layer state (laminar or turbulent) and where transition takes place. All told, viscous effects play a major role in the analysis and design of aircraft.

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

Boundary Layer Equations

The concept of a thin, viscous layer next to a body over which a fluid is flowing is due to Prandtl.1 According to Prandtl, the fluid velocity relative to the surface of the body increases from zero at the surface to its maximum value away from the surface in a thin region called the boundary layer. This concept is well established and has become a fundamental postulate of fluid dynamics. The concept has been directly confirmed by careful measurements of velocity distribution through the boundary-layer region. Indirect confirmation is provided by the excellent agreement with measurements of solutions to the boundary-layer equations—a set of differential equations derived from the more general equations of motion using the boundary-layer concept to drop certain terms from the more general equations.

-Dorrance, William H.. Viscous Hypersonic Flow: Theory of Reacting and Hypersonic Boundary Layers (Dover Books on Engineering) . Dover Publications

Laminar Flow

The computation of laminar flow is relatively straightforward when compared to turbulent flow. Since Sutherland's law relates laminar viscosity to temperature (see Equation 3.32 and Table 3.1), that relation can be used directly in the fluid equations of motion, and laminar flow predictions can be made directly. For example, the Unmanned Combat Air Vehicle (UCAV) shown in Fig. 8.5 was simulated using the Navier-Stokes equations solved with laminar viscosity only, in order to simulate results from a low-speed wind tunnel test. The details of the flowfield are apparent in the visualization, including the leading-edge vortex formation and the breakdown of the vortex at approximately 60 percent of the length of the vehicle.

Cummings, Russell M.; Mason, William H.; Morton, Scott A.; McDaniel, David R.. Applied ComputationalAerodynamics:(CambridgeAerospaceSeries) . CambridgeUniversity Press.

Laminar Flow

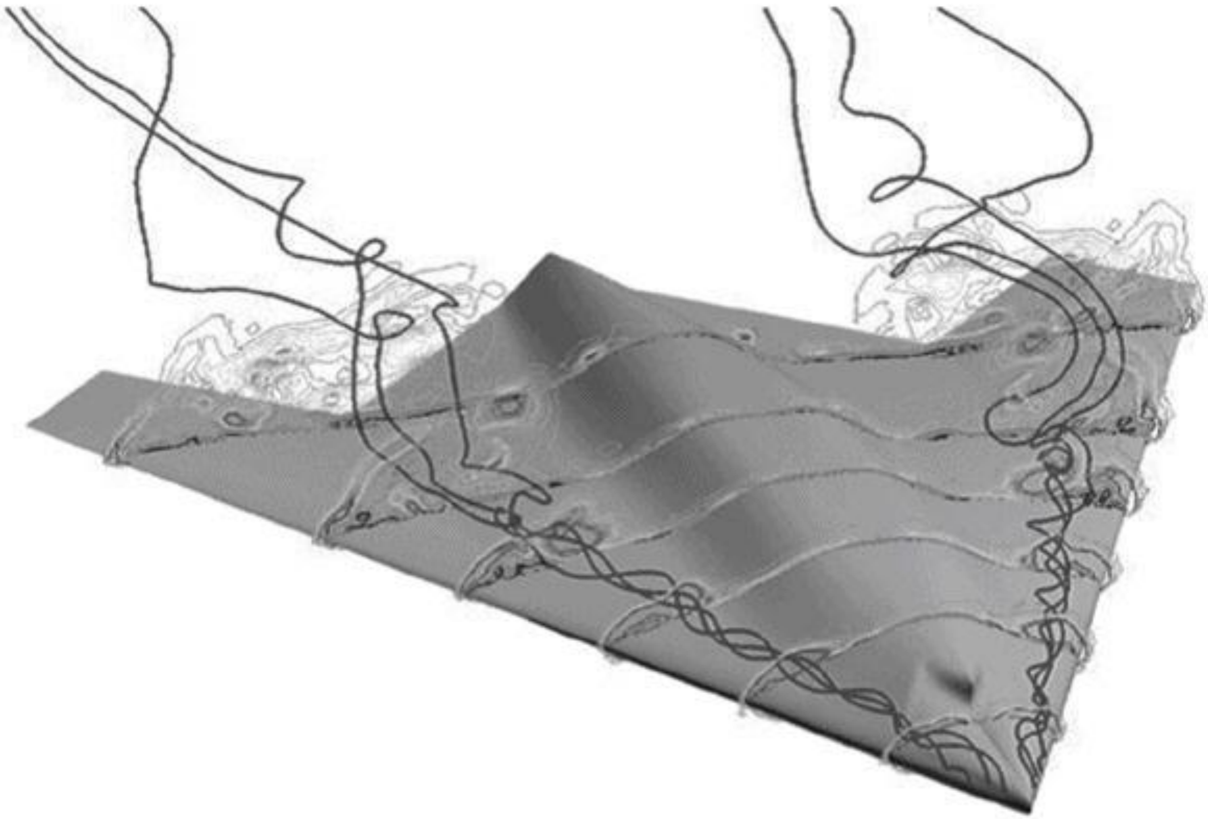


Figure 8.5 Laminar flow over a UCAV at 15-degree angle of attack showing vortical flow structures and vortex breakdown (Ref. 7; a full color version of this image is available on the website: www.cambridge.org/aerodynamics).

Cummings, Russell M.; Mason, William H.; Morton, Scott A.; McDaniel, David R.. Applied Computational Aerodynamics:(CambridgeAerospaceSeries) . CambridgeUniversityPress.

Transition

Another key aspect of computational simulation is the estimation of transition. For a low-speed flowwith nopressuregradients and relatively high freestream turbulence levels, we said in Chapter 4 that an approximate location for transition could be estimated to be where the local Reynolds number is 500,000. However, a laminar boundary layer is sensitive to a number of factors that affect the transition location. In addition to the Reynolds number and maintaining favorable pressure gradients or suction as described, the boundary layer is also affected by surface roughness.

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

Note: In the context of hypersonic flow , transition refers to the process by which the boundary layer changes from laminar to turbulent as the fluid moves along a surface (like the skin of a spacecraft or missile). This transition is a critical phenomenon that significantly influences thermal loads, skin friction, and overall aerodynamic behavior.

Transition

Transition occurs over a fairly short distance at low speeds and is often assumed to occur instantly in CFD simulations. However, at hypersonic speeds transition occurs over a significant distance, and, in fact, the uncertainty associated with transition has been a major issue in the development of hypersonic vehicles.

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

Transition

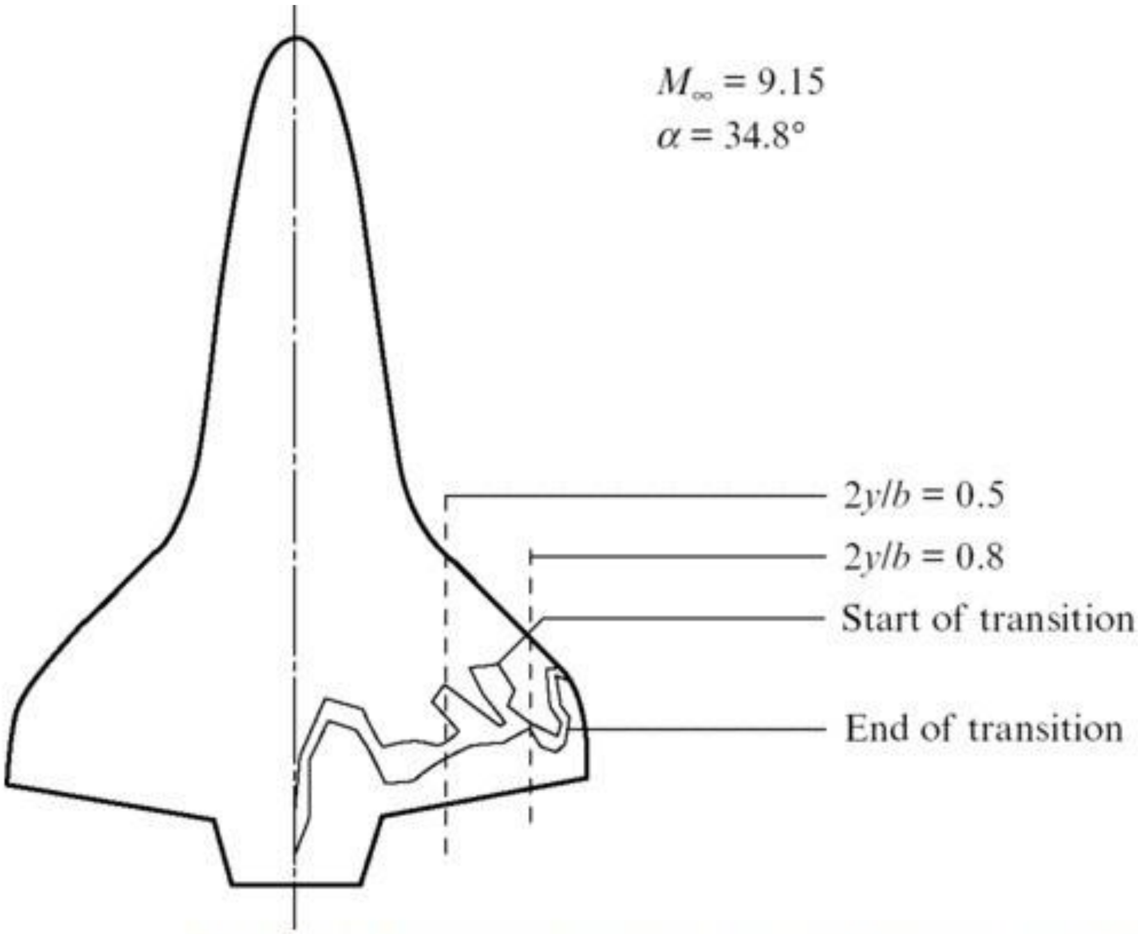


Figure 8.6 Transition location on the Space Shuttle Orbiter measured during flight (Ref. 9; reprinted by permission of the American Institute of Aeronautics and Astronautics, Inc.).

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

The Morkovin-Reshotko-Herbert “Roadmap”

he Morkovin-Reshotko-Herbert “Roadmap” refers to a conceptual framework or guidelinefor systematically studyingand modelingboundarylayertransition— the process by which a laminar (smooth) flow becomes turbulent—particularly in high-speed and hypersonic flows.

This “roadmap” was shaped by the contributions of three leading researchers:

1. Morkovin – Known for his work in high-speed and compressible flows.
2. Reshotko – Pioneered research on stability and transition, especially in supersonic/hypersonic regimes.
3. Herbert – Specialized in numerical methods for stability and transition prediction.

It has guided much of the theoretical, computational, and experimental research into boundary layer transition over decades.

The Morkovin-Reshotko-Herbert "Roadmap"

The roadmap organizes the transition process into a sequence of stages, with distinct physical mechanisms and modeling needs at each step. 1. **Receptivity**

- Describes how external disturbances (such as freestream turbulence, acoustic waves, or surface roughness) are introduced into the boundary layer. Critical in hypersonics, where even small disturbances can trigger
- early transition due to strong compressibility effects. Modeling
- approaches: Linearized Navier-Stokes, asymptotic methods.

2.Linear Stability Analysis (LSA)

- Assesses how small disturbances grow or decay under the linearized flow equations. Identifies instability modes such as:
  - First Mode (Tollmien-Schlichting waves) – Weak in hypersonics.
  - Second Mode (Mack Modes) – Dominant in hypersonic boundary layers.
- Hypersonic flows tend to favor high-frequency second-mode instabilities driven by compressibility.

3.Nonlinear Growth & Secondary Instabilities

- Beyond a certain amplitude, disturbances interact and nonlinear effects become significant. May involve secondary instability mechanisms, leading to faster breakdown to turbulence. Methods: Nonlinear Parabolized Stability Equations (NPSE), Direct Numerical Simulation (DNS).

4.Breakdown to Turbulence

- Final stage where flow becomes fully turbulent. This phase is
- highly complex and chaotic, often requiring DNS or experiments for detailed study.

The Morkovin-Reshotko-Herbert "Roadmap"

Underlying Principles

Morkovin's Hypothesis

- Suggests that many subsonic and supersonic boundary layers exhibit transition mechanisms similar to incompressible flows, once certain compressibility effects are properly scaled out.
- In hypersonic regimes, additional mechanisms (like dilatational instability) must be considered.

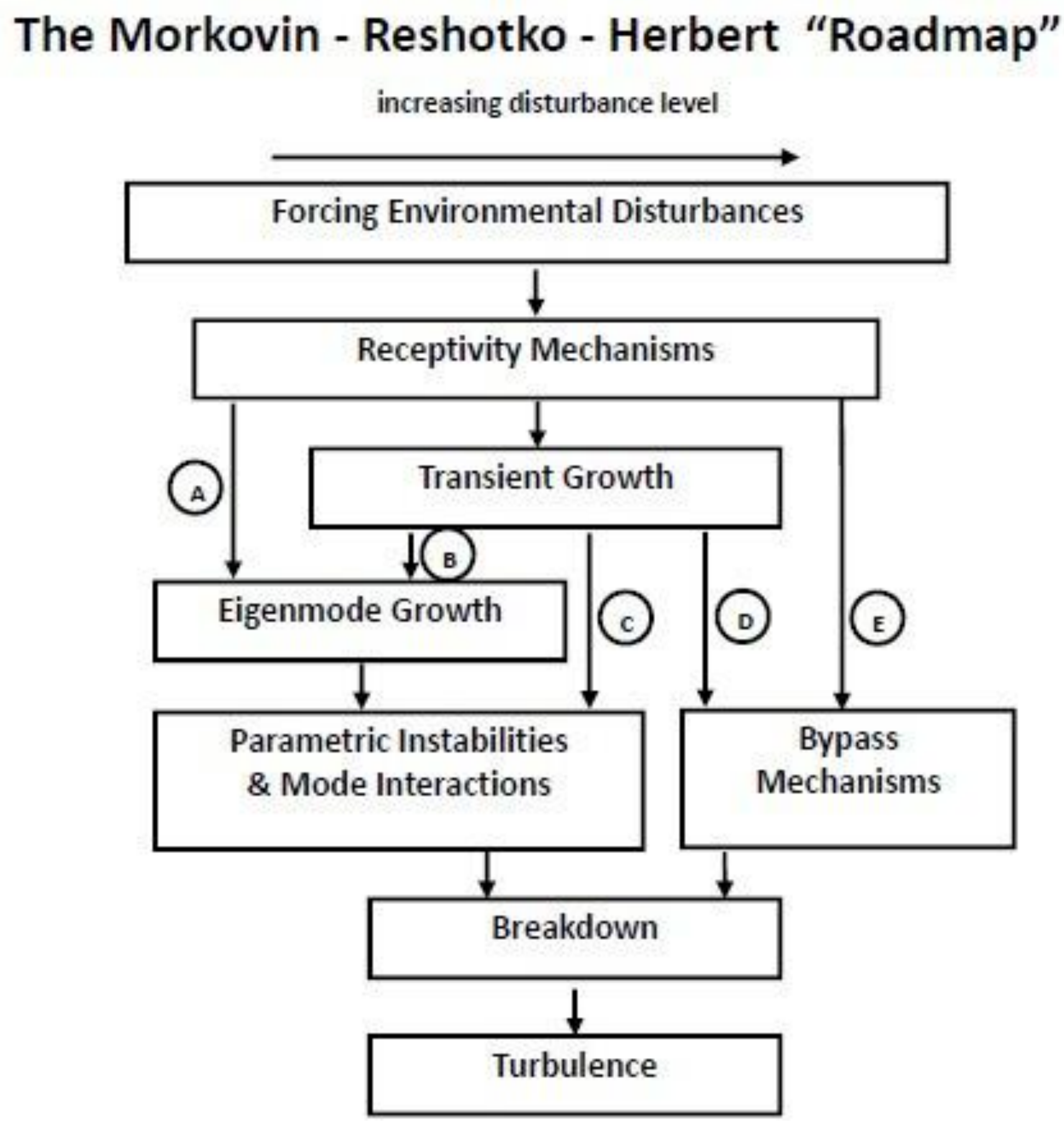
Reshotko's Work

- Focused on linear stability and receptivity, particularly emphasizing the importance of external disturbance environments and freestream turbulence.

Herbert's Contributions

- Advanced computational tools for nonlinear stability analysis.
- Developed Parabolized Stability Equations (PSE) and NPSE approaches for practical transition predictions.

Paths to Transition



Compressible Turbulence Models

Compressible turbulence models applicable to hypersonic flow regimes:

- Reynolds-Averaged Navier–Stokes (RANS) Models
- k–ω and SST (Shear Stress Transport) Models
- Reynolds Stress Models (RSM
- Large Eddy Simulation (LES) Models
- Detached Eddy Simulation (DES) and Hybrid RANS–LES Approaches
- . Direct Numerical Simulation (DNS)

Compressible Turbulence Models

Model Type	Key Feature	Hypersonic Applicability	Computational Cost
k–ε (with compressibility corrections)	Simple, empirical	Limited accuracy near shocks	Low
k–ω / SST	Good near-wall and separation modeling	Widely used in hypersonic RANS	Low–Moderate
RSM	Captures anisotropy	Accurate in shock–turbulence	High
LES (Dynamic SGS)	Resolves large eddies	Excellent fidelity	Very High
DES / DDES	Hybrid RANS–LES	Practical compromise	Moderate–High
DNS	Fully resolved	Benchmark only	Extremely High

Part II

Physical Design

Nose Cone Design

Typical Nose Cone Shapes for Hypersonic Vehicles

A. Blunt Cones

- Derived from simple cones with rounded tips to mitigate stagnation heating.
- Used for reentry vehicles and ballistic missiles. Example: Capsule-type reentry
- vehicles.

B. Spherically Blunted Cones

- Cone with a spherical nose tip, transitioning to a conical afterbody.
- Provides a good compromise between heat protection and drag.

C. Power-Law Bodies (Power Nose Cones)

- Use mathematical equations to tailor curvature for specific aerodynamic and thermal needs.

•Can be optimized for specific Mach ranges.

D. Elliptical and Ogive Shapes (Secant Ogive)

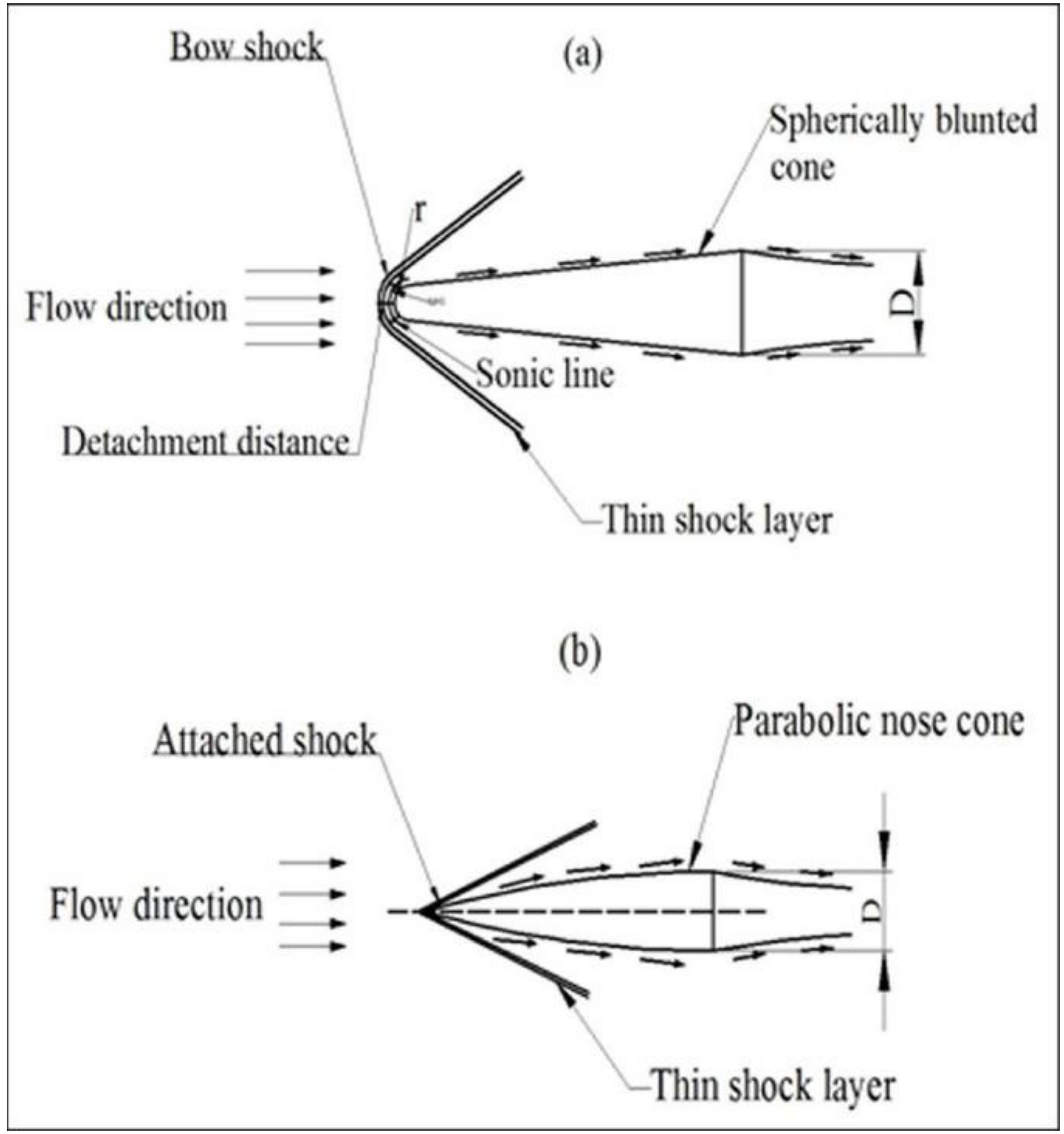
- Ogive shapes (derived from sections of circles or ellipses) allow gradual pressure gradients, reducing wave drag.
- Elliptical nose cones have higher curvature near the tip, softening shock waves.

Nose Cone Design

Nose Cone Type	Advantages	Typical Use
Blunt Cone	Lower heating at stagnation point	Reentry vehicles, warheads
Spherically Blunted Cone	Balance of heating & drag	HGVs, missile systems
Power-Law Shape	Optimized for specific performance	Hypersonic research vehicles
Ogive/Elliptical	Low drag, moderate heating	Cruise missiles, atmospheric vehicles

Dr. Chuck Easttom, M.Ed, MSDS, MBA, MSSE, Ph.D.2, D.Sc.

Nose Cone Design



Blunt Cone

A blunt cone nose cone is characterized by a rounded or flattened front (stagnation point) followed by a conical afterbody. This shape is specifically designed for hypersonic and reentry applications where aerodynamic heating is the primary concern.

Unlike sharp or ogive shapes, blunt cones intentionally produce detached bow shocks that shield the surface from extreme thermal loads. Geometric Features **A. Nose Tip** • A rounded or flat tip (typically spherical) forms the stagnation point. • Radius of curvature at the tip is a key parameter affecting heating. **B. Conical Section** • The afterbody of the cone retains a conical shape with a specific half-angle. • Common half-angles range between 10° and 30°, depending on the mission. **C. Geometric Parameters**

- Stagnation Radius (rs): Defines the bluntness at the nose tip.
- Cone Half-Angle (θ): Controls the spread of the conical section.
- Overall Length (L): From the tip to the base of the nose cone.

Blunt Cone

Blunt cones produce a detached bow shock in front of the nose.

The separation between the shock wave and the nose surface reduces heat flux directly onto the surface.

High wave drag due to the detached shock wave.

Drag increases with increasing bluntness, but heating reduction is prioritized over drag in hypersonic applications.

Blunt cones tend to have stable aerodynamic behavior during atmospheric reentry and hypersonic flight, making them favorable for controlled descent.

The detached bow shock reduces direct stagnation point heating dramatically compared to sharp or ogive shapes.

Heat loads concentrate near the stagnation region but aresignificantly reduced by the shock stand-off distance.

Blunt Cones

Application	**Purpose** Safe	**Example Vehicles**
Reentry Capsules	atmospheric reentry	Apollo, Soyuz, Orion capsules
Ballistic Missiles (RV)	High-speed reentry with warhead	Minuteman III, Trident II RVs
Hypersonic Test Vehicles	Aerothermal experiments	NASA X-38, IRVE inflatable reentry tests
Planetary Probes	Entry into planetary atmospheres	Mars Pathfinder, Galileo Jupiter Probe

Ogive and elliptical nose cones

Ogive and elliptical nose cones are among the most common aerodynamic shapes used in high-speed flight vehicles, particularly in the subsonic to supersonic range, but also adapted for certain hypersonic applications where drag and heating must be balanced. An ogive nose cone is derived from a segment of a circle (a circular arc), often used to approximate the curve of the nose cone.

These shapes are primarily designed to:

- Minimize aerodynamic drag.
- Manage shock wave behavior.
- Provide structural simplicity for manufacturing.

The ogive shape is determined by radius of the generating circle and length of the nose cone.

Common types:

- Tangent Ogive: The arc is tangent to the body cylinder, providing a smooth junction.
- Secant Ogive: The arc is not tangent, leading to a sharper or blunter transition.

Ogive and elliptical nose cones

Equation:

For a tangent ogive:

$$y(x) = \sqrt{r^2 - (x - a)^2} - (r - a)$$

Where:

r = radius of generating circle. a = distance from base to circle center. x = position along the nose cone axis.

Ogive and elliptical nose cones

Feature Shape	**Ogive Nose Cone**	**Elliptical Nose Cone** Elliptical
Drag at Supersonic	Circular arc-based	curve-based Low (in
	Low-to-moderate	subsonic to low supersonic)
Drag at Hypersonic	Moderate	Moderate-to-high (not ideal for extreme hypersonic) Higher at tip, smooth
Heating	Higher at tip, moderate elsewhere	heating gradients Moderate
Manufacturing	Simple	Reentry capsules,
Typical Use Cases	Missiles, rockets, ballistic vehicles	spaceplane noses, hypersonic cruisers

Power- law nose cones

Power-law nose cones are aerodynamic shapes generated using mathematical power-law functions. They allow precise control of nose cone profiles to optimize drag, heating, and flow behavior across a wide range of speeds, including hypersonic regimes.

These shapes are particularly effective for:

- Balancing aerodynamic drag and heating.
- Designing vehicles for long-range hypersonic flight or reentry where precise control of aerodynamic forces is required.

Power Law Nose Cone

The general form of a power-law shape is: y=k·xn

Where:

y = radius at a point along the axis.

x= axial distance from the nose tip.

k = scaling factor, typically derived from the base radius and length.

n = power-law exponent, which determines the shape's curvature.

Exponent (n): Controls the curvature.

n < 1: Blunt shapes (high stagnation radius).

n = 1: Linear (conical).

n > 1: Sharp, elongated shapes

Length (L): Length of the nose cone from tip to base.

Base Radius (R):Radius at the nose cone base

von Kármán-Haack series

The **von Kármán-Haack** series is a special case ofpower-law profilesoptimized forminimal drag: Derived from compressible flow theory.

Minimizesdrag for a given length and base diameter.

$$y = \frac{R}{\sqrt{\pi}}\sqrt{\theta - \frac{1}{2}\sin(2\theta)}$$

Where:
θ=arccos(1−2x/L) L = nose cone length. R = base radius.

Two common variants: •**LD-Haack (Length-Drag Optimized)**: Prioritizes minimum drag for a given length. •**LV-Haack (Length-Volume Optimized)**: Balances drag with internal volume

Trade-Offs

Feature	Power-Law Nose Cone	Ogive/Elliptical	Blunt Cone
Drag	Minimal	Moderate	High
Heating	Moderate-to-High (depends on tip)	Moderate	Low (with blunt tip)
Stability	High (if designed properly)	Moderate	High
Manufacturability	Moderate (depends on exponent)	Simple	Simple
Best Use	Hypersonic Glide, Missiles	Supersonic Missiles, Capsules	Reentry Capsules, Test Vehicles

Adaptive Nose Cones

Adaptive Nose Cones are advanced aerodynamic structures designed to change their shape or properties during flight to optimize:

- Aerodynamic performance.
- Thermal protection.
- Stability and control.

They are also referred to as:

- Morphing Nose Cones.
- Shape-Adaptive Nose Tips.
- Smart Nose Cones (when integrated with active sensing and control).

This technology is inspired by the need to adapt to varying flight conditions, such as:

- Atmospheric density changes during ascent and reentry.
- Variable Mach number regimes (e.g., subsonic, supersonic, hypersonic).
- Maneuverability in hypersonic glide vehicles (HGVs).

Adaptive Nose Cones

The nose cone can dynamically alter its external geometry to suit flight conditions. This may involve:

- Changing nose cone length or bluntness.
- • Adjusting surface curvature. Deploying or retracting appendages.

How? A. Smart Materials • Shape Memory Alloys (SMAs): Change shape under temperature or electrical stimuli. • Piezoelectric Actuators: Enable precise small- scale deformations using electric fields. • Elastomers and Polymers: Allow soft-body deformations under pressure.

B. Mechanical Actuation • Miniaturized mechanical actuators or linkages for larger deformations. • Hydraulic or pneumatic systems for bluntness adjustments. C. Thermal Control Coatings • Phase-change materials that modify surface properties as heating changes.

Objective Drag	**Adaptive Functionality** Sharpen or
Reduction	streamline nose during cruise phases.
Thermal Protection	Blunt nose during high heating to reduce heat flux.
Stability Optimization	Adjust shape to counteract aerodynamic instabilities.
Control Authority	Modify shock wave position for directional control.

Morphing Structures Resources

Morphing Aircraft Systems: Historical Perspectives and Future Challenges
https://arc.aiaa.org/doi/abs/10.2514/1.C031456?journalCode=ja

---

MORPHING AIRCRAFT STRUCTURES: RESEARCH IN AFRL/RB
https://apps.dtic.mil/sti/tr/pdf/ADA487327.pdf

Design and analysis of biomimetic nose cone for morphing of aerospace vehicle

https://link.springer.com/article/10.1016/S1672-6529(16)60400-6

Design and performance analysis of morphing nose cone driven by a novel bionic parallel mechanism for aerospace vehicle

https://www.sciencedirect.com/science/article/abs/pii/S1270963823002626

U.S. Unveils 'MUTANT' Missiles That Morph In the Air
https://www.vice.com/en/article/us-unveils-mutant-missiles-that-morph-in-the-air/

Materials Science- Tungsten

Tungsten (W) is a common material in the design and construction of hypersonic vehicles, especially for components that face extreme thermal and mechanical stresses.

Property **Melting**	Value/Description ~3422°C (6192°F) –
Point Thermal	highest of all metals ~170 W/m·K –
Conductivity	excellent heat dissipation
Density	19.3 g/cm³ – very high, can act as a heat sink or ballast
Mechanical Strength	Retains strength at temperatures above 2000°C
Creep Resistance	Superior performance under sustained high temperatures
Oxidation Resistance	Poor without coatings – oxidizes rapidly above 400°C in air

Materials Science- Tungsten

- There are also tungsten alloys

Material	Purpose Improves ductility and creep
W–Re (Tungsten–Rhenium)	resistance Enhanced thermal conductivity,
W–Cu (Tungsten–Copper)	machinability Under research for
Tungsten CMCs	combining W with ceramic matrices to reduce brittleness

Materials Science- Inconel

- Inconel is a nickel-chromium-based superalloy often utilized in extreme environments where components are subjected to high temperature, pressure or mechanical load. The name Inconel is a registered trademark of Special Metals Corporation out of New Hartford, New York
- Since Inconel is a group of superalloys and not just one type of superalloy, its chemical composition varies across the different alloy types. However, all alloys in the Inconel family are nickel-based. Additionally, chromium is typically the second most abundant element in the chemical makeup of Inconel. Virtually every Inconel has some amount of iron in its composition, almost always greater than 1%. Other elements that are found in some Inconel alloys include:
  - Cobalt
  - Molybdenum
  - Niobium
  - Titanium

Materials Science- Inconel

The original Inconel alloy was coded 600 and consists of >72% nickel, 14–17% chromium, 6–10% iron, and ~1% manganese, plus traces of copper, silicon, carbon, and sulfur. All of the Inconel alloys are of high strength. Inconel 718, one of the higher- strength superalloys, delivers around 1,375 Mpa (Mega Pascals) of tensile strength and yield strength of around 1,100 MPa. Precipitation-hardened stainless steels can achieve tensile strengths of 850 MPa to 1,700 MPa and yield strengths of 520 MPa to over 1,500 MPa. However, precipitation-hardened stainless steels degrade fairly rapidly in strength above 650 °C, whereas Inconel 718 generally maintains its strength to over 1,000 °C.

- Inconel 600: General-purpose alloy with good resistance to heat and corrosion. Common in chemical industries.
- Inconel 625: Excellent fatigue and corrosion resistance; used in aerospace and marine industries.
- Inconel 718: Precipitation-hardenable for high strength; widely used in aerospace, especially in turbine blades and rocket motors.
- Inconel X-750: Suitable for high-temperature springs and gas turbines.

Materials Science- Ceramics

Composition: Carbides, borides, and nitrides of early transition metals. Common Examples:

- ZrB_2 (Zirconium diboride)
- HfB_2 (Hafnium diboride)
- TaC (Tantalum carbide)
- Melting Points: Often above 3000°C (5432°F).

Uses: Nose tips, wing leading edges, control surfaces where thermal loads peak.

Materials Science- Ceramic Composite Matrices

Structure: Ceramic fibers embedded in a ceramic matrix (e.g., SiC-SiC, C-SiC). Advantages: •Improved fracture toughness • Lightweight •Better damage tolerance than monolithic ceramics Common CMCs: •Silicon Carbide–Silicon Carbide (SiC–SiC) •Carbon–Silicon Carbide (C–SiC) Uses: Control surfaces, propulsion components, and structural parts under extreme loads.

Silicon Nitride

- Silicon Nitride (Si_3N_4) is a high-performance ceramic material known for its exceptional combination of mechanical strength, thermal resistance, wear resistance, and chemical stability. It is widely used in applications where traditional metals or other ceramics would fail under stress, high temperature, or corrosive environments.

- Chemical Formula: Si_3N_4

- Crystal Structure: Exists in multiple polymorphic forms:

- α-Si_3N_4: Fine-grained, metastable, transforms to β-phase at high temps.

- β-Si_3N_4: Elongated grains, tougher and more thermally stable.

- Bonding: Strong Si–N covalent bonds, giving it high strength and stability.

Silicon Nitride

Property **Density Hardness**	Value / Behavior ~3.2 g/cm³ ~15 GPa
Flexural Strength	(Vickers) 600–1,000 MPa 6–10
Fracture Toughness	MPa·√m (very high for ceramics)
Thermal Conductivity Coefficient	
of Thermal Expansion	
Maximum Use Temperature	10–90 W/m·K (moderate; varieswith microstructure)
Corrosion Resistance **Electrical Conductivity**	Very low (~3 × 10^{-6} /°C)
	~1,300–1,600°C in air
	Excellent in most acids and bases
	Electrically insulating

Materials Science- Reinforced Carbon-Carbon (RCC)

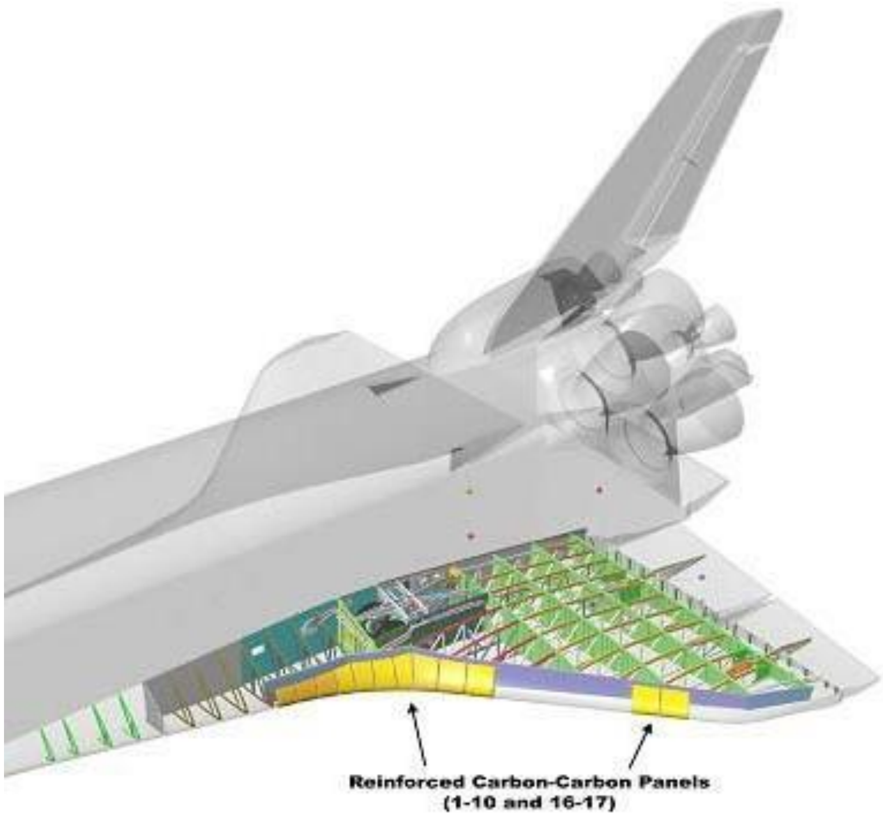
Composition: Carbon fiber reinforced carbon matrix.
Characteristics:

- Extremely high-temperature resistance (up to 3000°C)
- Low density Historical Use: Used on the
- Space Shuttle's

leading edges and nose cone.

- Challenges: Oxidation at high temperatures requires protective coatings. RCC is made by reinforcing a carbon-carbon composite with carbon fiber. Here's a breakdown of its structure: •Matrix Material: Carbon (derived from a polymer resin that is carbonized)

- Reinforcement: Carbon fibers woven into 2D or 3D fabrics
- Coating: Typically includes a silicon-carbide layer to protect against oxidation



Materials Science Carbon-Carbon

- Scalable Composite Robotic Additive Manufacturing Carbon/Carbon (SCRAM C/C) is an industrial robotic 3D printer with the ability to layer continuous fiber-reinforced thermoplastics into components that meet the unique demands of hypersonic vehicle.

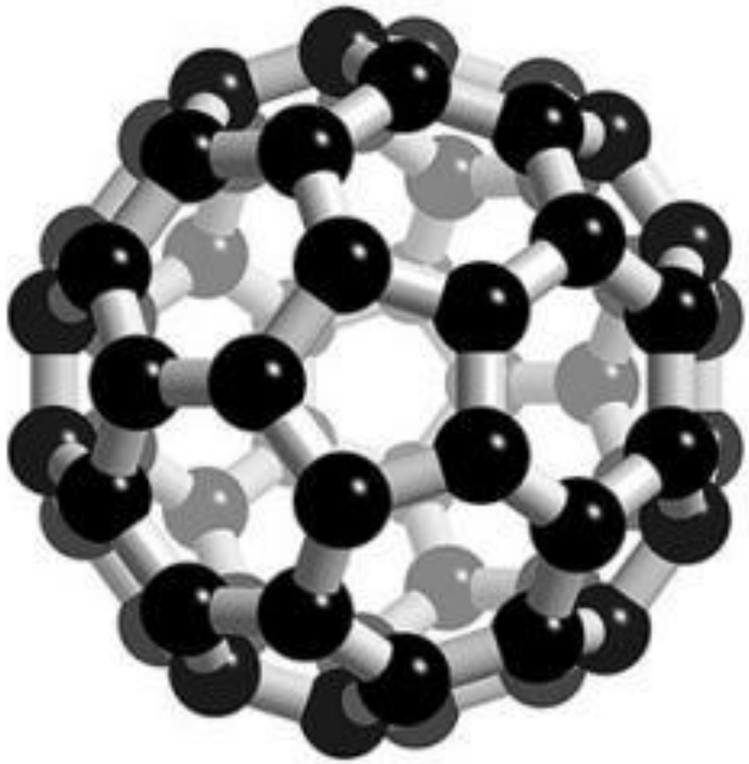
- https://www.northropgrumman.com/what-we-do/advanced-weapons/hypersonics/scram-c-c
- https://news.northropgrumman.com/hypersonics/northrop-grumman-reduces-manufacturing-time-and-cost-by-accelerating-development-of-high-temperature-materials

Materials Science- Carbon Nanotechnology

Carbon nanotechnology, particularly materials such as carbon nanotubes (CNTs), graphene, and carbon-based composites, is at the cutting edge of hypersonic vehicle design. These advanced materials offer unprecedented combinations of strength, thermal resistance, low density, and multifunctionality, making them extremely attractive for overcoming the extreme demands of flight above Mach 5.

Carbon nanotechnology

The C60 molecule was first discovered in 1985 by Robert Curl, Harold Kroto, and Richard Smally. They used lasers to recreate stellar nucleation events. The researchers accidentally discovered C60 closed cages in the soot from using lasers on graphite. These structures are often referred to colloquially as Bucky-balls, named after Buckminster Fullerene, who was an architect who had designed similar structures in buildings. Sir Harry Kroto was awarded the Nobel Prize in Chemistry for his methodology for engineering fullerenes. An example of a Bucky-ball is shown here:

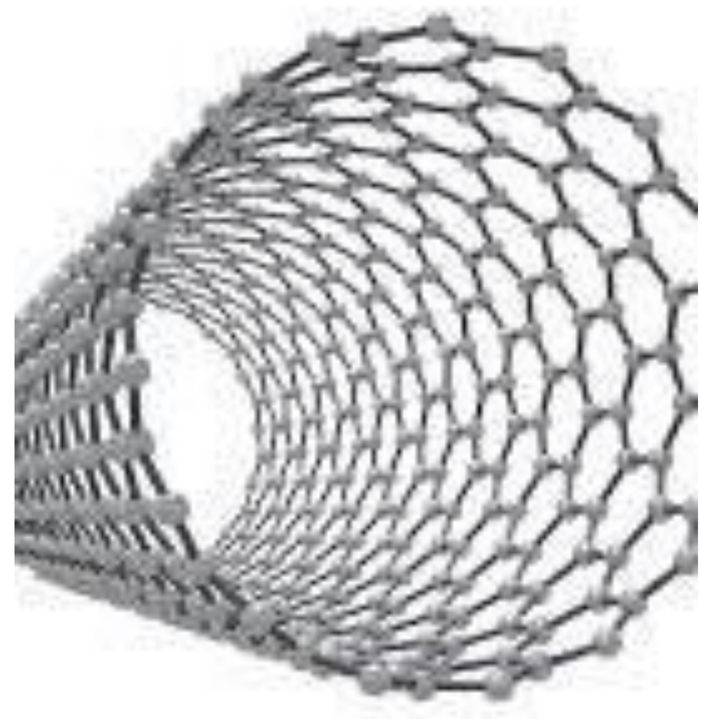


Materials Science- Carbon Nanotechnology

•

Carbon Nanotubes (CNTs)

- **Structure**: Cylindricaltubes of rolled graphene sheets, with single-walled (SWCNT) and multi-walled (MWCNT) forms.
- **Properties**:
  - **Tensile strength**: Up to 100× that of steel by weight.
  - **Thermal conductivity**: ~3500 W/m·K (along the tube axis).
  - **Melting point**:Theoretically above 3500°C.
  - **Low density**: ~1.3–1.4 g/cm³.



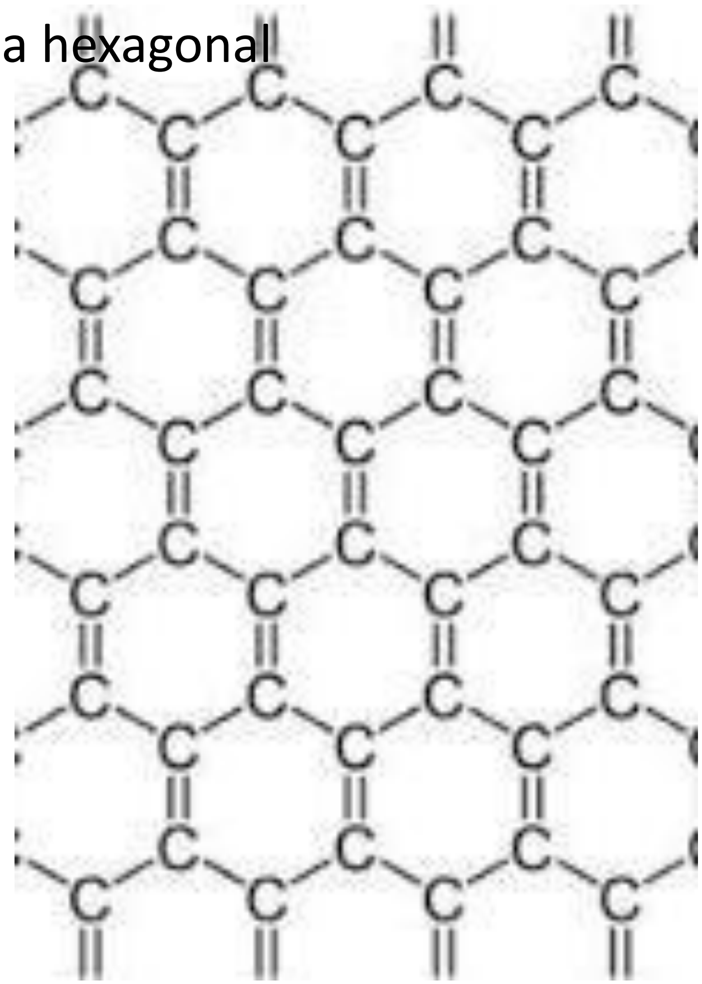
Materials Science- Carbon Nanotechnology

Graphene

•**Structure**: Single layer of carbon atoms arranged in a hexagonal lattice.

• **Properties**:

- •Strongest known material (130 GPa tensile strength).
- •High thermal and electrical conductivity.
- •Excellent thermal stability and radiation shielding properties.



Materials Science- Graphene

Property	Value
Young's Modulus	~1.0 TPa
Tensile Strength	~130 GPa
Fracture Toughness	Very high for a 2D material, though brittle in bulk
Flexibility	Extremely high — can be bent up to 20% strain without breaking

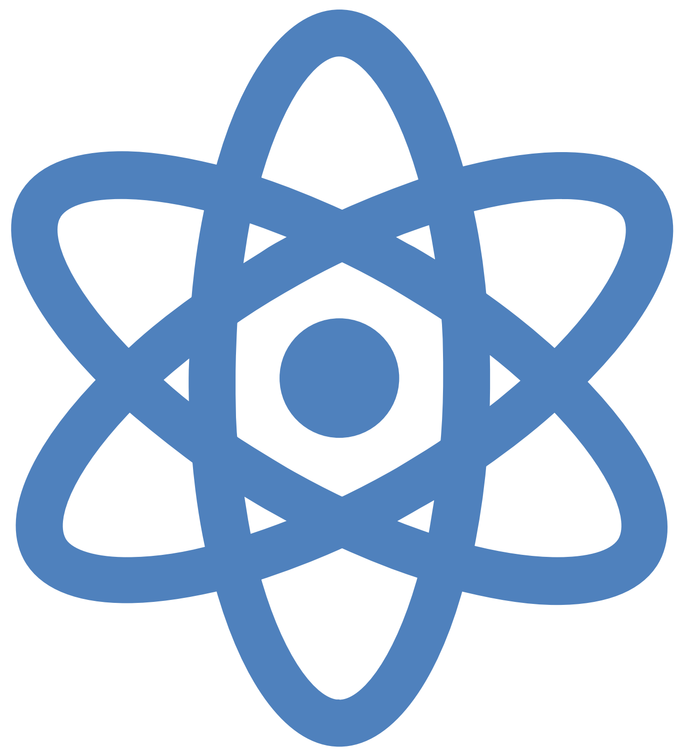
Gigapascals (GPa) and Bars (BPa): These are units that represent higher values of tensile strength. 1 GPa is equivalent to 1 billion pascals, and 1 BPa is equivalent to 1 bar. These units are used for materials with exceptionally high tensile strength.

Hairy nanoparticles

Researchers at Wright-Patterson Air Force Base are seeking to patent a novel process for manufacturing a type of material called preceramic polymer-grafted nanoparticles, or “hairy nanoparticles” (HNP). An HNP is a hybrid material consisting of a polymer shell bound to a solid nanoparticle core. The polymer - a chain of repeating molecules – forms the “hair” around the nanoparticle, which is roughly the size of a small virus. Although HNPs have been around for many years, what makes this one different is the type of polymer being attached to the core particle. It is a pre-ceramic polymer, a special class of polymer used in the formation of high performance ceramic fibers and composites. This silicon and carbon chemistry allows the polymer to convert to a silicon carbide ceramic when heated to high temperatures. The HNPs that result from this special process will be used in the manufacture of aircraft parts made of ceramic composite material. “Ceramic composites are used for high-temperature US Air Force applications that benefit from materials that are lower in density than metals, including jet engine and hypersonic vehicle components,” said Dickerson. “The HNPs we synthesized are envisioned for those type of applications.” https://www.afrl.af.mil/News/Article-Display/Article/2338581/hybrid-nanomaterials-hold-promise-for-improved-ceramic-composites/

Hairy nanoparticles

Hairy nanoparticles are a class of nanomaterialswhere a solid nanoparticle core (inorganic or organic) is covered with a dense layer of polymer chains or biomolecules, often referred to as "hairs." These polymer chains are either grafted or adsorbed onto the nanoparticle surface, giving it a "brush-like" structure.



Materials Science- Graphene Variations

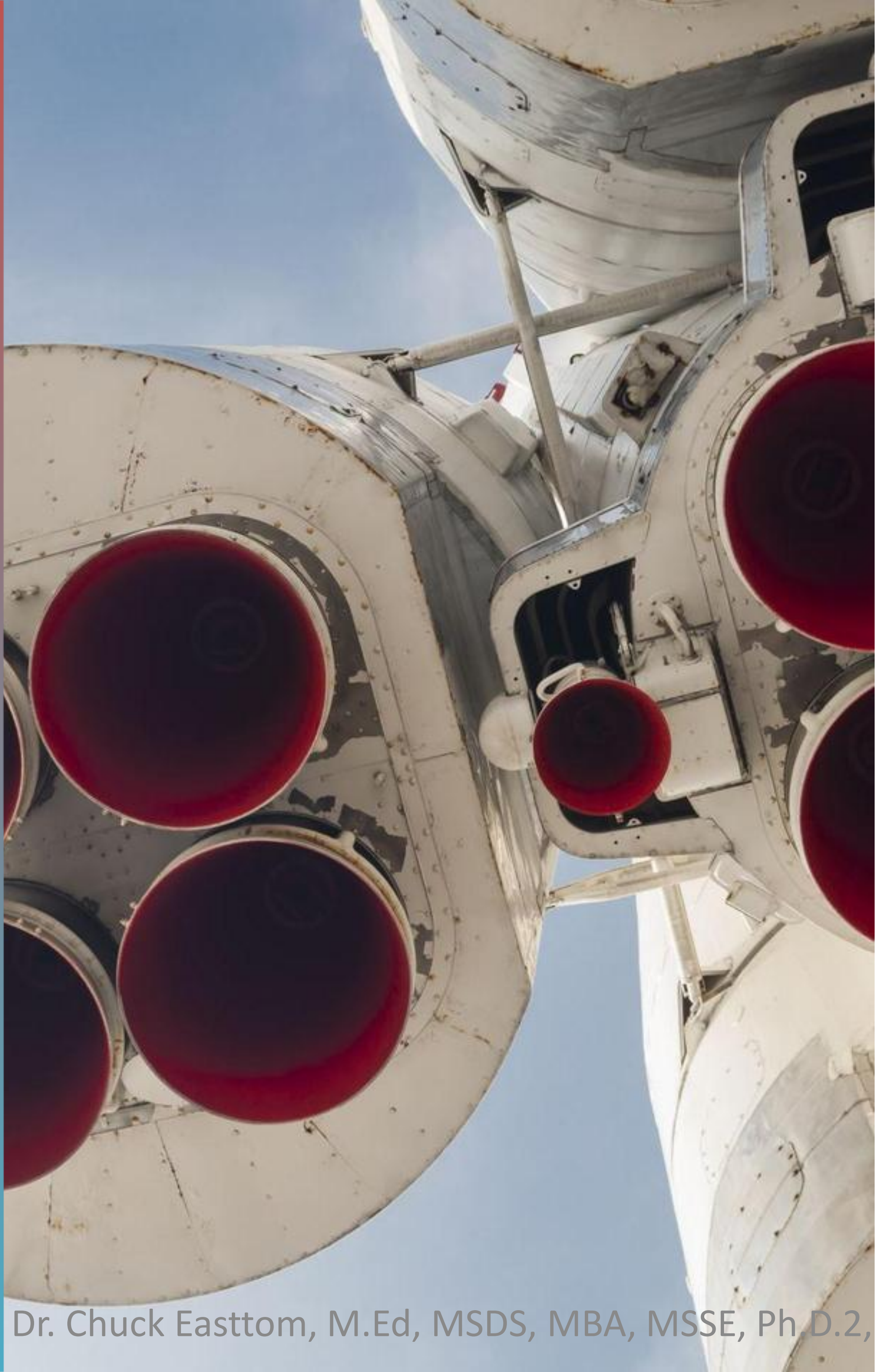
Variant **Monolayer**	Description Single atomic layer, highest
Graphene	performance 2–10 layers, more stable but
Few-Layer Graphene (FLG)	lower performance
Graphene Oxide (GO)	Graphene with oxygen-containing groups; dispersible in water, used in composites
Reduced Graphene Oxide (rGO)	Partially restored conductivity from GO
Graphene Nanoplatelets (GNPs)	Short stacks (~10 nm thick), used in bulk composites
CVD Graphene	Large-area, high-quality monolayer grown by Chemical Vapor Deposition
Exfoliated Graphene	Produced via mechanical/chemical exfoliation from graphite

SiO2 aerogels

SiO2 aerogels are a highly popular choice for thermal insulation due to theirexceptionalporosity and lowspecific gravity.However, at temperatures exceeding700 °C, their internal bonds weaken, making reinforcement essential. Reinforcing SiO2 insulations with polymeric or fiber composites is a common industrial practice.

A research study by Han *et al*. explored the use of 3D network modifier dimethyl-dimethoxy silane to reinforce SiO2-based aerogel via a sol-gel process. This modification increased the pore volume by 100 % and reduced thermal conductivity from 0.3013 Wm−1K−1 to 0.02332 $Wm^{-1}K^{-1}$. Duringhigh-temperature testingover extendedperiods, the aerogel maintained its structural integrity at temperatures over 1000 °C,3 making it suitable for aerospace systems.

- https://www.azonano.com/article.aspx?ArticleID=6850



Al2O3 Aerogels

Al_2O_3 aerogelsareamongthe most important insulation materialsfor supersonic and hypersonic aerospace vehicles due to their excellent thermal stability. Recently, researchers from China have developed an elastic aerogel with superior

insulating properties by combining Al2O3 nano-rods with graphene sheets. This modern aerogel

not only possesses improved thermal properties but also overcomes the brittleness typically

observed in conventional Al2O3 aerogels. During experimental testing, these aerogels

demonstrated ultra-low thermal conductivity values of0.0196 Wm−1K−1 at 25 °C and 0.0702

Wm−1K−1 at 100 °C.4 Al2O3 lightweight aerogels are, therefore, the preferred insulating material

for high-speed aerospace systems. https://www.azonano.com/article.aspx?ArticleI

D=6850

MXenes

Mxenes (pronounced "max-enes“) are a family of two-dimensional (2D) transition metal carbides, nitrides, or carbonitrides with exceptional mechanical, thermal, and electronic properties. They were first discovered in 2011. “Normally after we make MXenes, we have them suspended as single flakes in water,” Wyatt said. “We discovered that adding simple table salt (sodium chloride) can cause single sodium atoms to go into those defective holes. As a result, the alkali cations are capable of stabilizing the 2D material, even at 1,600 degrees Fahrenheit. It’s those high temperatures which MXenes can operate in that caught the attention of the Office of Naval Research (ONR), who are working on developing next-generation hypersonic vehicles. At high speeds, the compression of air creates tremendous amounts of heat and pressure on the surface of a hypersonic vehicle, which requires advances in material science to properly manage. While Anasori’s work is still at the fundamental scientific stage, he can envision a future where a thin coating of MXenes can be sprayed on to existing materials like a paint, making those materials incredibly resistant to heat and oxidation.” • https://engineering.purdue.edu/ME/News/2024/protecting-hypersonic-vehicles-with-nanomaterials

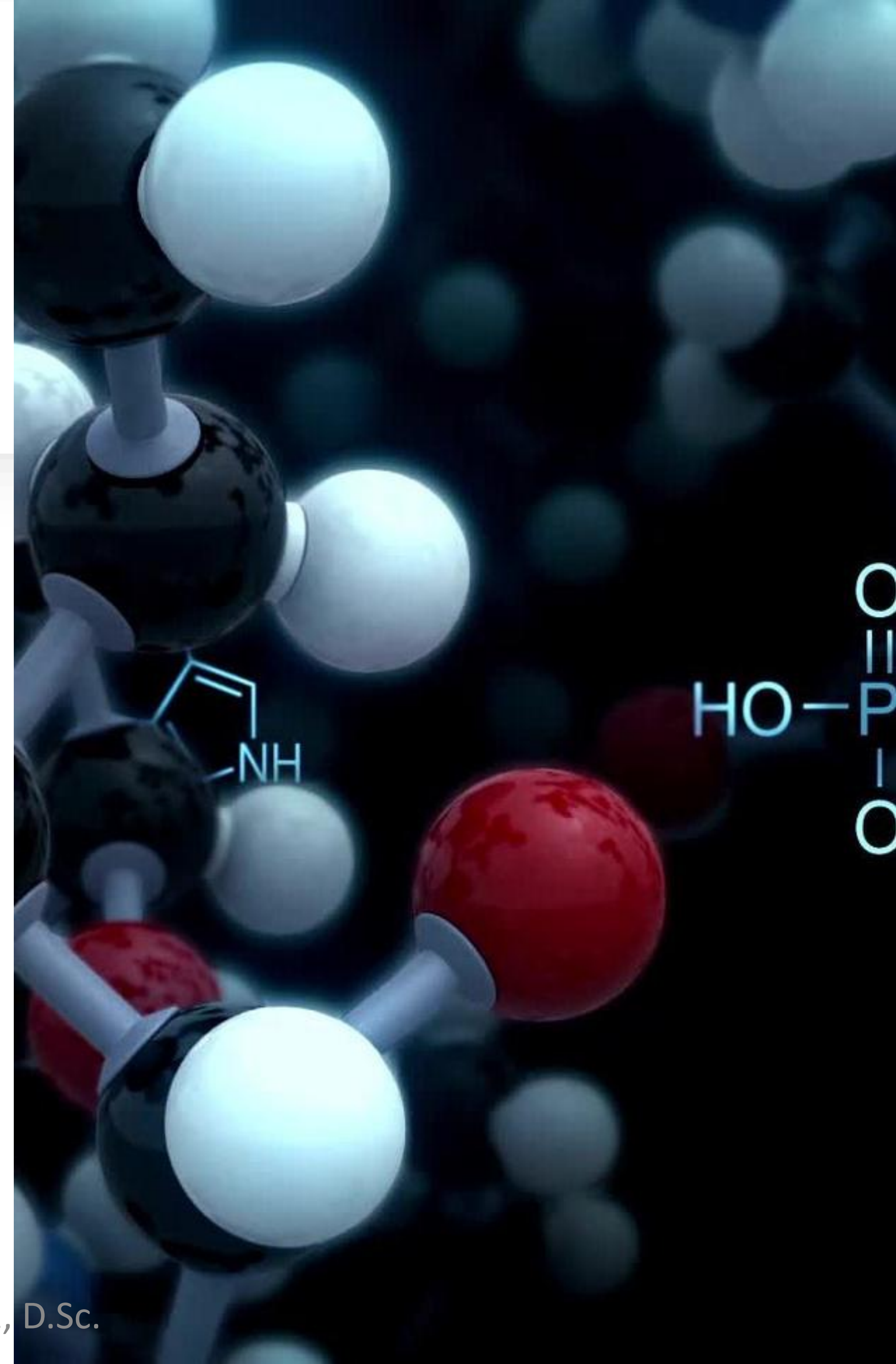
MXenes

MXenes are a family of two-dimensional (2D) inorganic compounds with the general formula of $M_{n+1}X_nT_x$, where M is an early transition metal, X is carbon and/or nitrogen, and T is a functional group on the surface of a MXene (typically O, OH and F)

MXenes have the high metallic conductivity of transition metal carbides, and are (unlike other 2D materials like graphene) hydrophilic because of their hydroxyl- and oxygen-terminated surfaces.

Due to their hydrophilicity, MXenes can be processed in aqueous and polar organic solvents to form stable colloidal solutions that can be filtered to form freestanding films and spray-coated to form transparent conductive coatings. This provides a greater of potential applications for this family of materials. The first MXene discovered was Ti_3C_2 and it was initially investigated for its electrochemical properties in batteries and supercapacitors (B. Anasori, et al. *Nature Reviews Materials*, 2017, **2**, 16098). In the past several years, however, over two dozen MXenes have been discovered along with dozens of other applications.

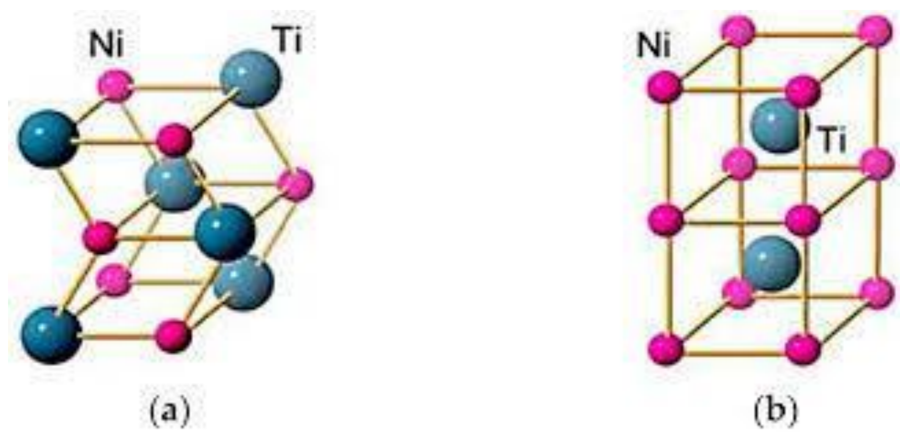
-https://drexel.edu/engineering/research-design/centers-institutes-labs/drexel-nanomaterials-institute/research/mxenes/



Shape Memory Alloy

Shape memory alloy (SMA) is a functional metal with unique properties that allow it to be trained to move on its own. SMAs can go through solid-state phase transformations, meaning they can be stretched, bent, heated, and cooled and still remember its original shape. This quality introduces opportunities for a variety of applications. The following are a few examples of NASA shape memory materials technologies that are ready to be licensed.

Austenite is the high-temperature phase, while martensite is the low-temperature phase, and these phases can be interconverted through temperature changes or mechanical stress.



- https://technology.nasa.gov/Shape%20Memory%20Materials%20Open%20Doors%20for%20Smart%20Tech

Shape Memory Alloy

- Shape memory alloys display two distinct crystal structures or phases. Temperature and internal stresses (which play a part in super-elasticity) determine the phase that the SMA will be at. The most common memory metal is called NiTinol, consisting of equal parts of nickel and titanium.

- https://depts.washington.edu/matseed/mse_resources/Webpage/Memory%20metals/how_shape_memory_alloys_work.htm

Alloys having a shape memory effect

Alloys	Composition Atomic or Weight Percent	Transformation Temperature Range (Celsius)
Ag - Cd	44/49 at.%	-190 to -50
Au - Cd	46.5/50 at.%	30 to 100
Cu - Al - Ni	14/14.5 wt% 3/4.5 wt%	-140 to 100
Cu - Sn	approx. 15 at%	-120 to 30
Cu - Zn	38.5/41.5 wt%	-180 to -10
Cu - Zn - (Si,Sn,Al)	a few wt.% of (Si, Sn,Al)	-180 to 200
In - Ti	18/23 at%	60 to 100
Ni - Al	36/38 at%	-180 to 100
Ni - Ti	49/51 at%	-50 to 110
Fe - Pt	approx. 25 at% Pt	approx. -130
Mn - Cu	5/35 at% Cu	-250 to 180

Shape Memory Alloy

In order to have the shape-memory function, the part must be shape set. The part is held in a mold under pressure while it is heat- treated at 500 degrees Celsius and then fast-cooled. Then, if the piece is later twisted or deformed below its transformation temperature, it will return to its remembered shape after it reaches the transformation temperature during reheating.

- https://www.asme.org/topics-resources/content/metal-that-remembers-its-shape