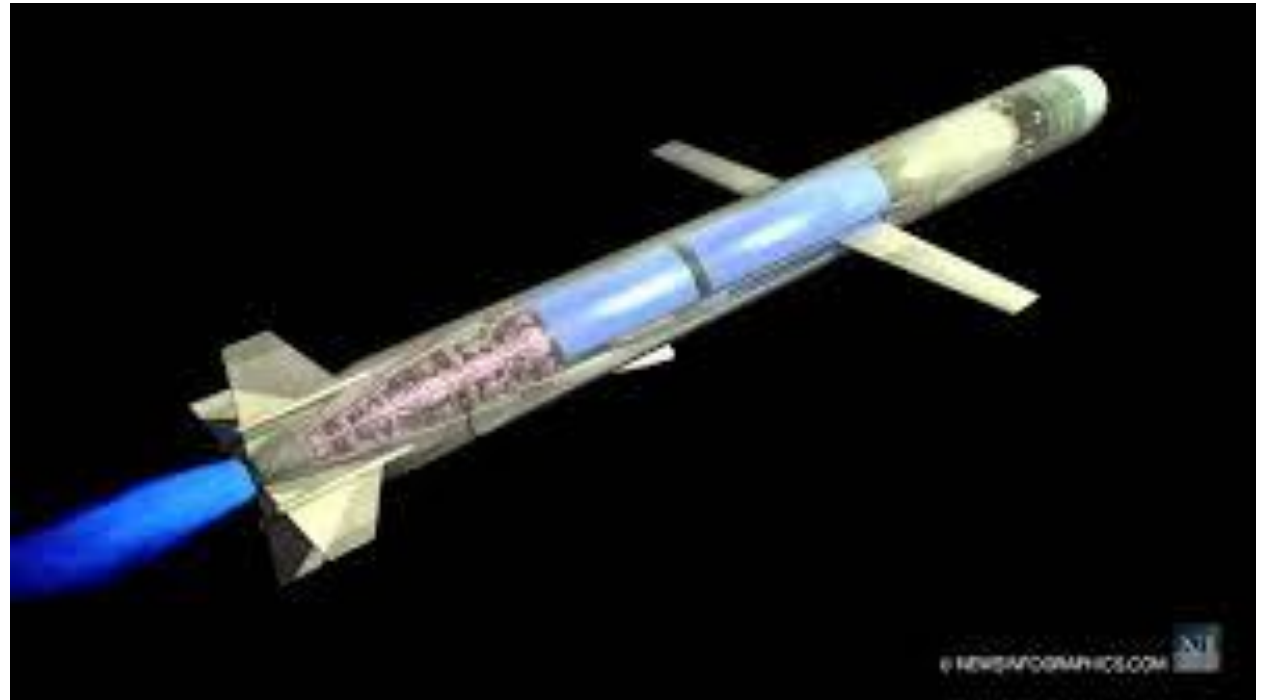
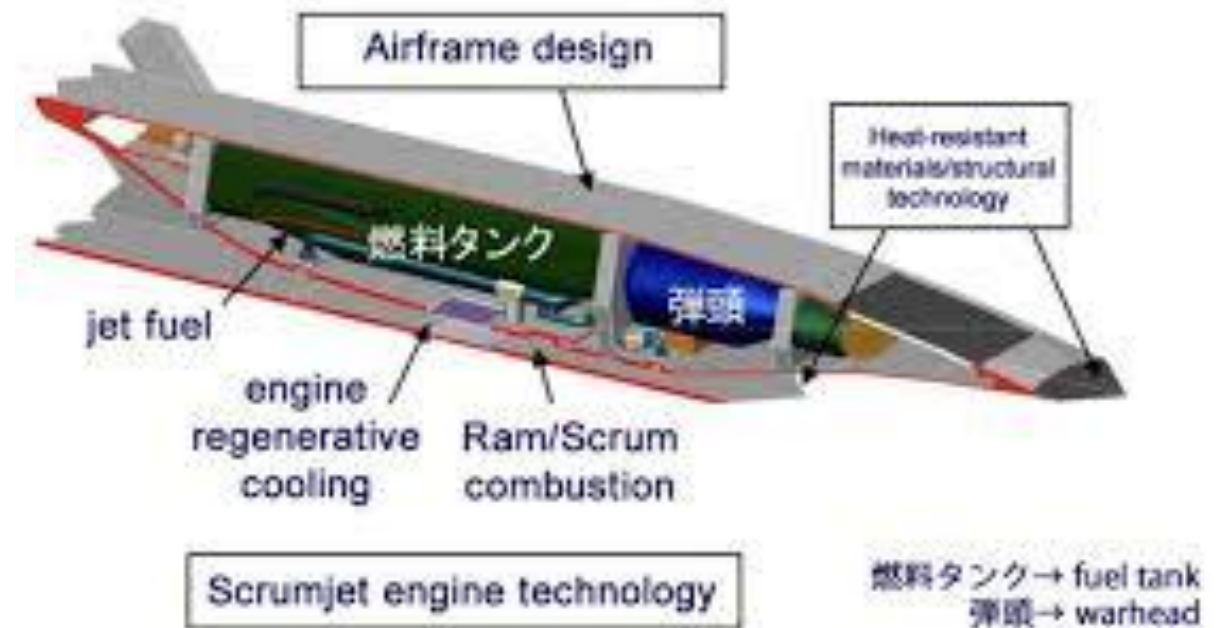


Hypersonic Missile Design



Focus of this lesson

While much of this could be applied to non-hypersonic missiles, our focus is on hypersonic missiles.



Terms

- **α (alpha)** refers to the angle of attack (AoA).
- **The dielectric constant** (also called the relative permittivity, symbol ϵ_r) is a material property that measures how well a substance can store electrical energy in an electric field compared to a vacuum.
- Transverse strength refers to the ability of a material or structural component to resist stresses and loads applied perpendicular (transverse) to its primary orientation or grain/fiber direction.
- **Isp**: Specific impulse (Isp) is the thrust produced per unit of propellant flow rate.
- **observable** refers to a measurable quantity or parameter that provides information about the performance, health, or state of the engine during testing or operation. Examples:
 - Chamber Pressure (P_c) – Indicates combustion stability and performance.
 - Thrust – Measured with load cells to verify performance.
 - Mass Flow Rates – Of fuel and oxidizer, from flow meters or turbopump sensors.
 - Temperatures – In turbopumps, injector face, nozzle walls, cooling jackets.
 - Vibrations/Acoustics – Microphones and accelerometers pick up combustion instabilities.
 - Exhaust Plume Characteristics – Infrared/optical imaging or spectroscopy can detect mixture ratio shifts, incomplete combustion, or contaminants.
 - Injector Pressure Drops – Helps monitor propellant distribution.

Terms

- **IR**

- Near-IR (NIR): $\sim 0.7\text{--}1.4\ \mu\text{m}$
- Short-Wave IR (SWIR): $\sim 1.4\text{--}3\ \mu\text{m}$
- Mid-Wave IR (MWIR): $\sim 3\text{--}5\ \mu\text{m}$
- Long-Wave IR (LWIR): $\sim 8\text{--}12\ \mu\text{m}$
- Far-IR: $>12\ \mu\text{m}$

- **Radome:** A radome (short for *radar dome*) is a protective structure that covers a radar antenna or other sensitive radio-frequency equipment, shielding it from the external environment without interfering with the transmission or reception of electromagnetic signals

- **Pultrusion** is a manufacturing process used to make strong, lightweight, continuous fiber-reinforced composite materials—commonly used in aerospace, automotive, civil engineering, and other industries where high strength-to-weight ratio is critical.

Transverse strength refers to the ability of a material or structural component to resist stresses and loads applied perpendicular (transverse) to its primary orientation or grain/fiber direction.

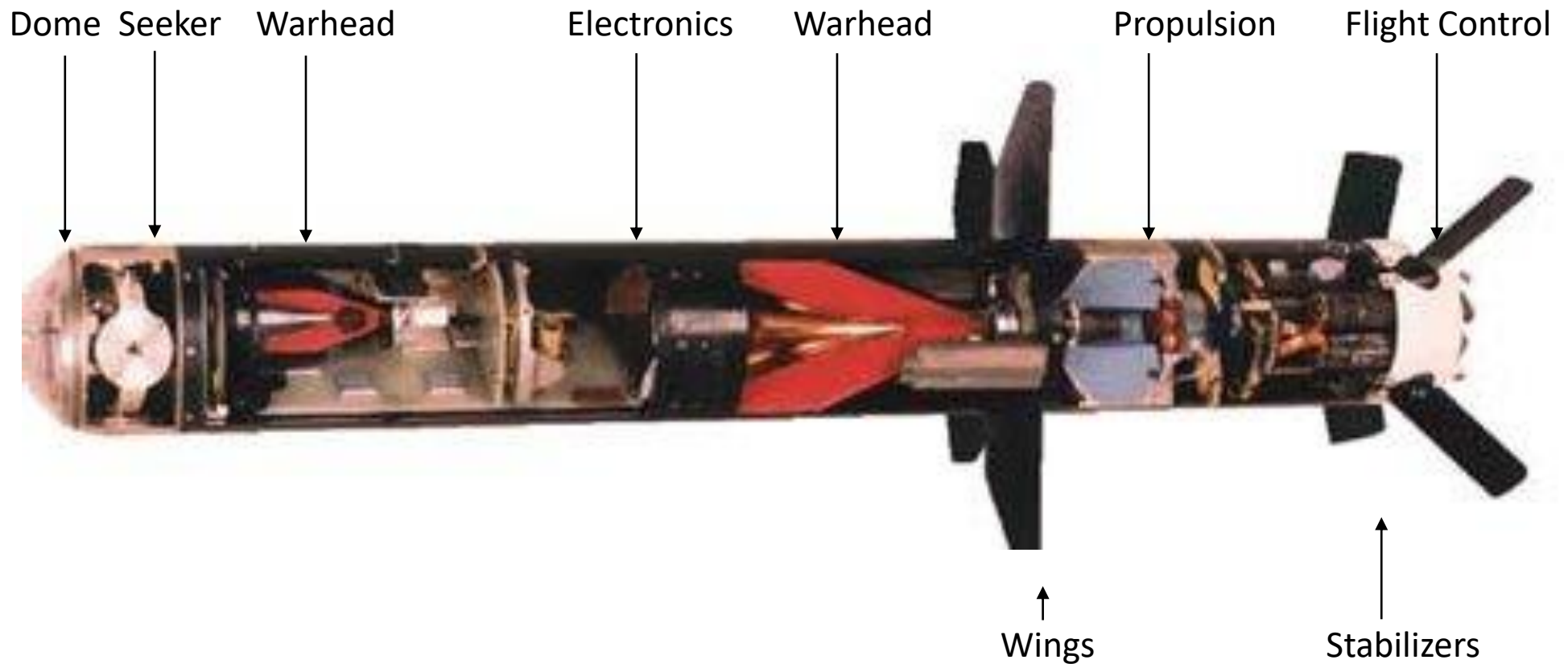


Note

A substantial portion of this lesson comes from a textbook:

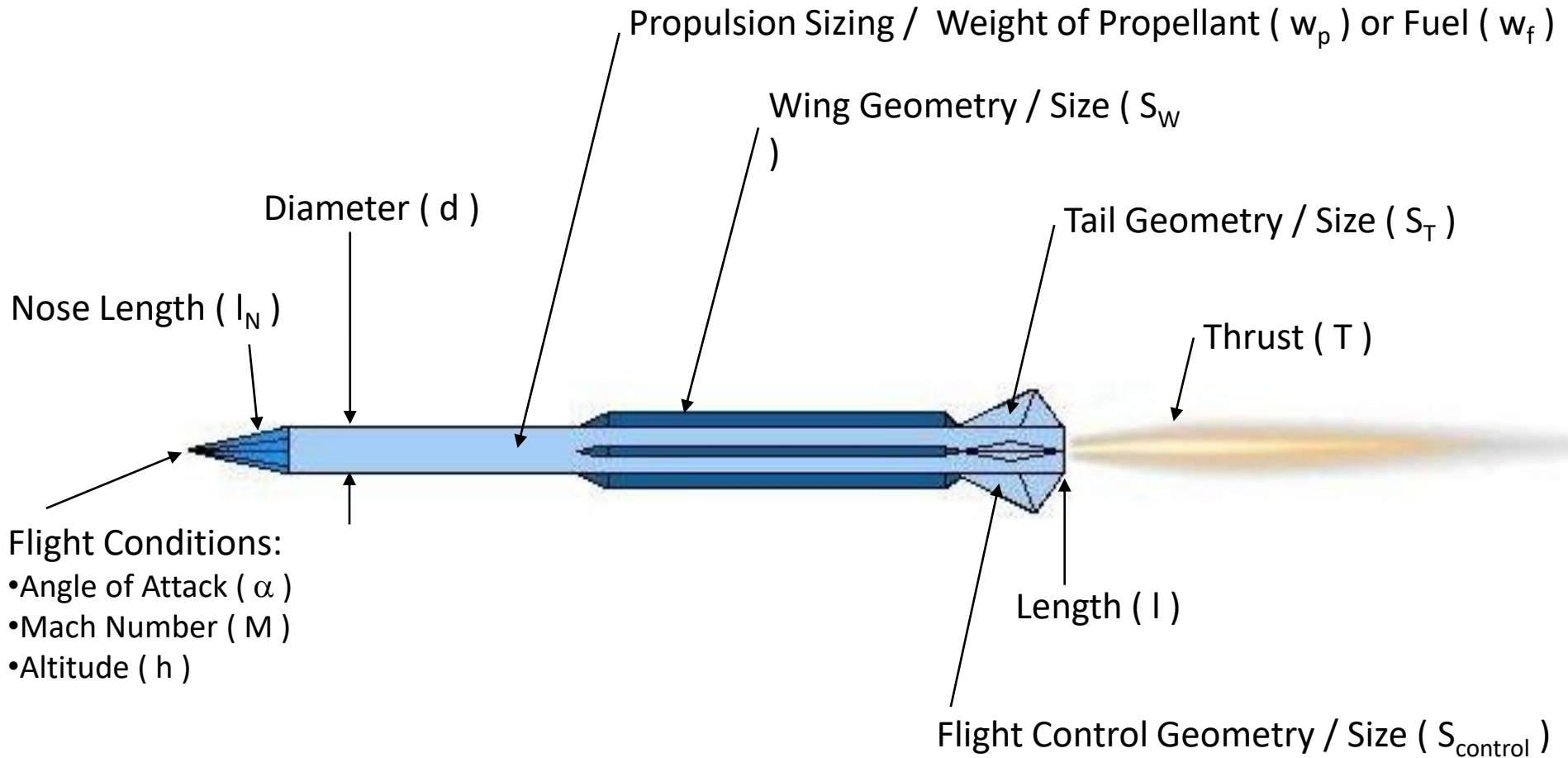
Fleeman, E. (2012).
Missile design and system engineering. American Institute of Aeronautics and Astronautics, Inc.

Typical Missile Subsystems - Packaging Is Longitudinal, with High Density



Fleeman, E. (2012). Missile design and system engineering. American Institute of Aeronautics and Astronautics, Inc.

Configuration Sizing Parameters



Fleeman, E. (2012). Missile design and system engineering. American Institute of Aeronautics and Astronautics, Inc.

Two primary types of hypersonics

- **Hypersonic Glide Vehicles (HGVs):**
 - Launch: Launched by a rocket booster to high altitudes and speeds.
 - Flight: The unpowered glide body detaches and glides through the atmosphere on a non-ballistic trajectory, utilizing the atmosphere to maneuver.
 - Characteristics: Designed with slender structures and sharp control surfaces for stable, long-distance flight and accuracy.
- **Hypersonic Cruise Missiles (HCMs):**
 - Launch: Typically require an initial acceleration from a booster or jet engine.
 - Flight: Are powered throughout their entire flight, using ramjet or scramjet engines to maintain hypersonic speeds.
 - Characteristics: Can reach speeds of Mach 10 or more, flying at lower altitudes than HGVs

Key Hypersonic Design Considerations & Challenges

Heat Management:

- At hypersonic speeds (Mach 5+), air friction creates extreme heat, requiring advanced thermal protection systems and specialized materials to prevent component failure.

Materials:

- Lightweight, high-strength composites and materials are necessary to form the missile's structure and heat shields, capable of withstanding the harsh hypersonic environment.

Airframe & Aerodynamics:

- Unlike traditional re-entry vehicles with blunt designs, hypersonics need slender airframes and sharp control surfaces to reduce drag and ensure stable, accurate flight.

Propulsion:

- For HCMs, air-breathing scramjet engines are critical, using the fast-moving air around the missile as an oxygen source for fuel combustion to sustain speed.

Guidance & Control:

- Achieving precision at over a mile per second requires sophisticated, high-accuracy guidance systems and maneuverability to alter trajectory.

Communication:

- Maintaining reliable communication and sensor systems while the missile is flying at high speeds through the atmosphere is a significant technical challenge

Body Fineness Ratio

In missile design, the Body Fineness Ratio (often abbreviated as BFR) is a key aerodynamic parameter used to describe the shape of a missile's body in terms of its slenderness.

- Body Fineness Ratio = Total length of the missile body / Maximum body diameter
- Mathematically:
- Fineness Ratio = $\frac{L}{D}$
- The fineness ratio has a significant impact on the missile's aerodynamic characteristics, such as:
 - Drag: A higher BFR (longer, thinner body) typically reduces pressure drag, especially in supersonic regimes.
 - Stability: A very high fineness ratio may lead to increased flexibility or flutter issues.
 - Internal Volume: A lower BFR (shorter, thicker body) provides more internal volume for fuel or payload but may increase drag.

Body Fineness Ratio

For subsonic or transonic missiles, BFR values are often in the range of 5 to 8.

For supersonic and hypersonic missiles, BFR can be 8 to 12 or higher, to reduce wave drag.

Slender bodies optimal at $L/D \approx 12.5-14$

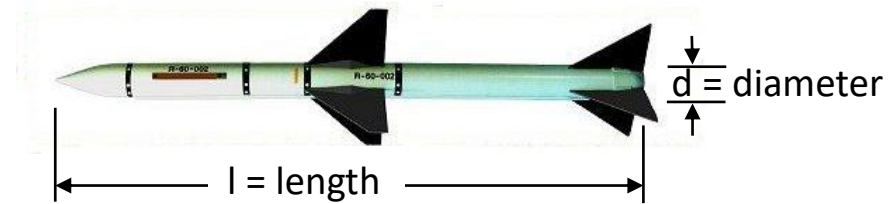
Research into minimum-drag shapes for hypersonic vehicles shows that fineness ratios in the range of 12.5 to 14 are ideal for reducing drag at Mach 6–12

Body Fineness Ratio

Component	Fineness Ratio (L/D)	Notes
Full hypersonic body (transport/glider)	$\approx 12-14$	Minimizes total drag at Mach 6–12
Nose/forebody	≈ 3	Transitions from blunt to sharp optimal shape
Aerospike missile	≈ 17.4	Example of high L/D in supersonic-hypersonic region

Missile Diameter Tradeoff Considerations

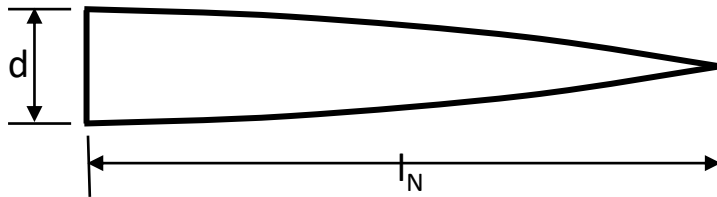
- Drivers toward Small Diameter
 - Decrease drag
 - Launch platform diameter constraint
- Drivers toward Large Diameter
 - Increase seeker range and signal-to-noise, better resolution and tracking
 - Increase blast frag and shaped charge warhead effectiveness (larger diameter \Rightarrow higher velocity fragments or longer / higher velocity jet)
 - Increase body bending frequency
 - Increase rocket motor longitudinal acoustic frequency (shorter motor length)
 - Subsystem diameter packaging
 - Launch platform length constraint
- Typical Range in Body Fineness Ratio $5 < l / d < 25$
 - Man-portable anti-armor missiles: low (Javelin $l / d = 8.5$)
 - STA / ATA missiles: high (AIM-120 $l / d = 20.5$)



Nose Fineness and Geometry Tradeoffs

High Fineness Nose Ideal Low Supersonic Drag, Low RCS

Example: $l_N / d = 5$

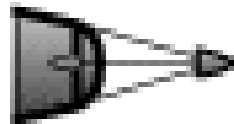


Low Fineness Nose Ideal for Seeker, More Length for Propellant / Subsystems

Example: $l_N / d = 0.5$ (hemisphere)



$l_N / d = 0.5$ (with spike)

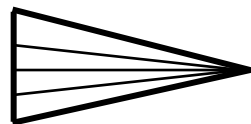


High Fineness Nose Geometry Alternatives

Conventional (e.g., Tangent Ogive)



Faceted



Window



Multi-lens



Lower Manufacturing Cost
Slope

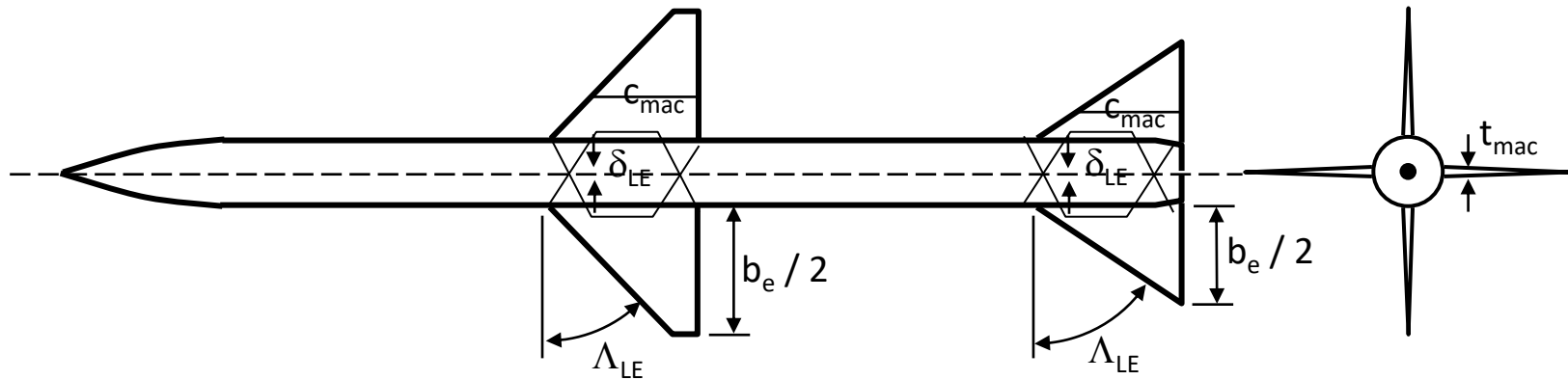
Low Distortion for Supersonic

Low RCS, Low Distortion

Low Dome Error

Fleeman, E. (2012). Missile design and system engineering. American Institute of Aeronautics and Astronautics, Inc.

Definition of Planar Aerodynamic Surface Geometry Parameters



c_{mac} = mean aerodynamic chord length

Λ_{LE} = leading edge sweep angle

δ_{LE} = leading edge section total angle

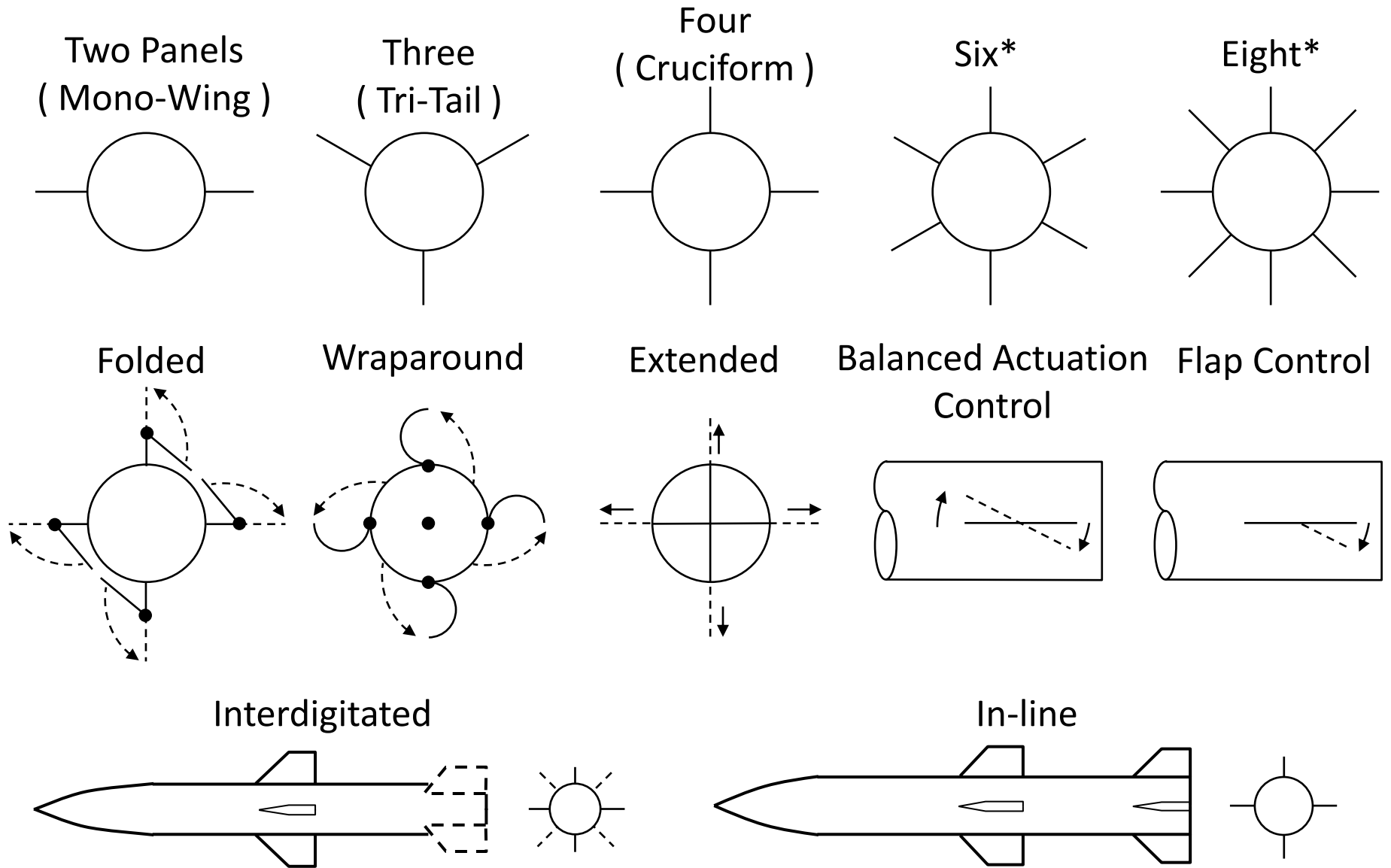
t_{mac} = max thickness of mean aerodynamic chord

b_e = span of exposed planform

S_e = area of exposed planform

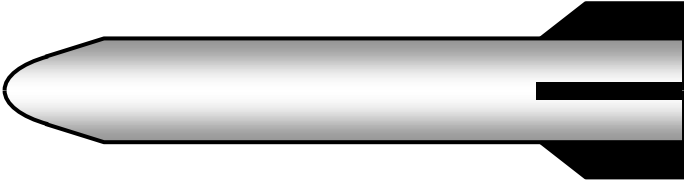
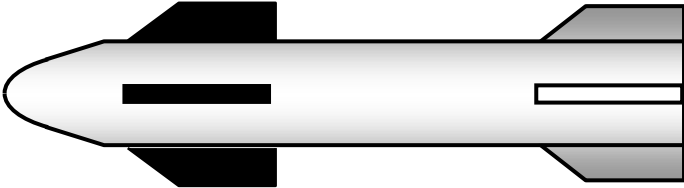
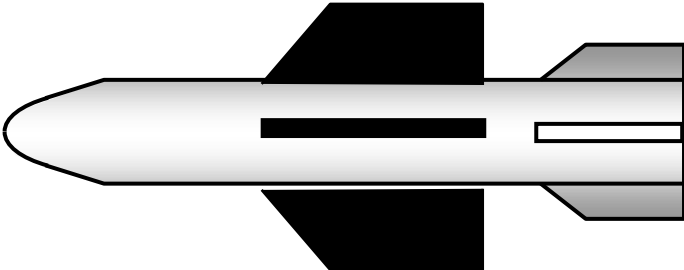
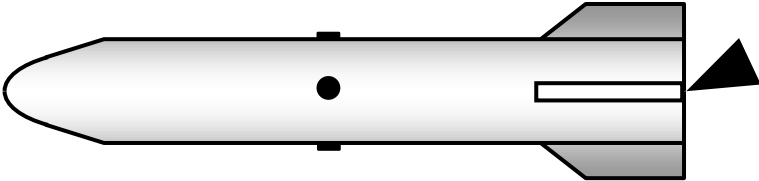
$A_e = b_e^2 / S_e$ = aspect ratio of exposed planform

Wing / Stabilizer / Control Surface Arrangements and Alternatives



*Note: More than four tails have lower induced roll.

There Are Many Flight Control Aerodynamic Configuration Alternatives

	<u>Control</u>	<u>Control Design Alternatives</u>	<u>Fixed Surface Alternatives</u>
	Tail	Cruciform (4) Tri-tail (3) Not Compressed Folded Wraparound Switchblade	Wingless Wing Strake / Canard In Line with Controls Interdigitated with Controls
	Canard	Above Rolling Airframe (2)	Number (2, 3, 4) Tail (3, 4, 6, 8) Tail + Wing In Line with Controls Interdigitated with Controls
	Wing	Above	Tail (3, 4, 6, 8) Strake / Canard & Tail In Line with Controls Interdigitated with Controls
	TVC or Reaction Jet Control	Movable Nozzle Jet Tab Jet Vane Axial Plate Secondary Injection Normal Jet / JI Spanwise Jet / JI	Controls Tail (3, 4, 6, 8) Tail + Canard / Strake Tail + Wing

Canard

In aircraft, a canard is a control surface located at the front of the aircraft, ahead of the main wings. It functions similarly to a horizontal stabilizer, providing pitch control (up and down movement of the nose). Unlike traditional aircraft with a tail-mounted stabilizer, canard-equipped planes have this control surface at the front. The canard generates lift and helps control the aircraft's pitch, similar to a horizontal stabilizer at the tail. Depending upon the installation, it may be a fixed, moveable or variable geometry surface and may or may not incorporate control surfaces.



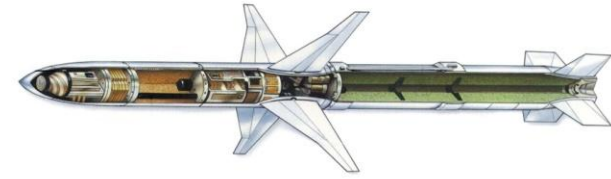
Examples of Missile Flight Control Alternatives



↑
Tail Control (TOW)



↑
Canard Control (Python V)



↑
Wing Control (HARM)



↑
Thrust Vector Control (IRIS-T),
IRIS-T Also Has Tail Control

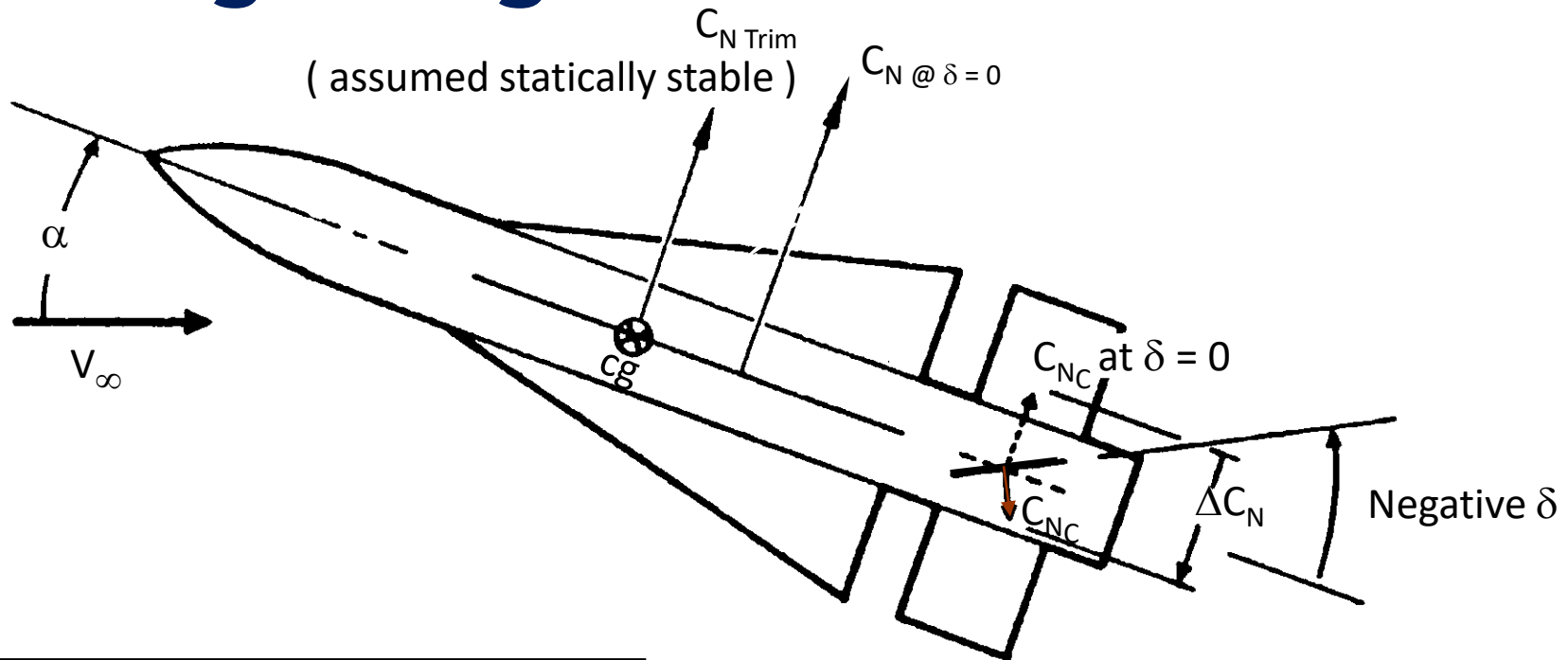


↑
Reaction Jet Attitude Control (PAC-3),
PAC-3 Also Has Tail Control



↑
Reaction Jet Divert (SM-3 3rd
Stage), SM-3 Also Has Reaction
Jet Attitude Control, Tail Control,
TVC)

Tail Control Is Efficient at High Angle of Attack



😊 Efficient Packaging

😊 Low Hinge Moment / Actuator Torque

😊 Low Induced Rolling Moment

😊 Efficient at High α

☹️ Decreased Lift if Statically Stable

☹️ Initial Motion in Wrong Direction if Statically Stable

Note:

$C_{N \text{ Trim}}$ = Trim normal force coefficient

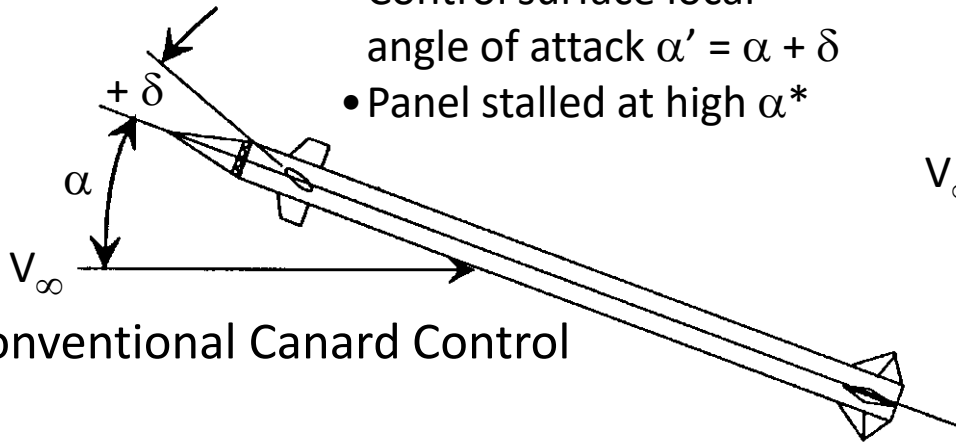
$C_{N @ \delta = 0}$ = Normal force coefficient at zero control deflection

C_{NC} = Normal force coefficient from control deflection

$\Delta C_N = C_{NC} - C_{N @ \delta = 0}$

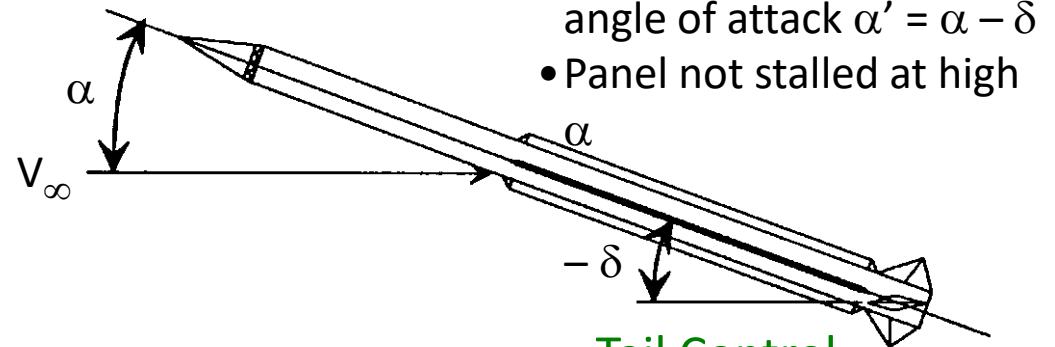
Tail Control Can Operate at Higher Angle of Attack Than Conventional Canard Control

- Assumed static stability
- Control surface local angle of attack $\alpha' = \alpha + \delta$
- Panel stalled at high α^*



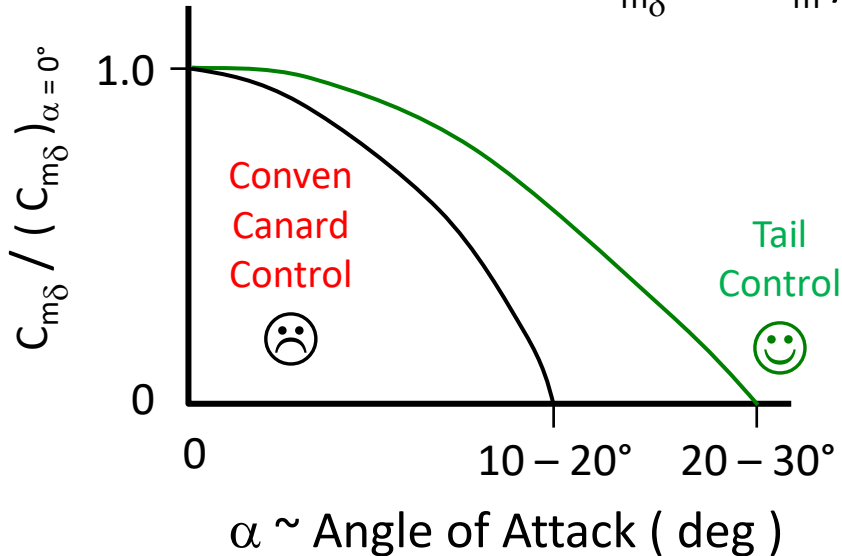
Conventional Canard Control

- Assumed static stability
- Control surface local angle of attack $\alpha' = \alpha - \delta$
- Panel not stalled at high α

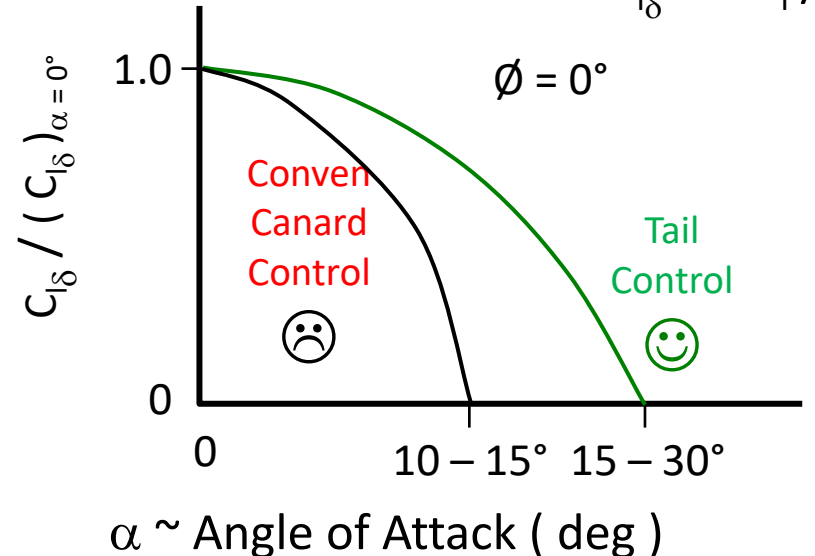


Tail Control

Pitch Control Effectiveness $C_{m_\delta} = \Delta C_m / \Delta \delta$



Roll Control Effectiveness $C_{l_\delta} = \Delta C_l / \Delta \delta$



*Note: Forward fixed surfaces (e.g., Python 4) in front of movable canards alleviate stall at high α . Free-to-roll tails (e.g., Python 4) and rollerons alleviate induced roll at high α . Blended canard – tail control reduce canard deflection.

About 70% of Tail Control Missiles Have Wings



JASSM AGM-158 



ANAM / Gabriel 



CALCM 



JSOW AGM-154 





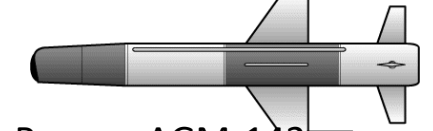
Tomahawk BGM-109 



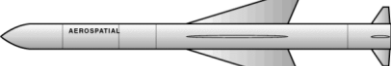
Taurus KEPD 350 



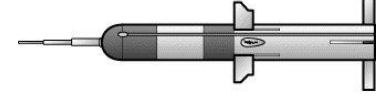
Storm Shadow / Scalp  



Popeye AGM-142 



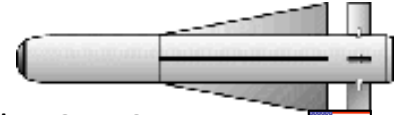
Exocet MIM40 




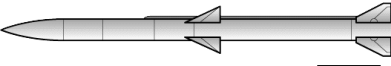
TOW2-BGM71D 



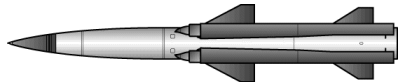
NSM 




Maverick AGM-65 



AMRAAM AIM-120 



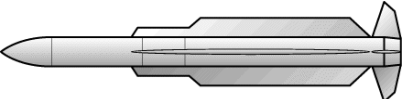
Sunburn SS-N-22 



SS-N-27 / Sizzler 




Brahmos (two stage)  



Standard RIM-66 / 67 




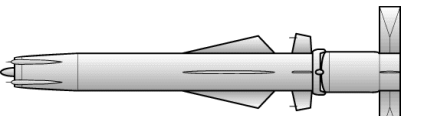
RBS-70 / 90 




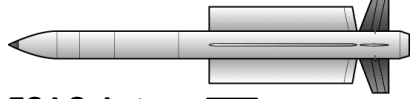
Shipwreck SS-N-19 



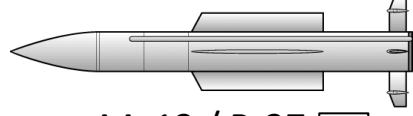
Super 530 




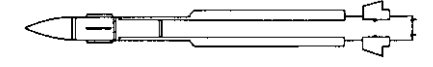
Sea Dart (two stage) 



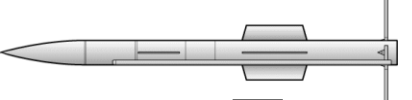
FSAS Aster 




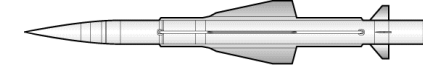
Arrow AA-13 / R-37 



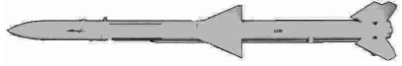
Mica 



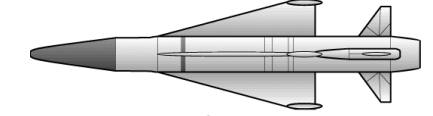
Adder AA-12 



Rapier 2000 

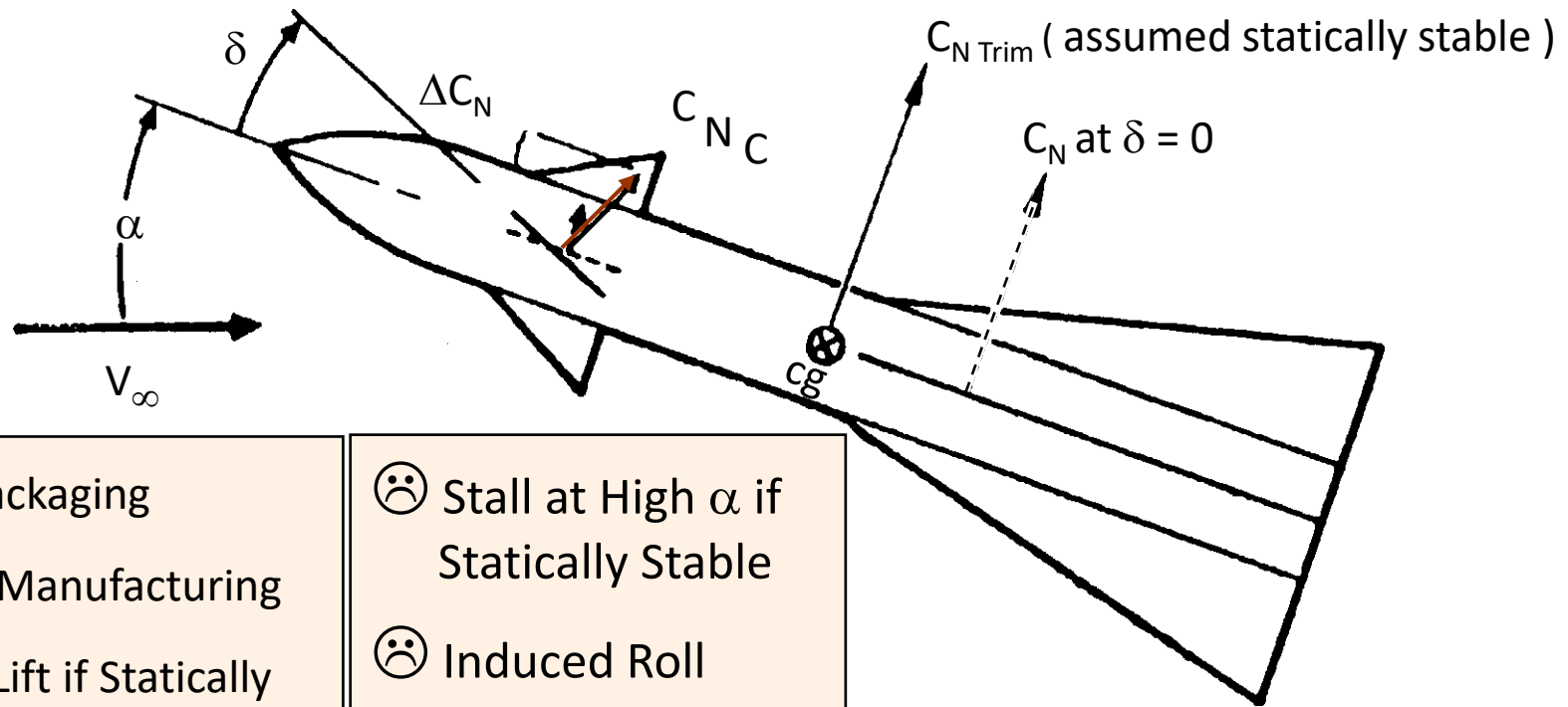


SD-10 / PL-12 



Seawolf 

Conventional Canard Control Efficient at Low α , but Stalls at High α with High Induced Roll



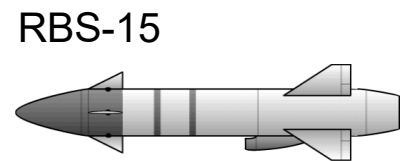
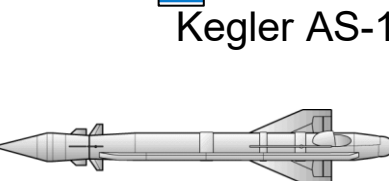
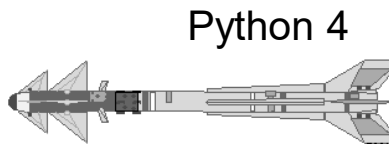
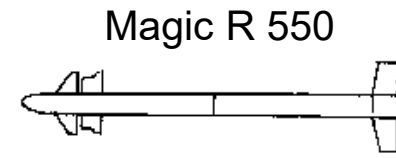
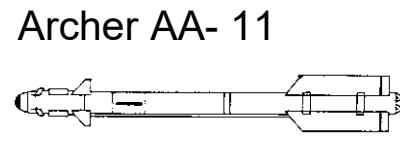
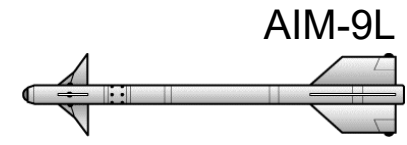
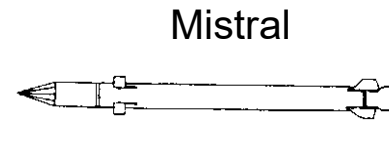
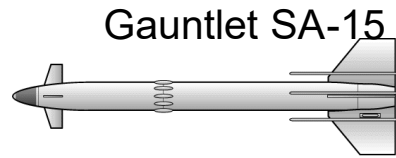
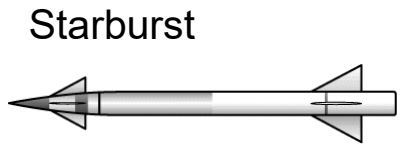
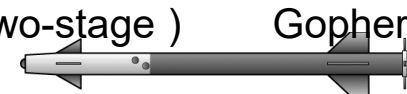
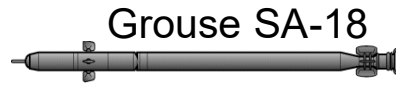
- 😊 Efficient Packaging
- 😊 Simplified Manufacturing
- 😊 Increased Lift if Statically Stable
- 😊 Initial Motion in Desired Direction if Statically Stable

- ☹️ Stall at High α if Statically Stable
- ☹️ Induced Roll

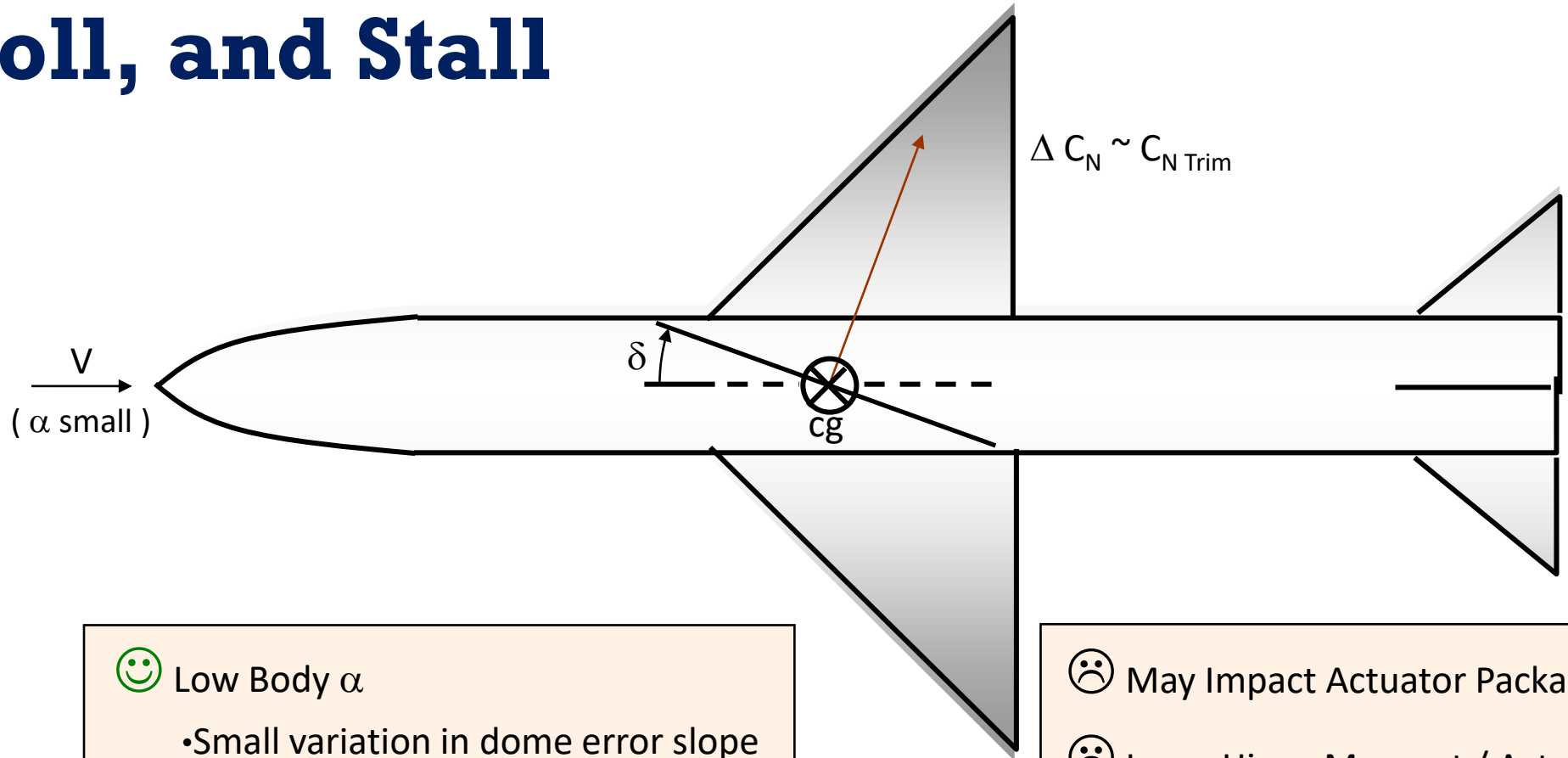
Note: = $C_{N C}$ at $\delta = 0^\circ$
 = $C_{N C}$ at $\delta = \delta$

*Note: Additional forward fixed surface in front of movable canard alleviates stall at high α . Free-to-roll tails alleviate induced roll at high α . Dedicated roll control surfaces avoid roll control saturation and simplify autopilot design. Blended canard – tail control reduces required deflection of canards.

Most Canard Control Missiles Are Wingless and Most Are Supersonic



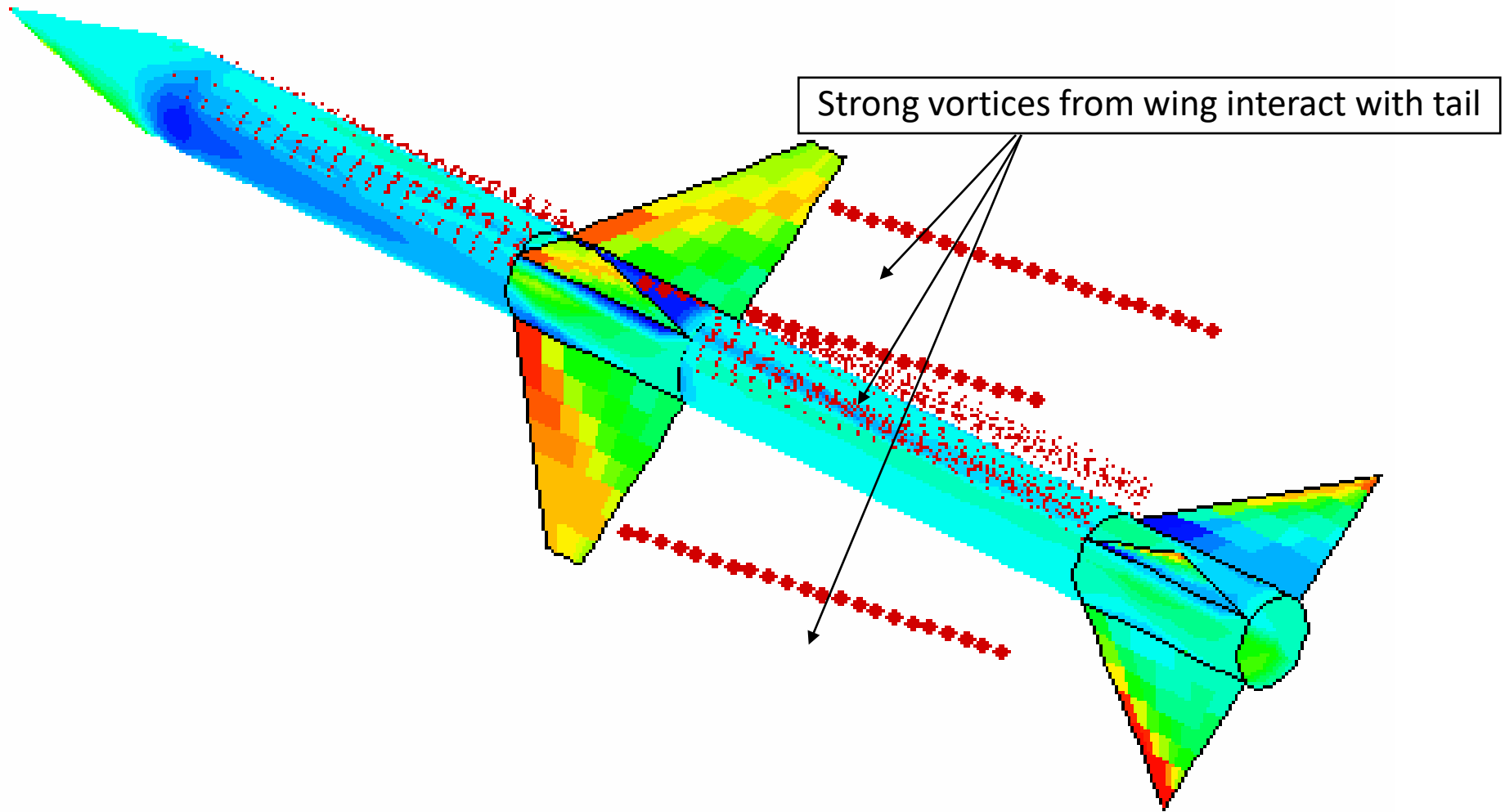
Wing Control Has Less Body Rotation, But Has High Hinge Moment, Induced Roll, and Stall



- 😊 Low Body α
 - Small variation in dome error slope
 - Compatible with strap-down seeker
- 😊 Fast Response / Lower Time Constant

- ☹️ May Impact Actuator Packaging
- ☹️ Large Hinge Moment / Actuators
- ☹️ Larger Wing Size
- ☹️ Induced Roll
- ☹️ Wing Stall

Wings Are Susceptible to Strong Vortex Shedding

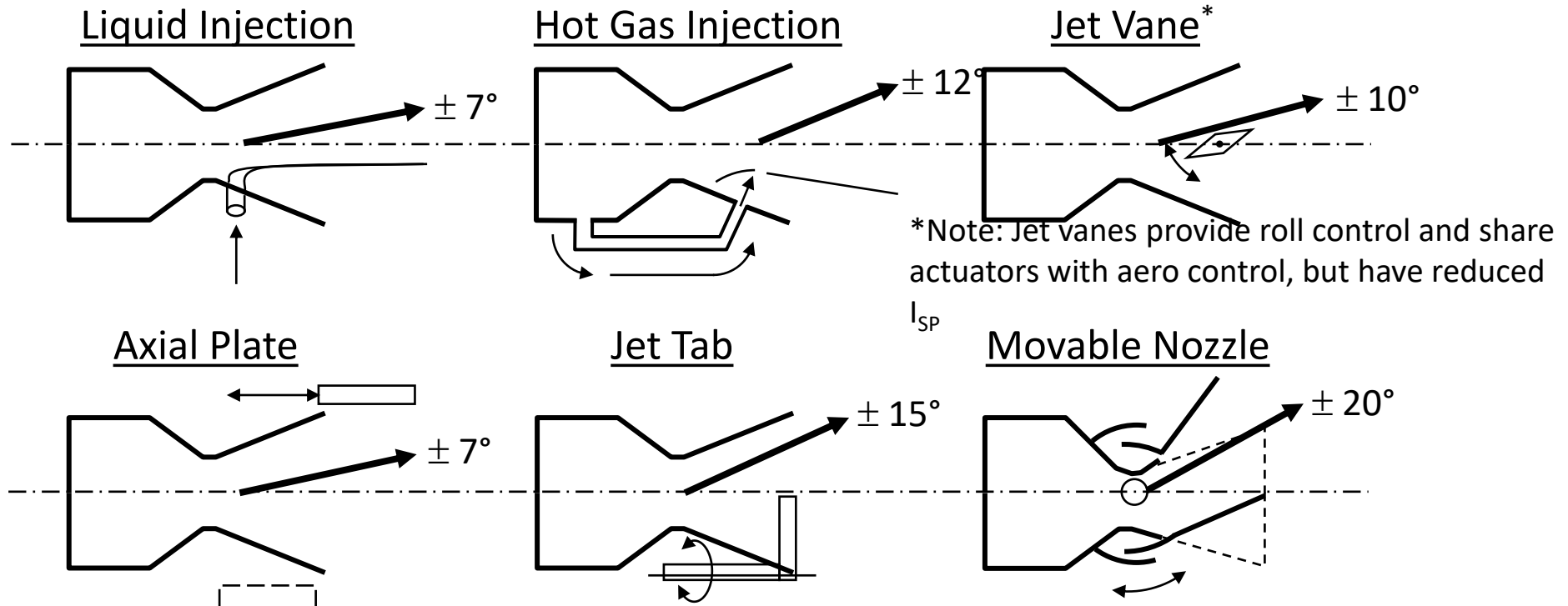


Source: University of Notre Dame web site:
<http://www.nd.edu/~ame/facilities/SubsonicTunnels.htm>

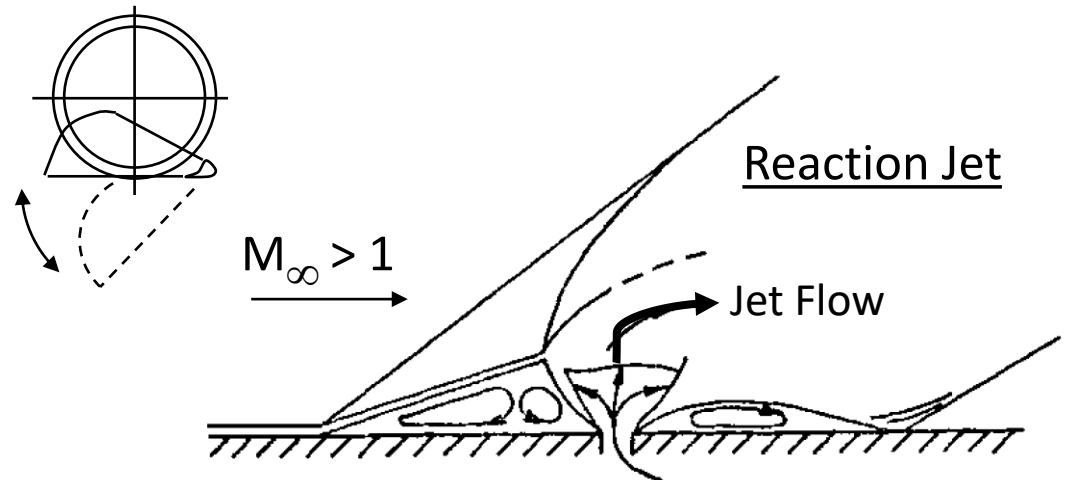
Source: Nielsen Engineering & Research (NEAR) web
site: <http://www.nearinc.com/near/project/MISDL.htm>

!

TVC and Reaction Jet Flight Control Provide High Maneuverability at Low Dynamic Pressure



- TVC and reaction jet flight control provide high maneuverability at low dynamic pressure
- TVC usually has lower time constant and smaller miss distance than aero control
- Reaction jets used for divert and attitude control
- Reaction jets usually have lower time constant and smaller miss distance than TVC
- Reaction jets can be either impulse jets or controlled duration jets



Skid-to-Turn Is the Most Common Maneuver Law for Missiles

Skid-To-Turn (STT)

Advantage: Fast response

Features

- Usually small roll attitude / rate commands from autopilot
- Best for axisymmetric cruciform missiles of low aspect ratio

Bank-To-Turn (BTT)

Advantage: Provides higher maneuverability for mono-wing, noncircular / lifting bodies, and airbreathers

Disadvantages

- Time to roll
- Roll rate limited by gain for radome error slope stability

Features

- Large roll attitude commands from autopilot
- Small sideslip

Rolling Airframe (RA)

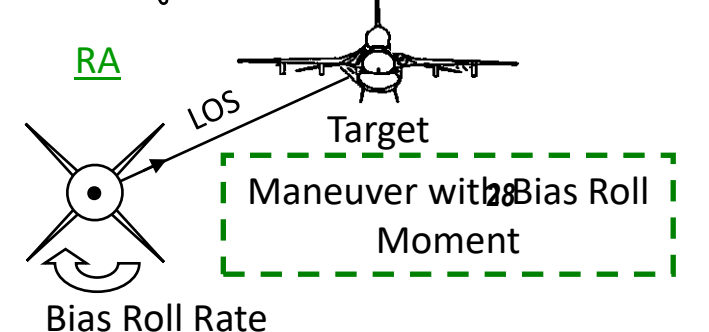
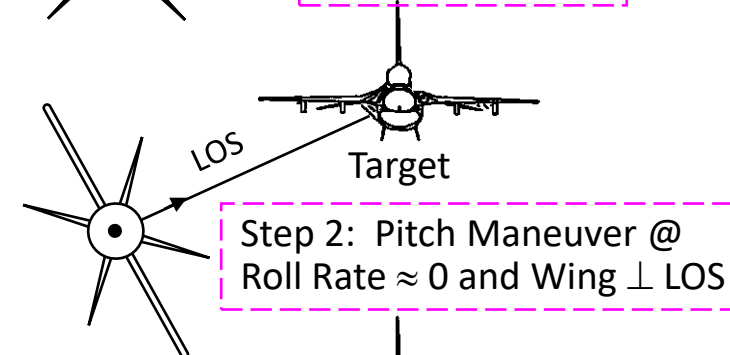
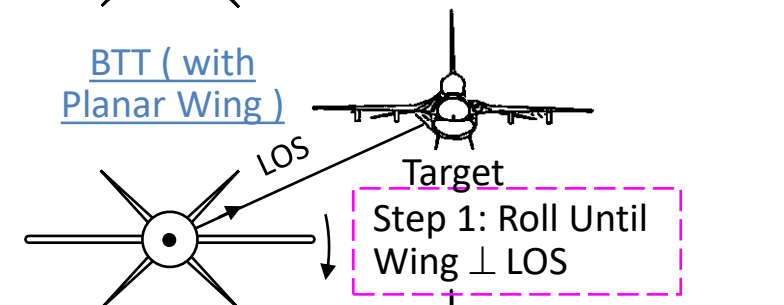
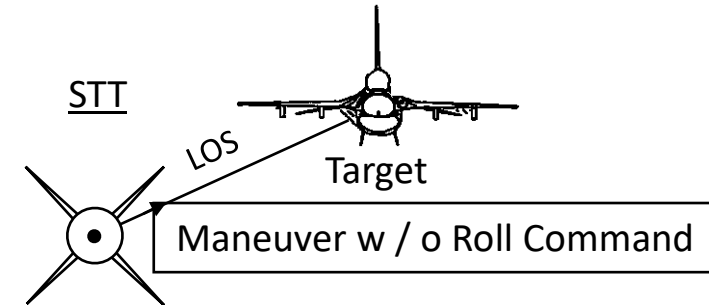
Advantage: Requires fewer gyros / accelerometers / actuators (packaging for small missile)

Disadvantages

- Reduced maneuverability for aero control
- Requires higher rate gyros / actuators / seeker tracking
- Higher drag with coning flight trajectory
- Requires precision geometry and thrust alignment

Features

- Bias roll rate (~ 10 Hz) from bias roll moment
- Can use "bang-bang" / impulse steering
- Compensates for thrust offset



Skid-to-Turn Is the Most Common Maneuver Law for Missiles

Divert

Advantages:

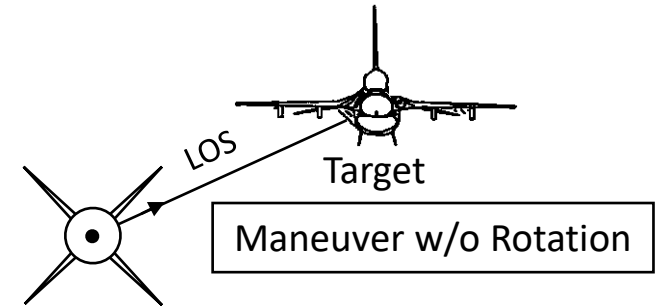
- Lower Time Constant
- Less Effect of Radome Error Slope
- Smaller Miss Distance

Disadvantage:

- Cost
- May not Provide Sufficient Maneuverability

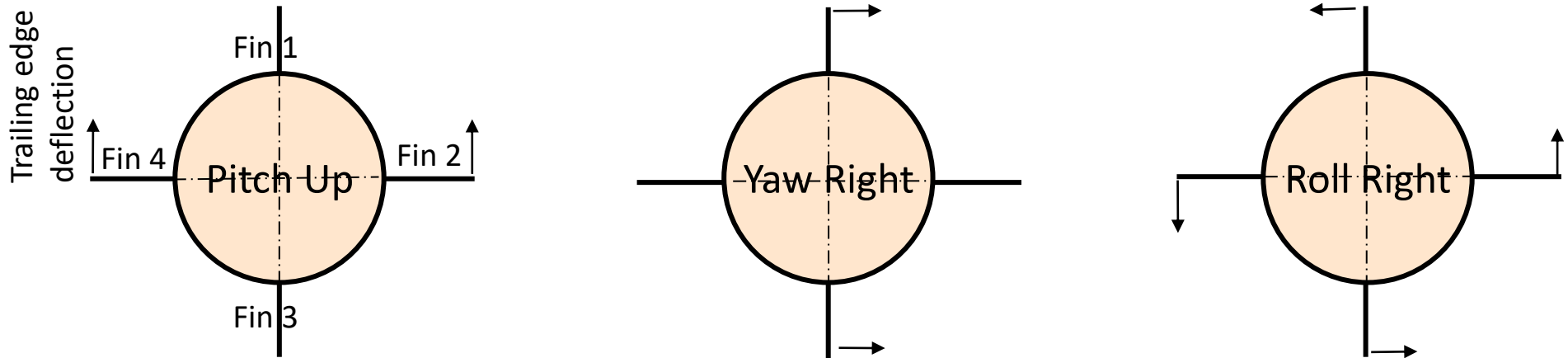
Features

- Direct Lift / Side Force w/o Rotation
- Either Wing, Blended Canard – Tail, or Divert Reaction Jet Control

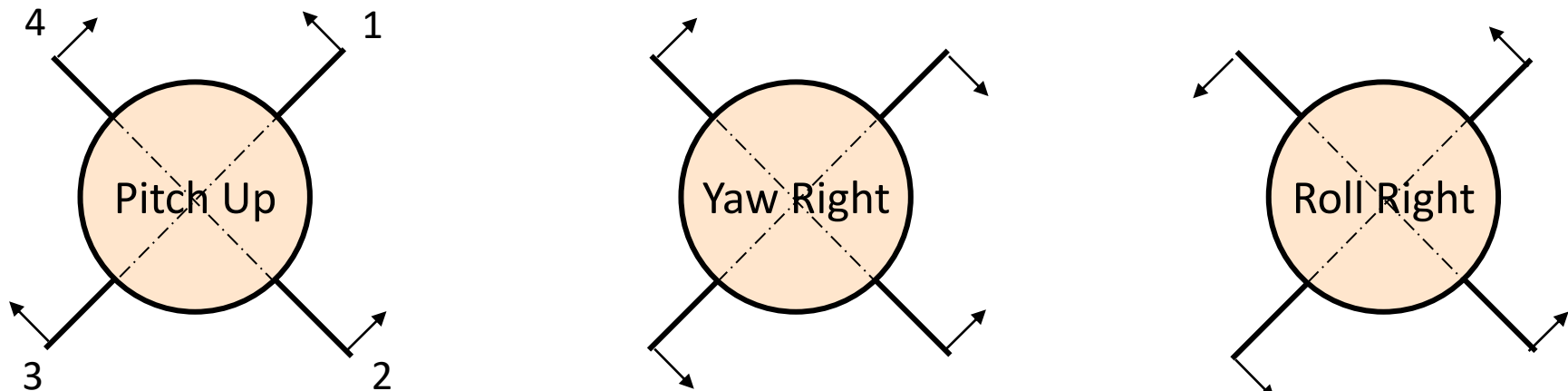


X Roll Orientation Flight Is Usually Better Than + Roll Orientation Flight

+ Roll Orientation ($\phi = 0$ deg), Cruciform Tail Control, Looking Forward from Base

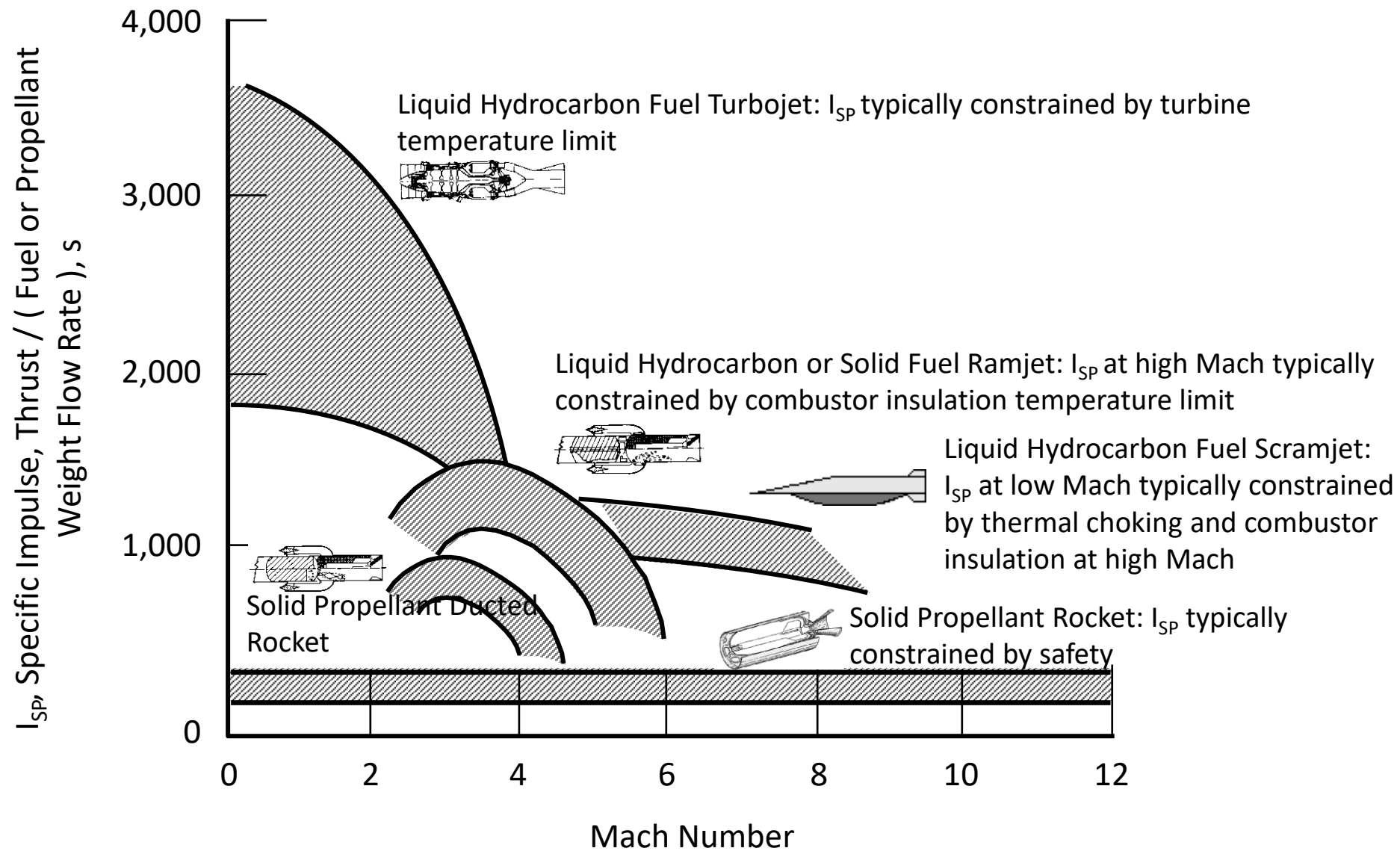


X Roll Orientation ($\phi = 45$ deg), Cruciform Tail Control, Looking Forward from Base



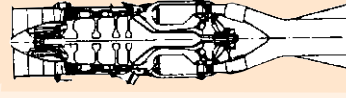
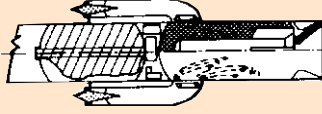

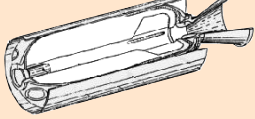
Note: + roll orientation sometimes has lower trim drag and less static stability and control effectiveness in pitch and yaw.
 + roll often has statically unstable roll moment derivative ($C_{l\phi} > 0$) in supersonic flight.
 X roll orientation has better launch platform compatibility, higher L / D, higher static stability and control effectiveness in pitch and yaw. X roll often has statically unstable roll moment derivative ($C_{l\phi} > 0$) in subsonic flight.

Each Type of Air Breathing Propulsion Has an Optimum Mach Number for Max Specific Impulse



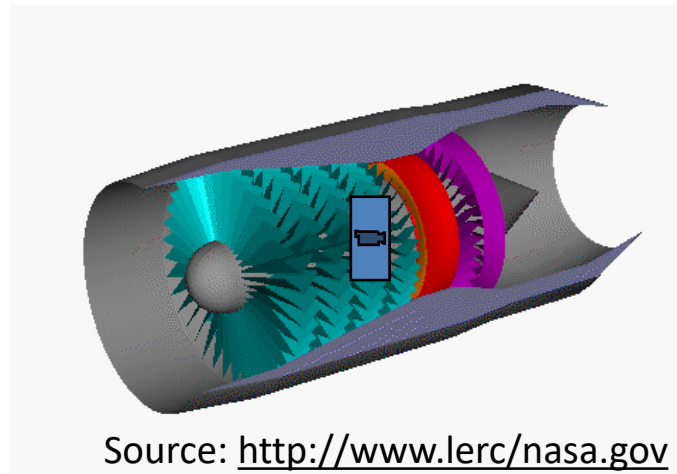
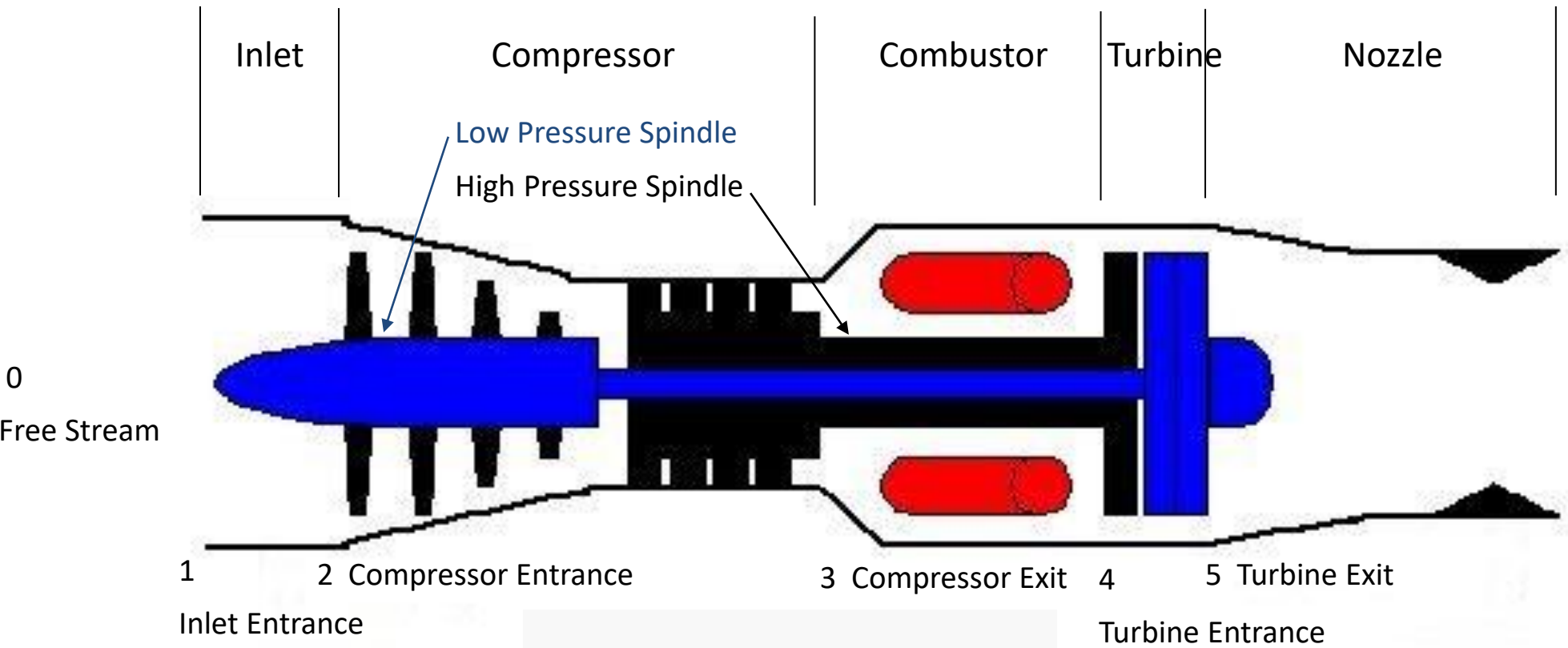
Cruise Range Is Driven by L/D, I_{sp}, Velocity, and Propellant or Fuel Weight Fraction

$$R = (L/D) I_{sp} V \ln [W_L / (W_L - W_P)] , \text{ Breguet Range Equation}$$

Parameter	Typical Value for 2000 lb Precision Strike Missile			
	Subsonic Turbojet Missile 	Liquid Fuel Ramjet Missile 	Hydrocarbon Fuel Scramjet Missile 	Solid Propellant Rocket 
L / D, Lift / Drag	10	5	3	5
I _{sp} , Specific Impulse	3000 s	1300 s	1000 s	250 s
V _{AVG} , Average Velocity	1000 ft / s	3500 ft / s	6000 ft / s	3000 ft / s
W _p / W _L , Cruise Propellant or Fuel Weight / Launch Weight	0.3	0.2	0.1	0.4
R, Max Cruise Range	1800 nm	830 nm	310 nm	250 nm
t _{250 nm} , Time to 250 nm Range	25 m	7 m	4 m	8 m

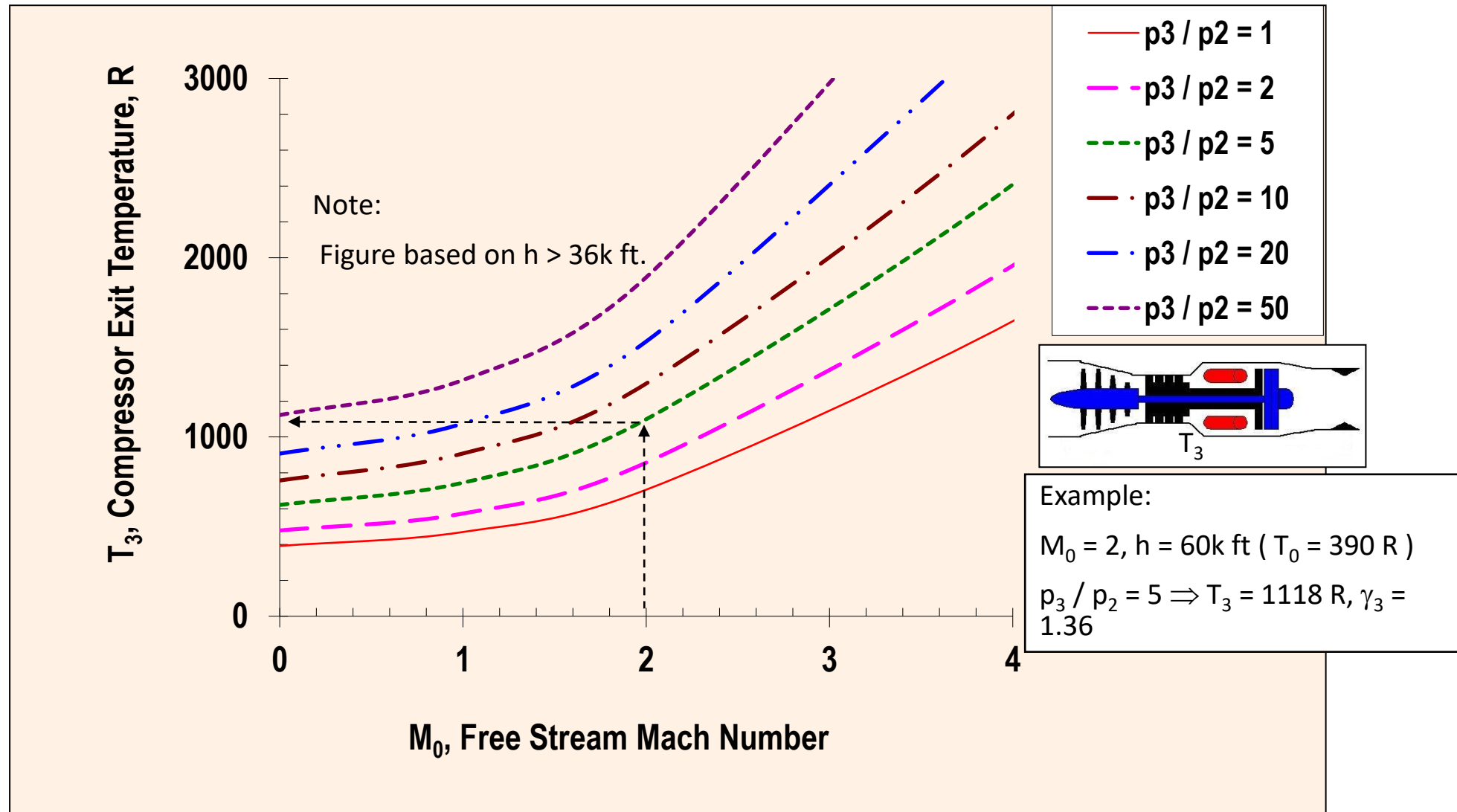
Note: Ramjet and Scramjet missiles booster propellant for Mach 2.5 to 4 take-over speed not included in W_p for cruise. Rockets require thrust magnitude control (e.g., pintle, pulse, or gel motor) for effective cruise. Max range for a rocket is usually a semi-ballistic flight profile, instead of cruise flight. Multiple stages may be required for rocket range greater than 200 nm.

Schematic of Turbojet Flow Path, Components, and Nomenclature



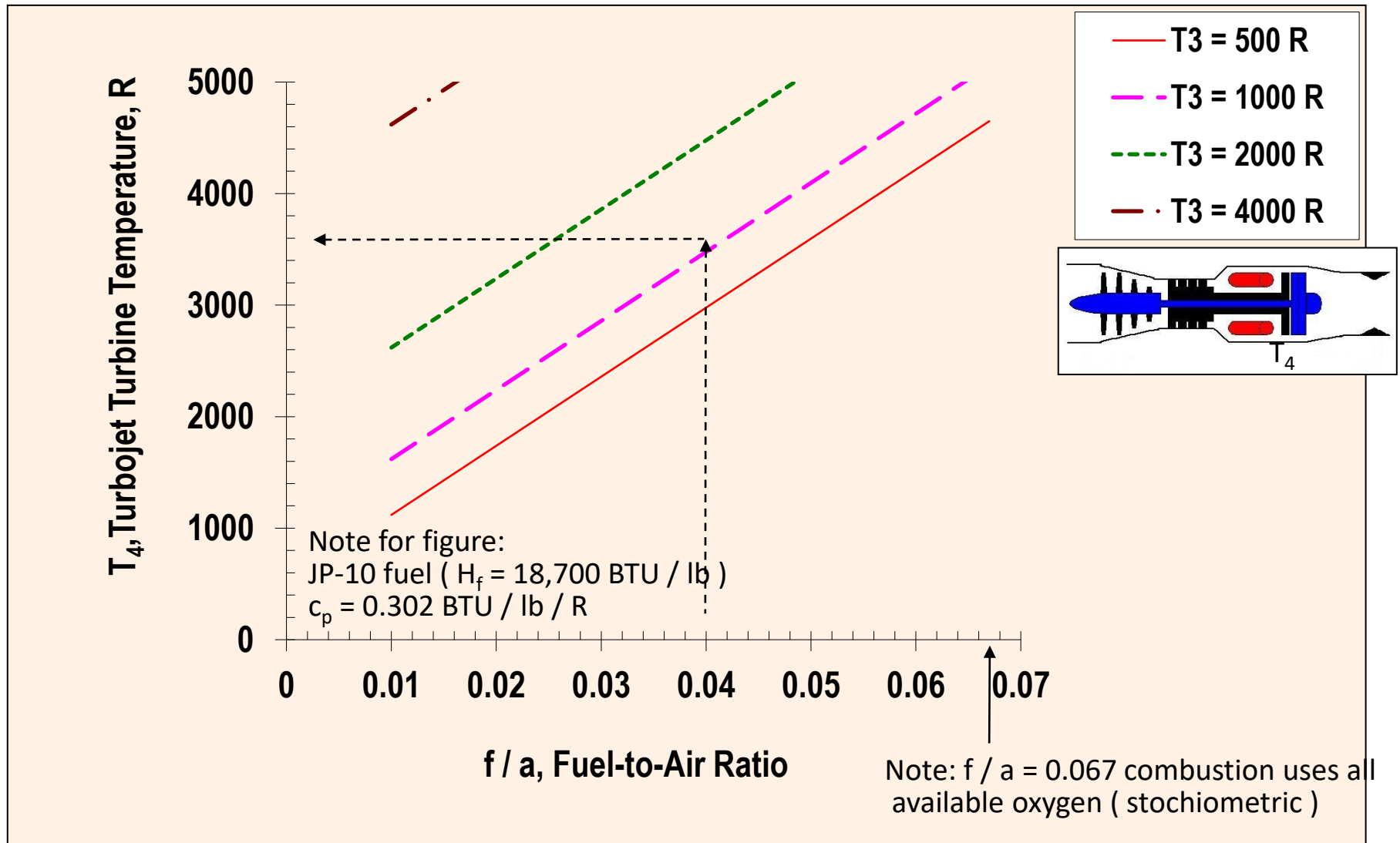
Source: <http://www.lerc.nasa.gov>

High Temperature Compressors Are Required to Achieve High Pressure Ratio at High Mach



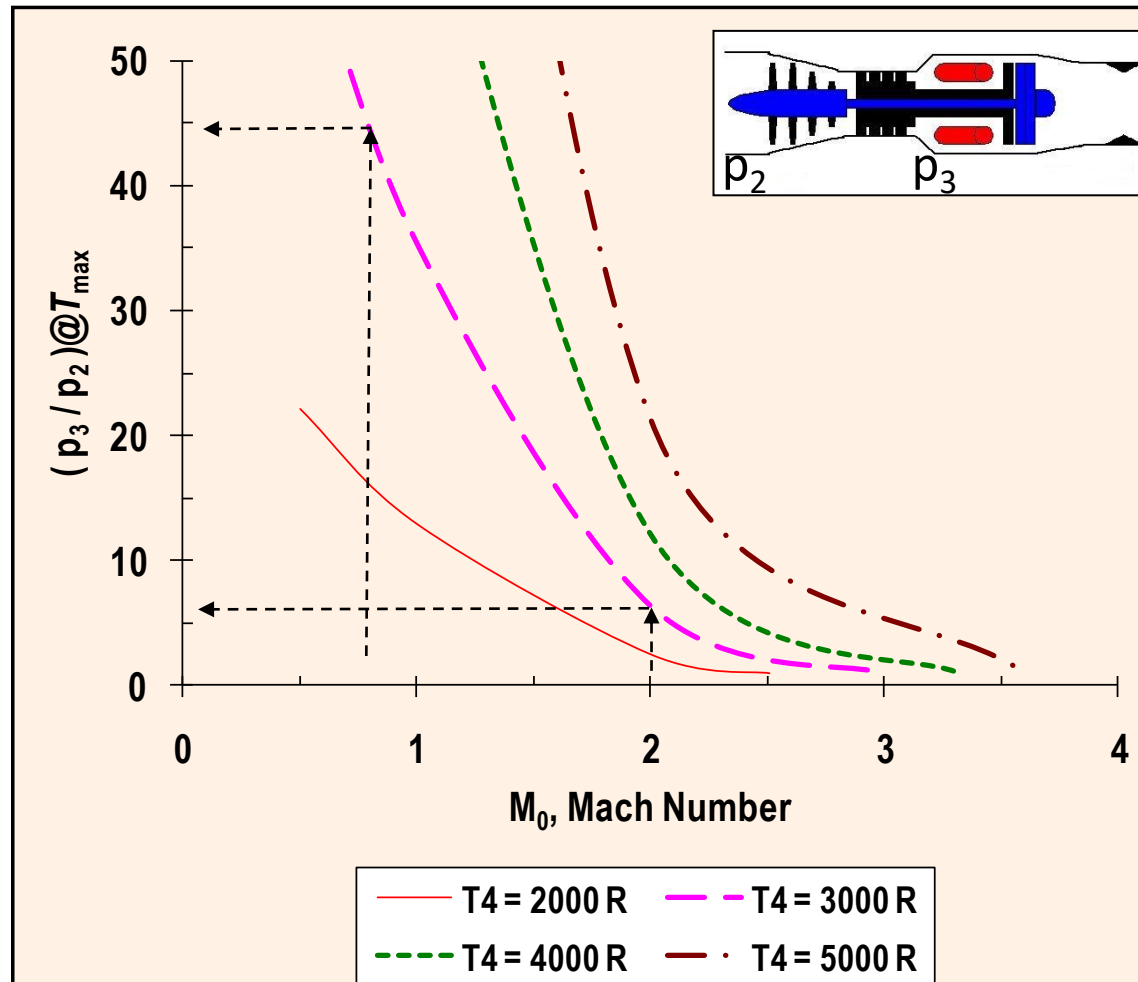
T_3 = Compressor exit temperature in Rankine, T_0 = free stream temperature in Rankine, γ = specific heat ratio, M_0 = free stream Mach number, p_3 = compressor exit pressure, p_2 = compressor entrance pressure

A High Temperature Turbine Is Required for a High Speed Turbojet Missile



T_4 = Turbojet turbine entrance temperature in Rankine, T_3 = compressor exit temperature in Rankine, H_f = heating value of fuel, c_p = specific heat at constant pressure, f/a = fuel-to-air ratio

Compressor Pressure Ratio and Turbine Temperature Limit Turbojet Maximum Thrust

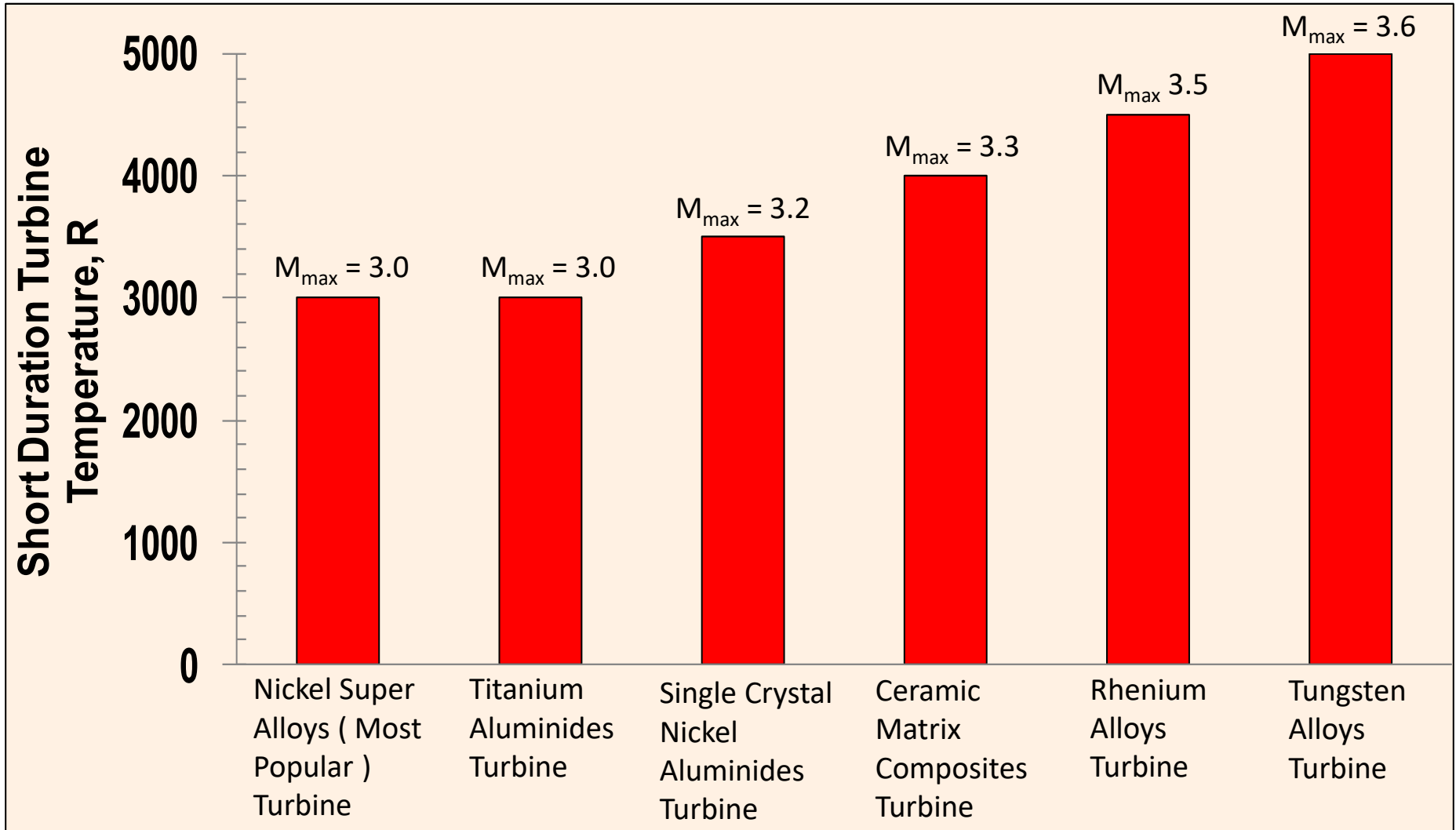


Note: A compressor ratio for maximum thrust may not be practical (large number of stages and 2 spindles with heavy weight / long length).

Source: Ashley, H., Engineering Analysis of Flight Vehicles, Dover Publications, Inc., New York, 1974

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Turbine Materials Allow Mach 3+ Turbojet



Note:

Turbine maximum temperature limits the max available turbojet Mach number and thrust.

M_{max} at $(p_3 / p_2) = 1$, $h > 36k$ ft ($T_0 = 390$ R), $T_4 =$ turbine temperature = combustor temperature

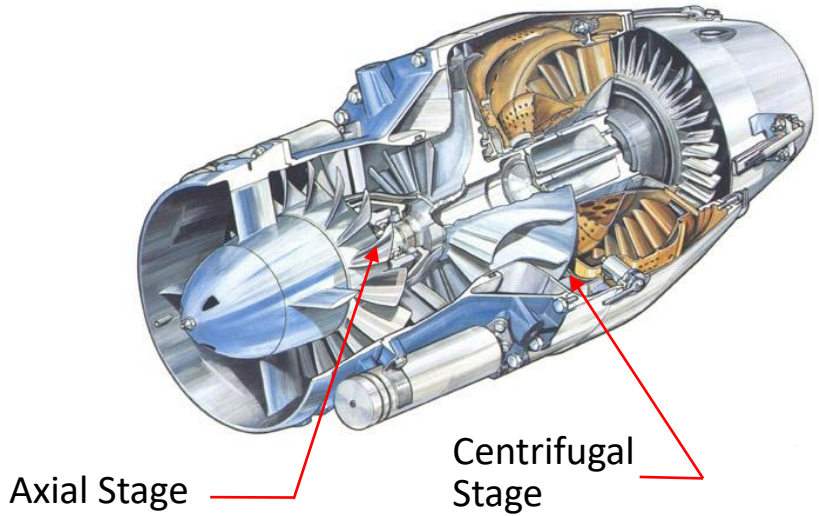
$$M_{max} = \{ 5 [(T_4 / 390)^{1/2} - 1] \}^{1/2}$$



Axial and Centrifugal Compressors

- An axial compressor is a type of gas compressor that uses a series of rotating and stationary airfoils (blades) to progressively increase the pressure of a gas flow. It's characterized by the working fluid moving essentially parallel to the axis of rotation.
- Centrifugal compressors elevate gas pressure by adding kinetic energy/velocity to the gas as it flows through an impeller. Kinetic energy increases potential energy/static pressure by slowing the flow through a diffuser. The pressure rise in the impeller (in most cases) is equal to the rise in the diffuser. An impeller, or impellor, is a driven rotor used to increase the pressure and flow of a fluid. It is the opposite of a turbine, which extracts energy from, and reduces the pressure of, a flowing fluid.

Compressor Alternatives: Multi-Stage Axial, Single Centrifugal, Multi-Stage Axial + Centrifugal

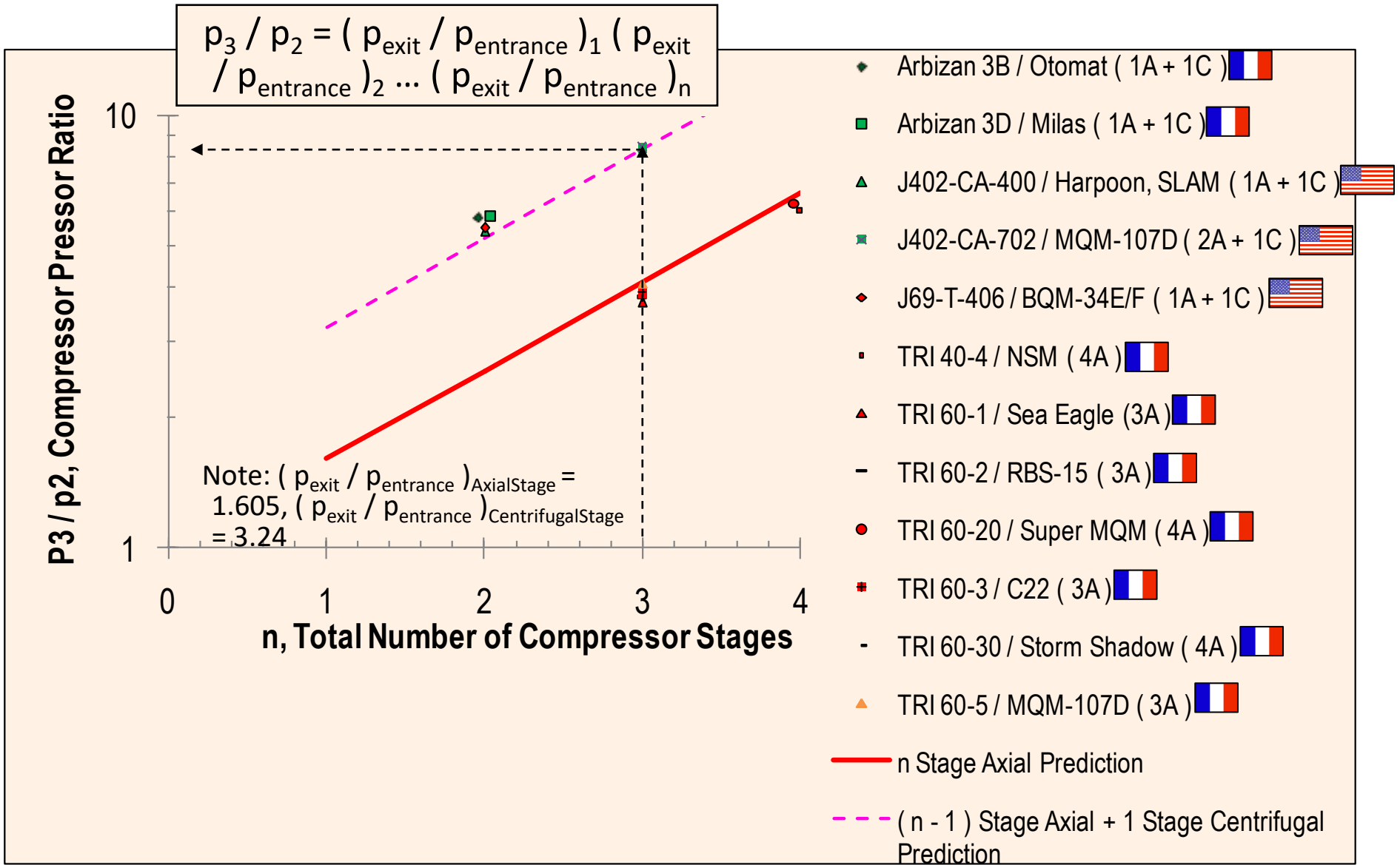


Example: Teledyne Model 370, J402-CA-400
 Compressor: 1 Axial Stage + 1 Centrifugal Stage (Harpoon, SLAM)

<u>Type</u>	<u>Single Stage Pressure</u>	<u>Multi-Stage Pressure</u>	<u>Diameter</u>	<u>Cost</u>
Axial	○	●	●	○
Centrifugal	●	—	—	●
Axial + Centrifugal	●	●	○	◐

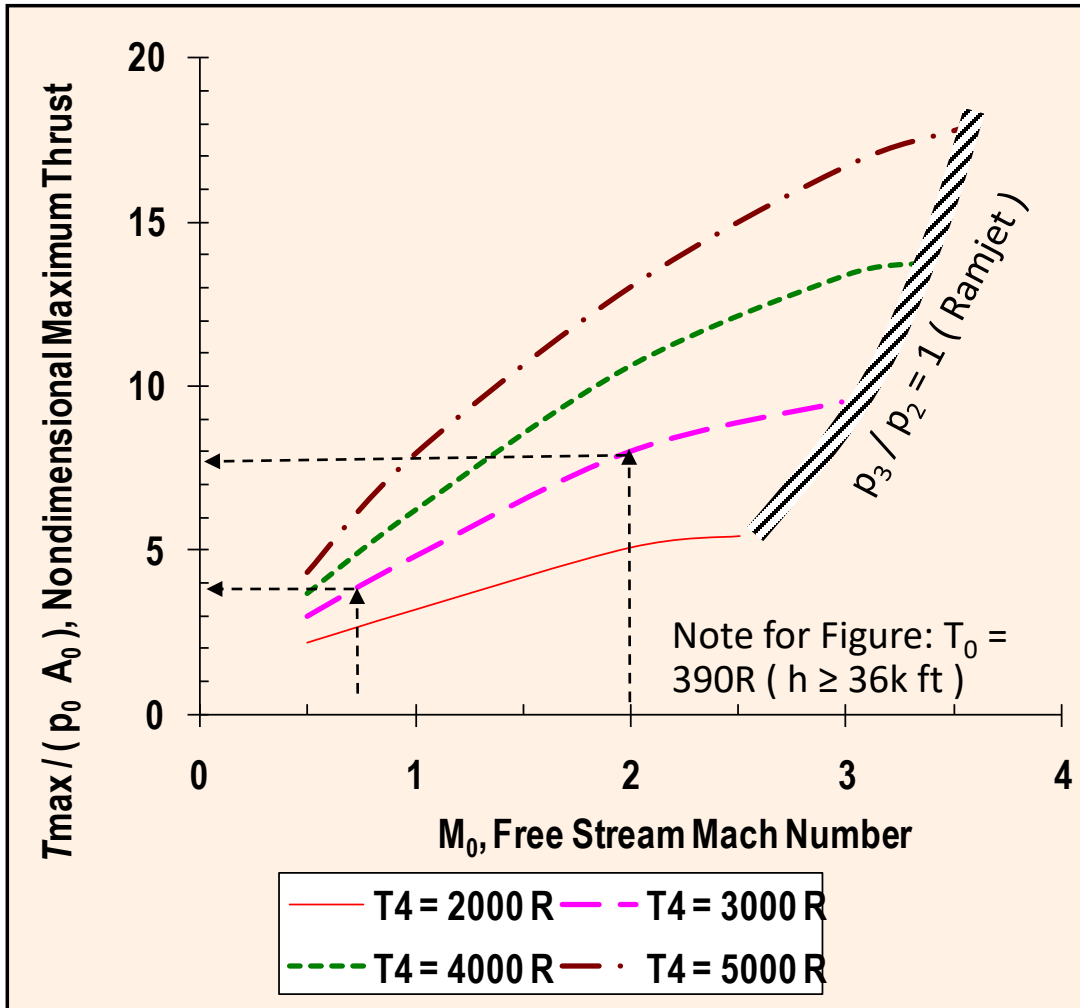
● Superior ◐ Good ○ Average — Poor

Multi-Stage Compressors Provide Higher Compressor Pressure Ratio

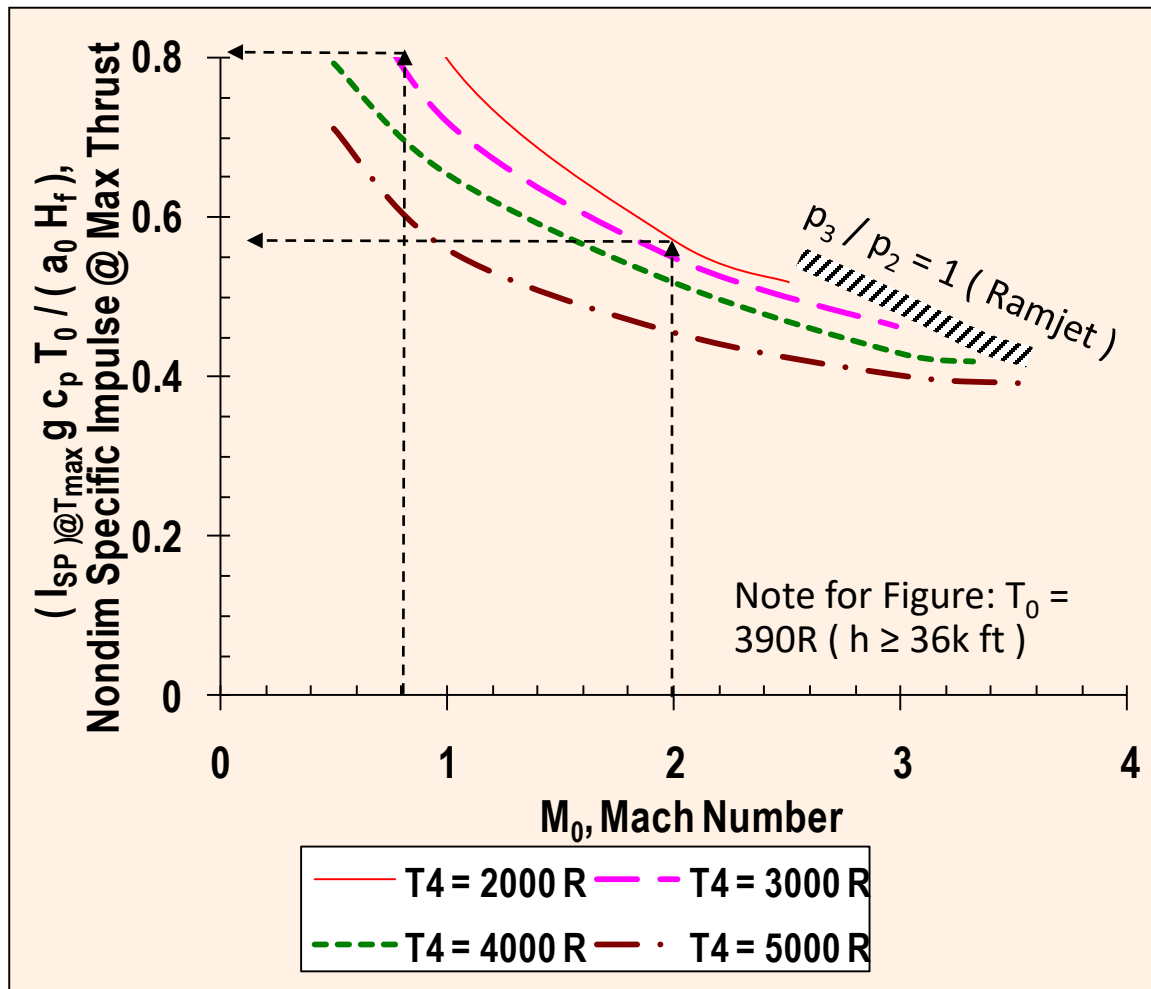


Source of Compressor Data: Howell Instruments Web Site
<http://www.howellinst.com/HowellWeb/engine.jsp>

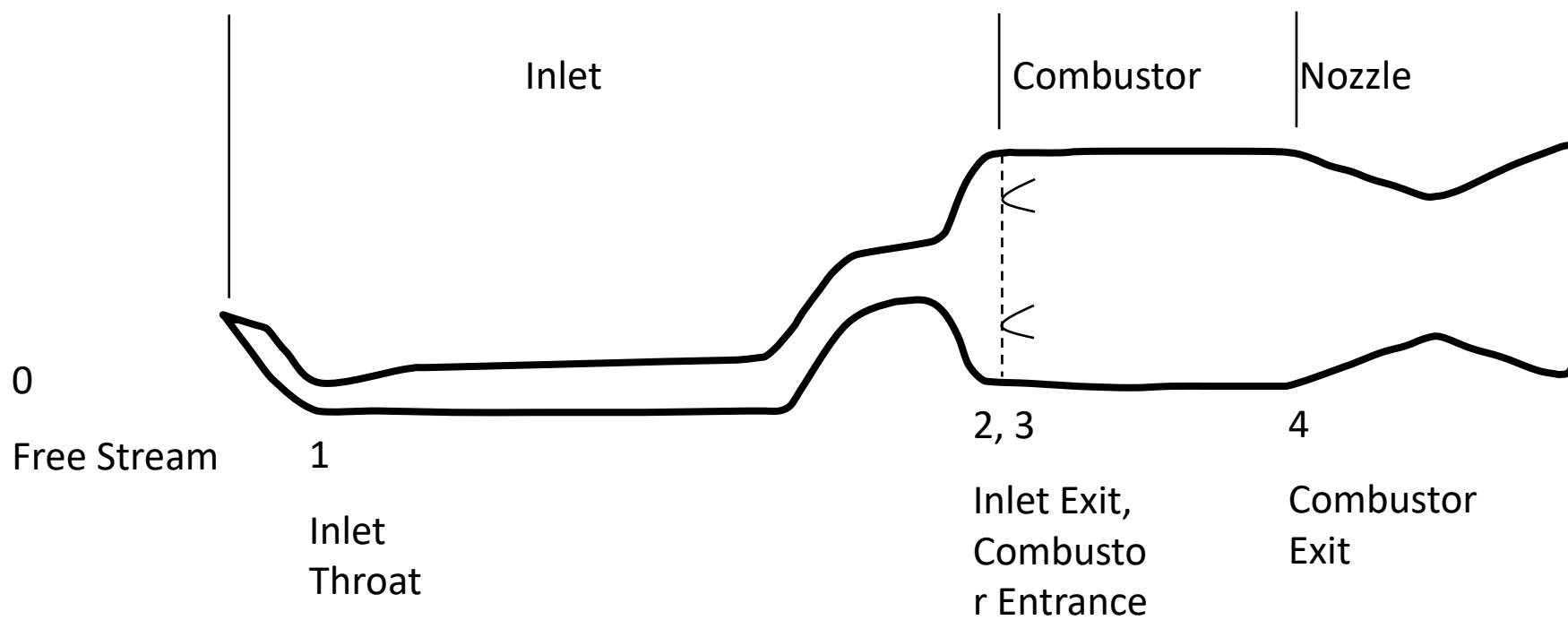
Turbojet Thrust Is Limited by Inlet Flow and Turbine Maximum Allowable Temperature



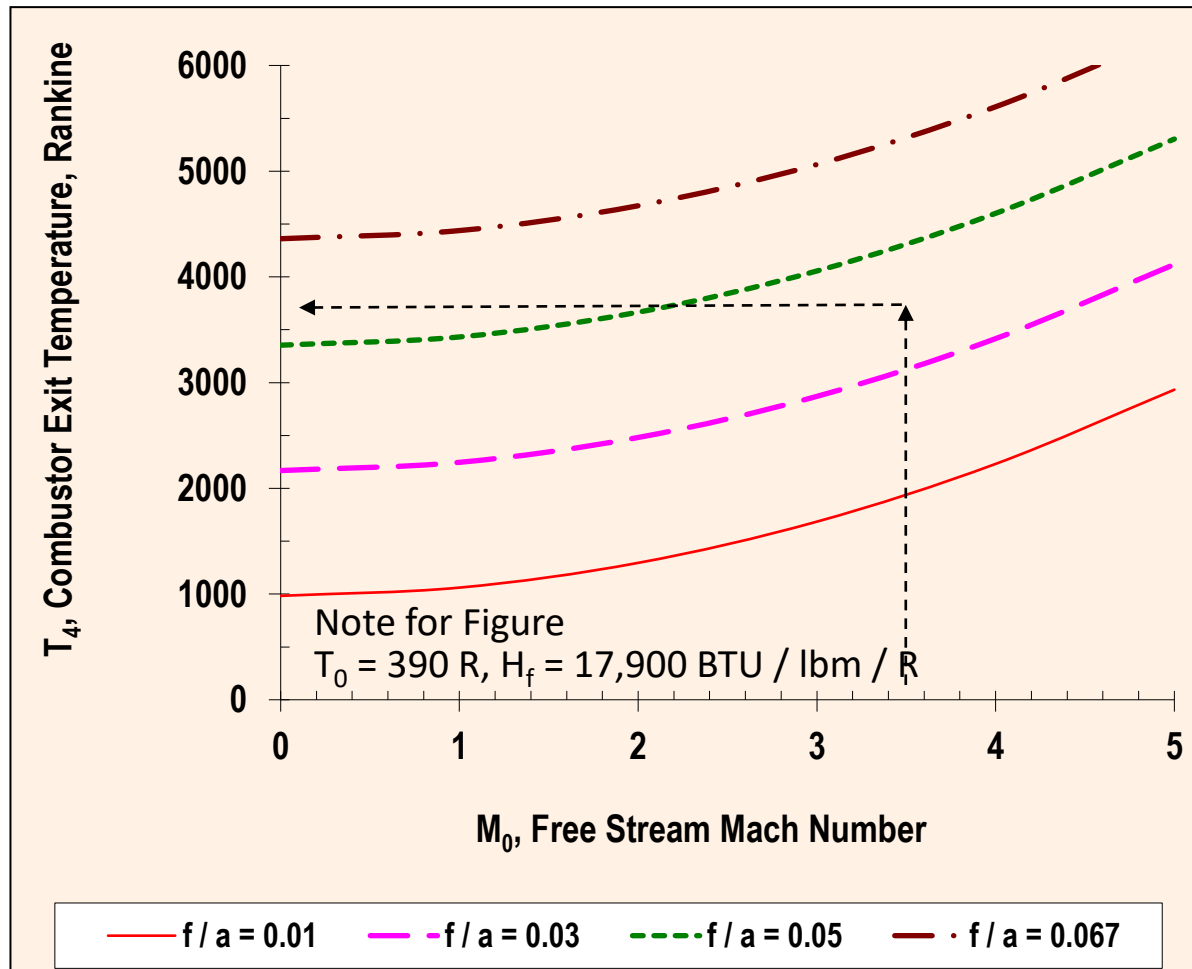
Turbojet Specific Impulse Decreases with Mach Number and Combustion Temperature



Schematic of Liquid Fuel Ramjet Engine Flow Path, Components, and Nomenclature

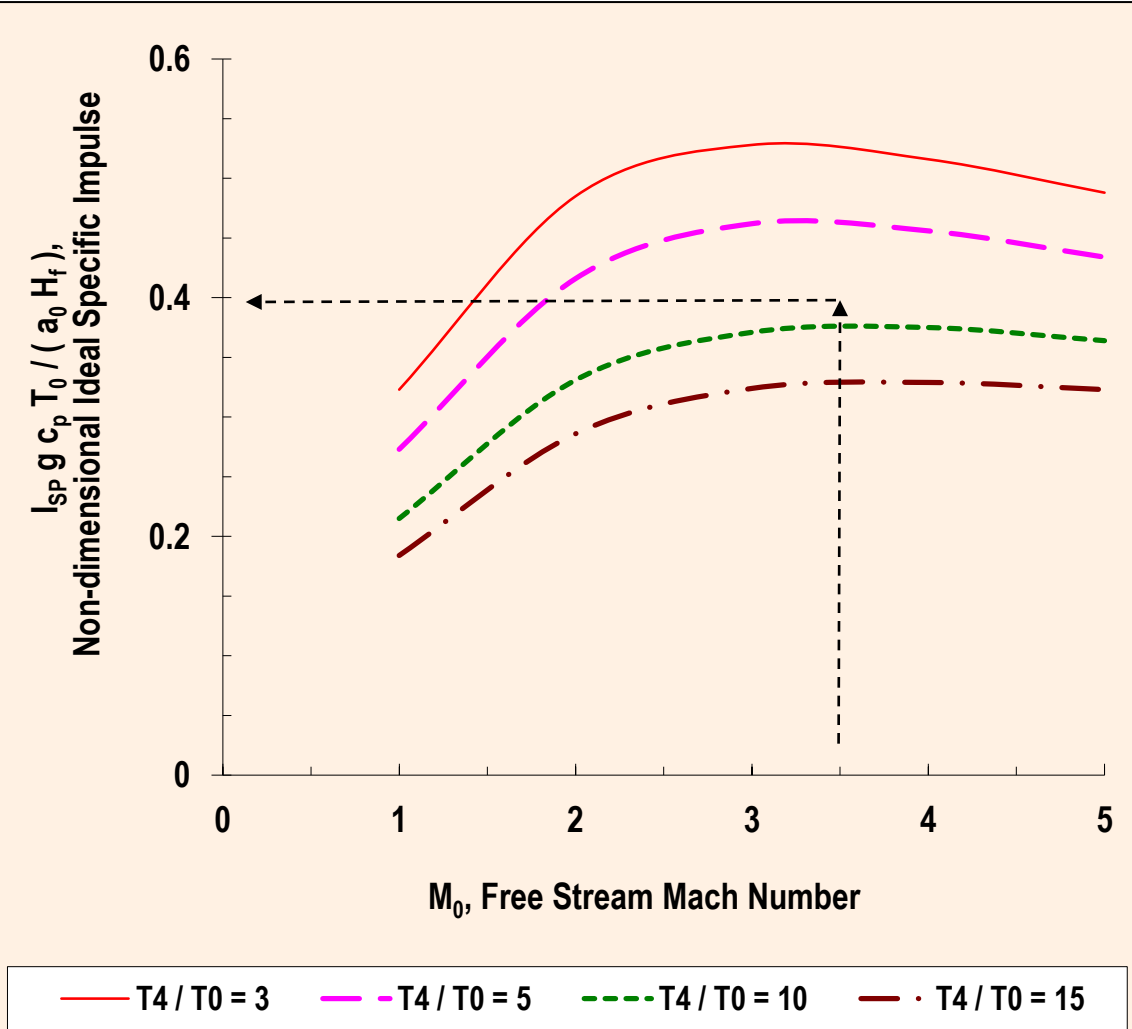


Ramjet Combustion Temperature Increases with Mach Number and Fuel Flow



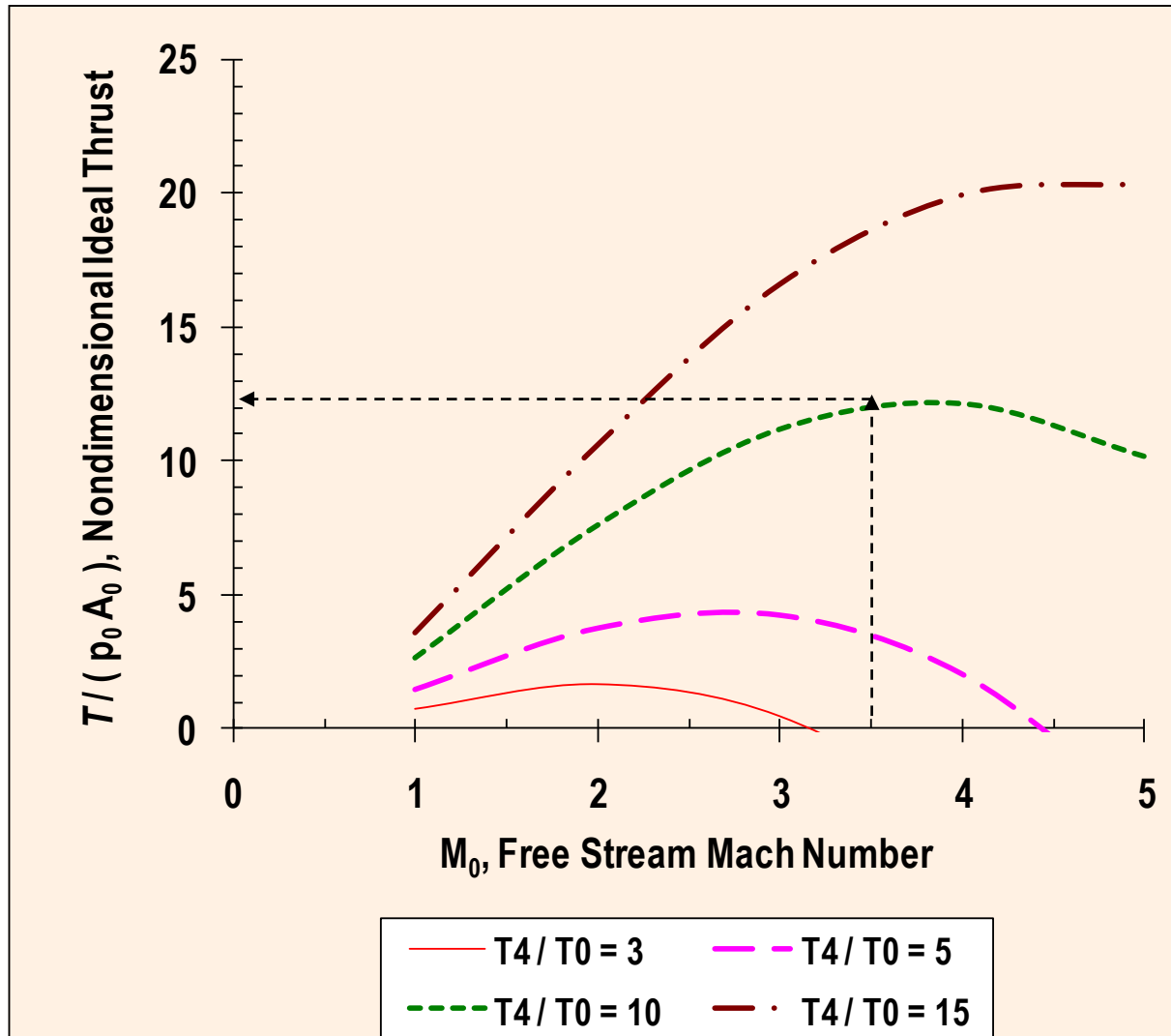
Note: $(f/a)_{\phi=1} \approx 0.067$ for stoichiometric combustion of liquid hydrocarbon fuel,

High Specific Impulse for a Ramjet Occurs with a High Heating Value Fuel in Mach 3 to 4 Flight



Source: Ashley, H., Engineering Analysis of Flight Vehicles, Dover Publications, Inc., New York, 1974
Dr. Chuck Easttom, M.Ed, MSDS, MBA, MSSE, Ph.D.², D.Sc.

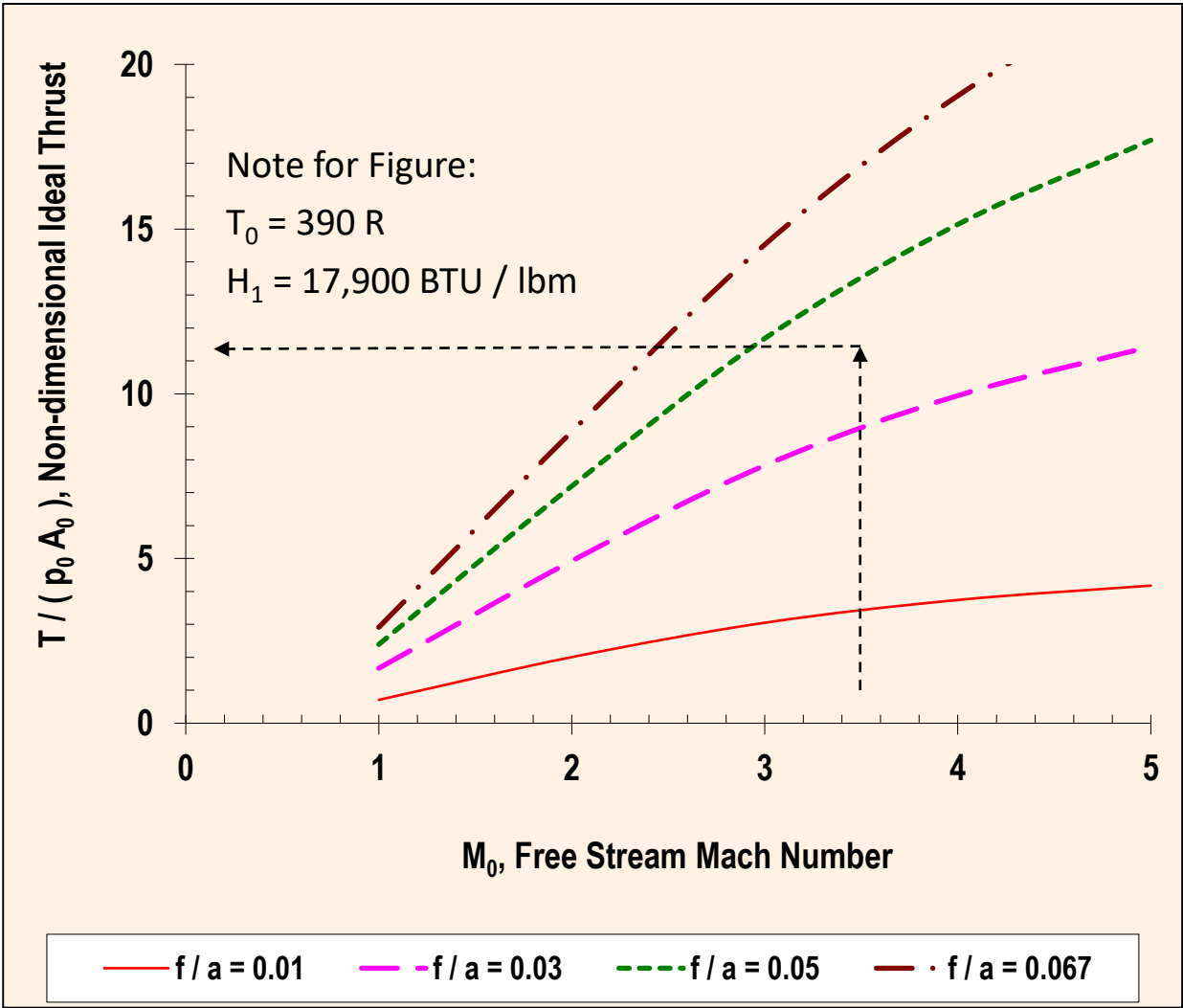
High Ramjet Thrust Occurs at Mach 3 to 5, High Combustion Temperature, and High Inlet Flow



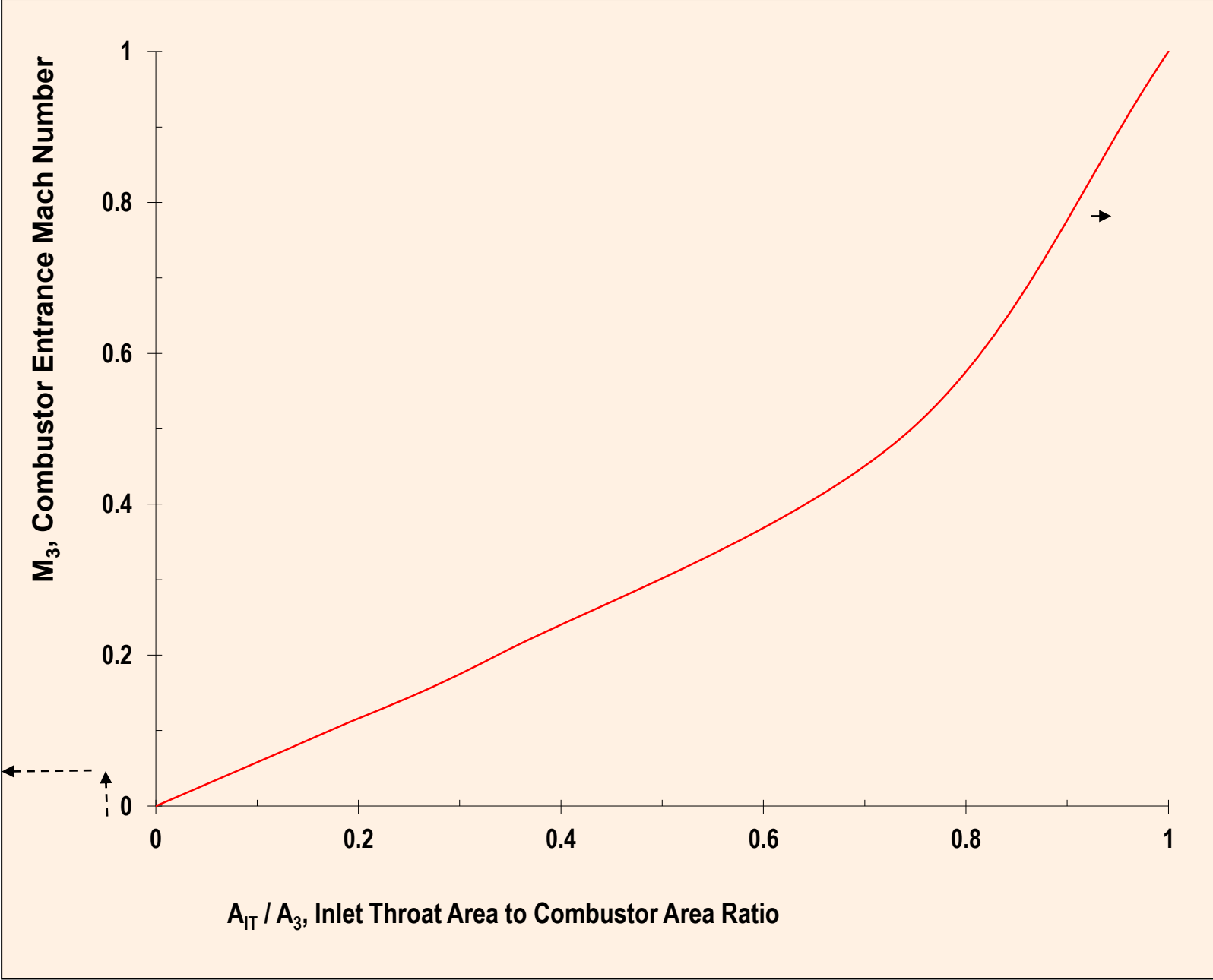
Source: Ashley, H., Engineering Analysis of Flight Vehicles, Dover Publications, Inc., New York, 1974

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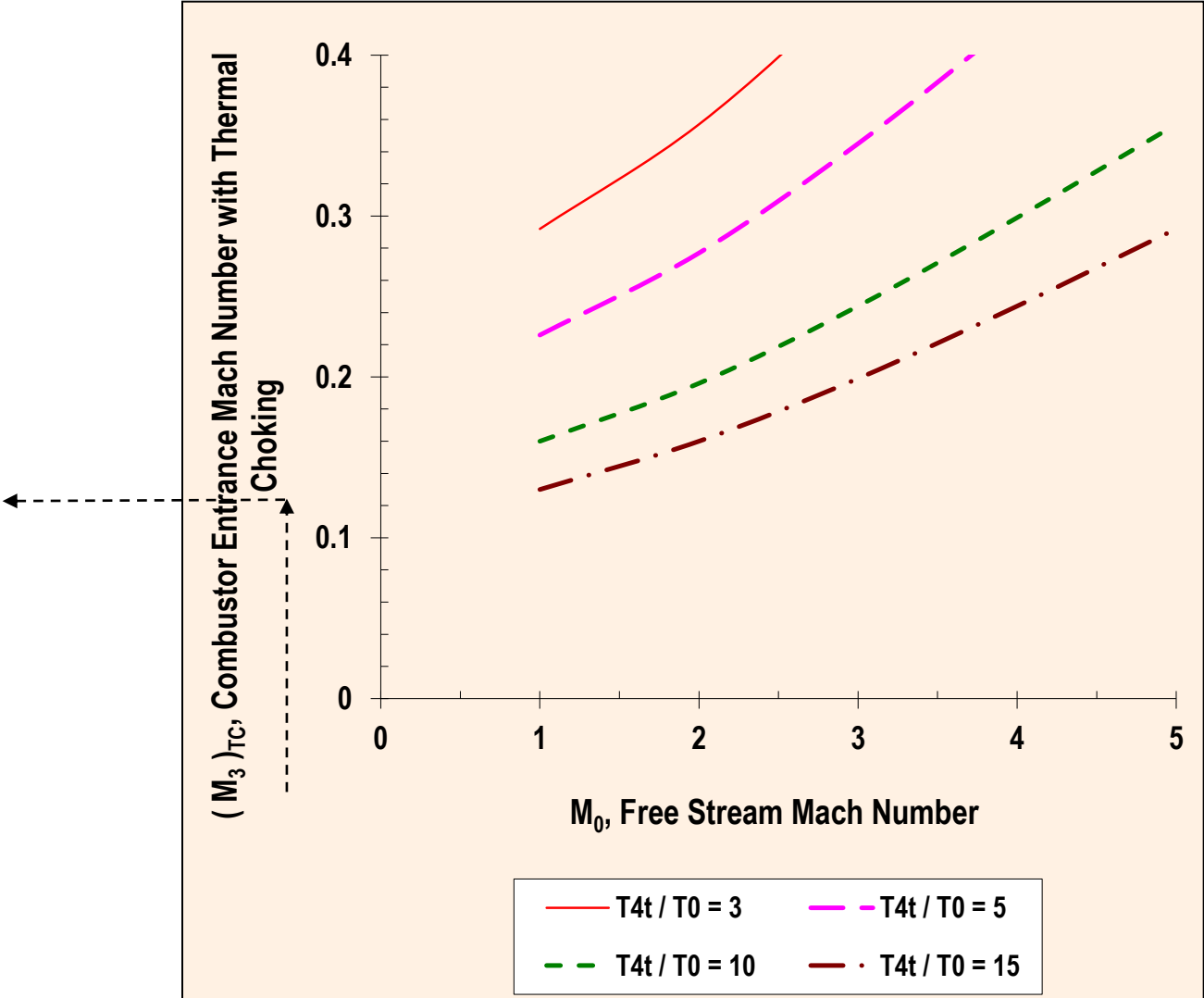
High Ramjet Thrust Occurs at High Mach Number, High Fuel Flow, and High Inlet Flow



Ramjet Inlet Throat Area Is a Tradeoff of Specific Impulse and Thrust

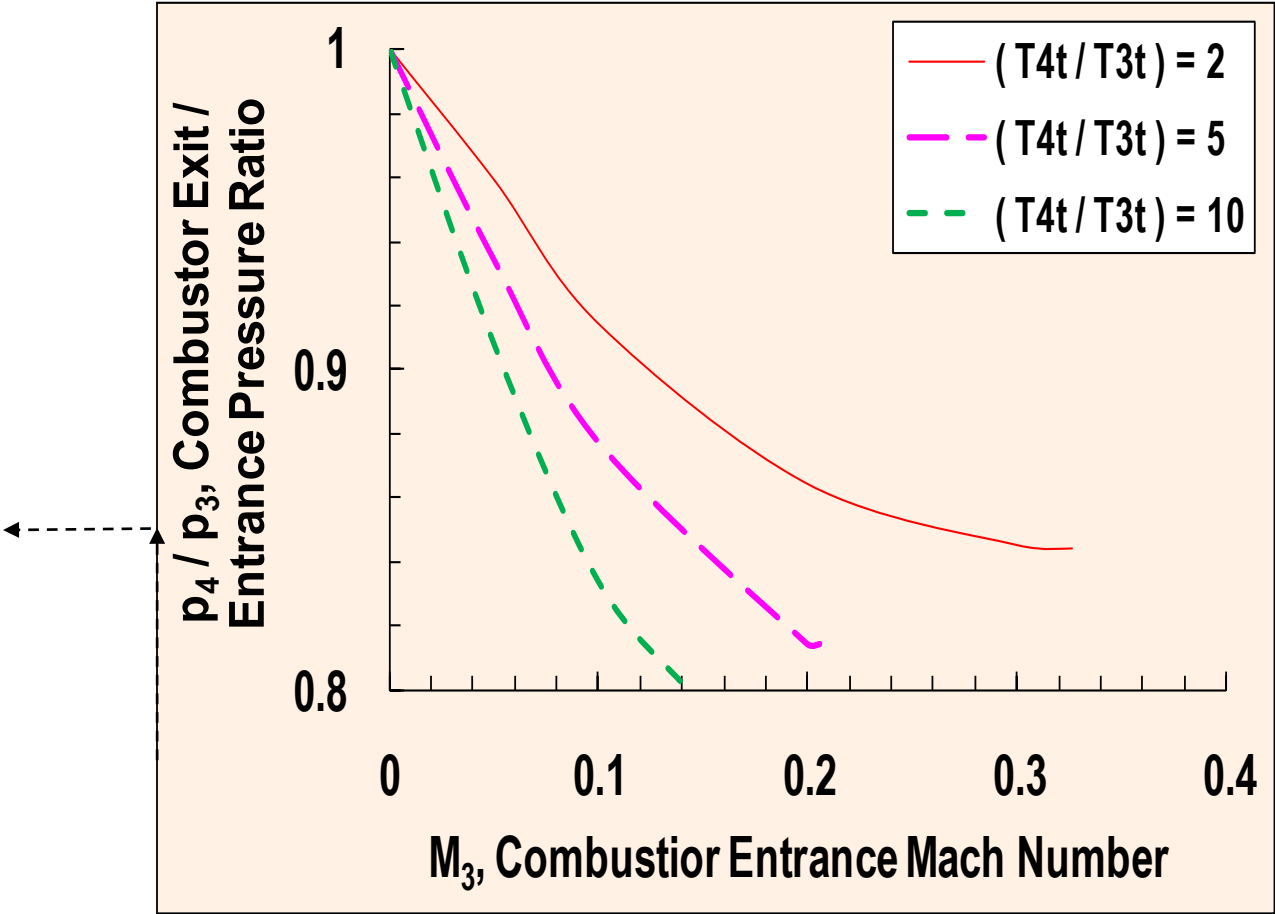


Ramjet in Low Supersonic Flight with High Temp Combustion Is Susceptible to Thermal Choking



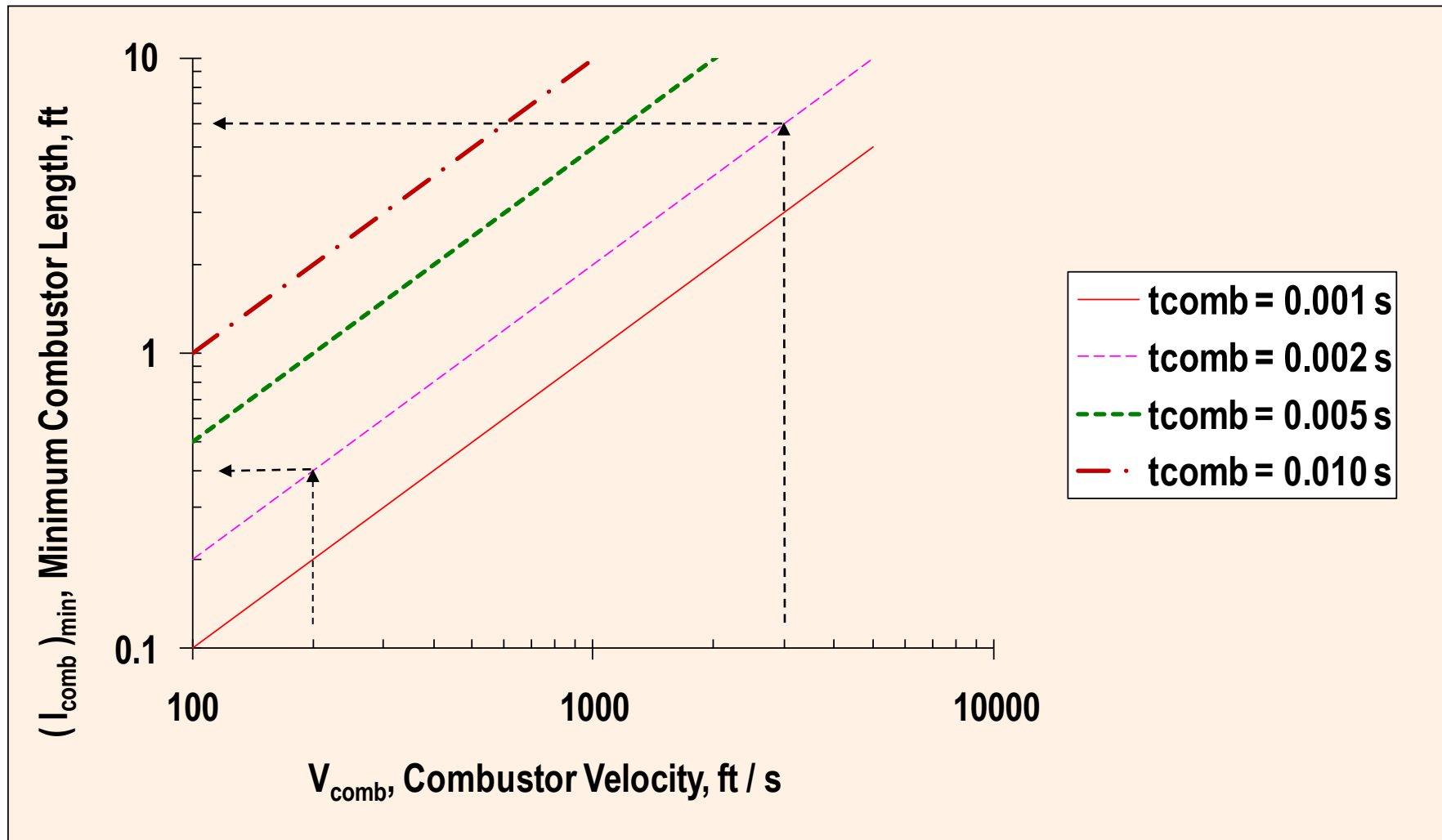
Reference: Anderson, "Modern Compressible Flow,"
 Dr. Chuck Easttom, M.Ed, MSDS, MBA, MSSE, Ph.D.², D.Sc.

A Low Mach Number into the Combustor Is Desirable for High Combustion Efficiency



Source: Anderson, "Modern Compressible Flow,"

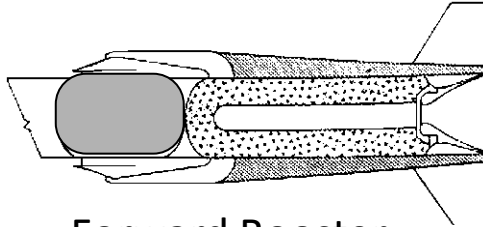
Required Length of the Combustor Is a Function of Combustor Velocity



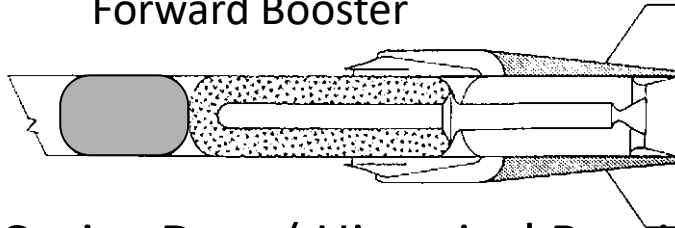
Ramjet Engine / Booster Integration Options

Low Cruise Drag (Modern Ramjets)

Integral-Rocket Ramjet (IRR)

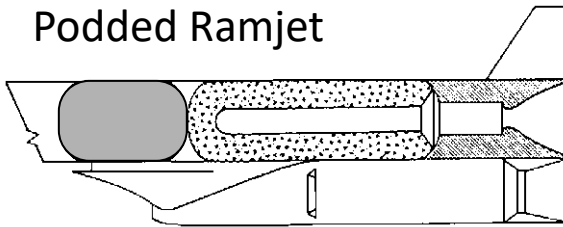


Forward Booster

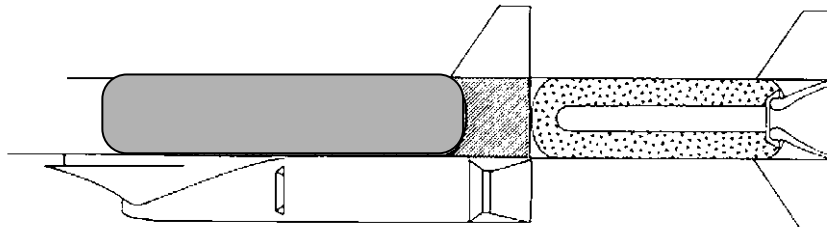


High Cruise Drag (Historical Ramjets)

Podded Ramjet



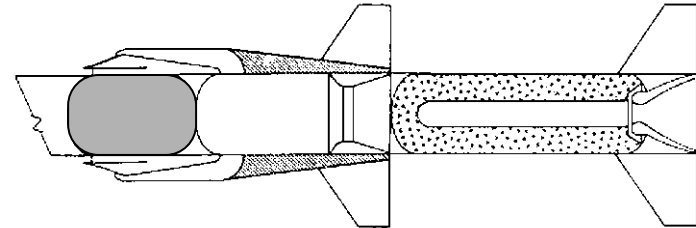
Podded Ramjet, Aft Drop-off Booster



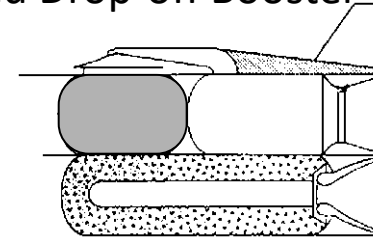
Fuel 

Boost Propellant 

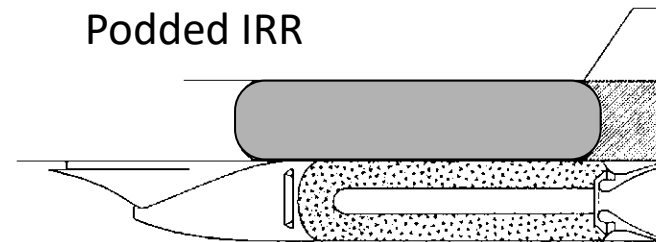
Aft Drop-off Booster



Podded Drop-off Booster



Podded IRR



Source: Kinroth, G.D. and Anderson, W.R., "Ramjet Design Handbook," CPIA Pub. 319, June 1980

Ramjet Engine / Booster / Inlet Integration Trades

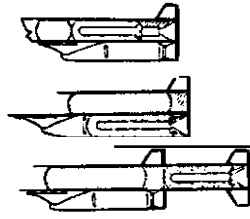
		Selection Factors						Engine - Booster Compatibility	Engine - Inlet Compatibility	
		Length	Diameter	Weight	Ejectables	Cruise Drag	Carry Drag	Cost		
Integral Rocket – Ramjet (IRR)		☐	●	●	☐	●	●	☐	☐	●
Aft Booster (Drop-off)		—	●	○	—	●	☐	●	☐	●
Forward Booster		—	●	○	●	☐	●	○	○	○
Podded Booster (Drop-off)		●	—	○	—	●	○	●	☐	☐
Podded Ramjet		☐	—	○	●	—	○	☐	○	—
Podded IRR		●	—	☐	☐	—	○	○	○	—
Podded Ramjet Aft Booster (Drop-off)		○	—	—	—	—	—	☐	○	—

● Superior ☐ Good ○ Average — Poor

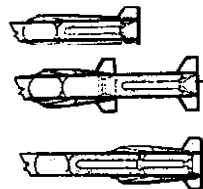
Source: Kinroth, G.D. and Anderson, W.R., "Ramjet Design Handbook," CPIA Pub. 319, June 1980

Ramjets with Internal Boosters and No Wings Have Lower Drag

- Podded Ramjet
- Podded IRR
- Podded Ramjet, Aft Drop Off Booster



- IRR
- Aft Drop Off Booster
- Forward Booster



With Wings

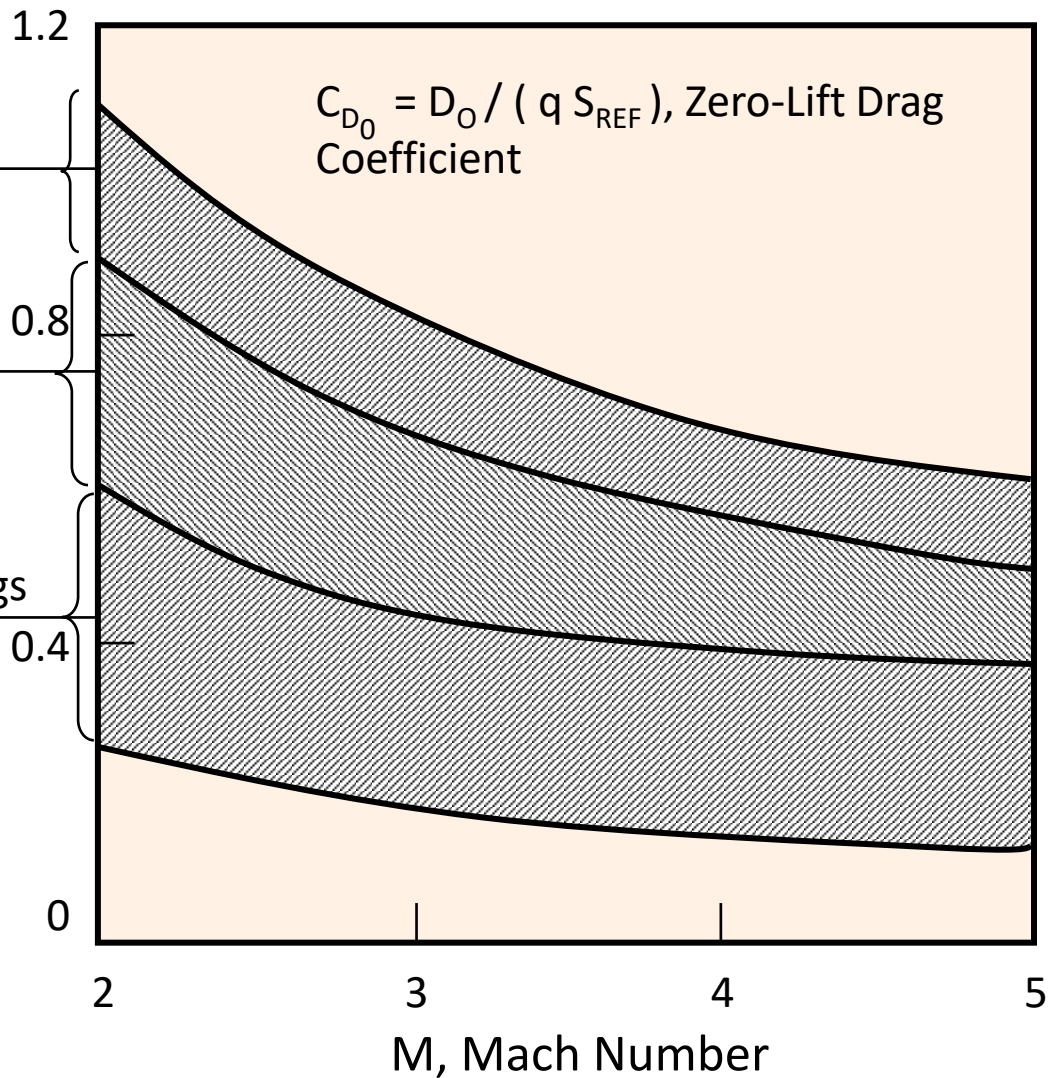
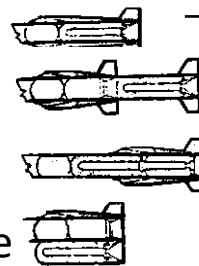
- Podded Drop Off Booste



C_{D0}

Without Wings

- IRR
- Aft Drop-off Booster
- Forward Booster
- Podded Drop-off Booste



Note:

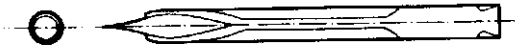
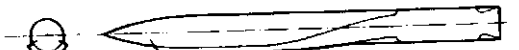
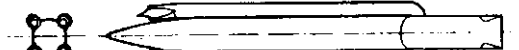
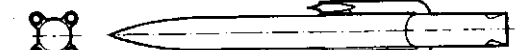
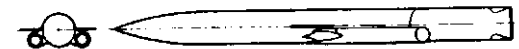
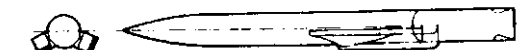
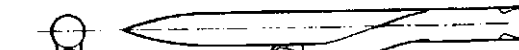
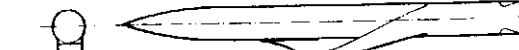
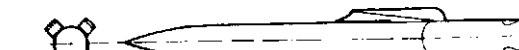
Nose Fineness Ratio ≥ 2.25

Nose Bluntness Ratio ≤ 0.20

Source: Kinroth, G.D. and Anderson, W.R., "Ramjet Design Handbook," CPIA Pub. 319, June 1980

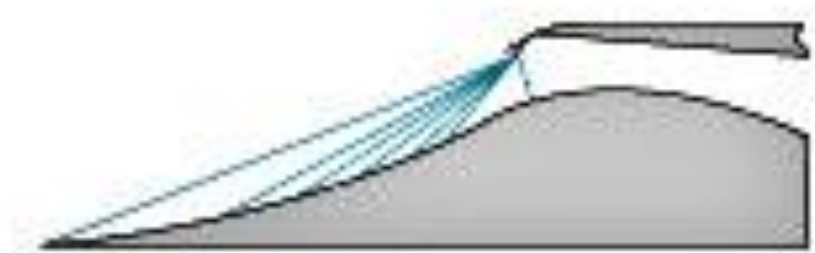
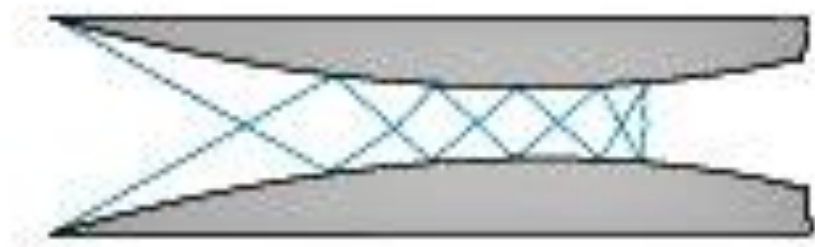

Dr. Chuck Easttom, M.Ed, MSDS, MBA, MSSE, Ph.D.², D.Sc.

Ramjet Inlet Options

Type Inlet	Sketch	Placement
Nose		Annular nose inlet
Chin		Forward underside in nose compression field – partial annular
Forward Cruciform Annular		Forward in nose compression field - cruciform (four) annular inlets
Aft Cruciform Annular		Aft-cruciform (four) annular inlets
Under Wing Annular		In planar wing compression field - twin annular inlets
Twin Two-dimensional		Aft - twin cheek-mounted two dimensional inlets
Underslung Annular		Aft underside - full annular
Underslung Two-dimensional		Aft underside - belly mounted two dimensional inlets
Aft Cruciform Two-dimensional		Aft - cruciform (four) two dimensional inlets

Source: Kinroth, G.D. and Anderson, W.R., "Ramjet Design Handbook," CPIA Pub. 319, June 1980.

Supersonic Inlet / Airframe Integration Tradeoffs Include Drag, Pressure Oscillation, and Inlet Start

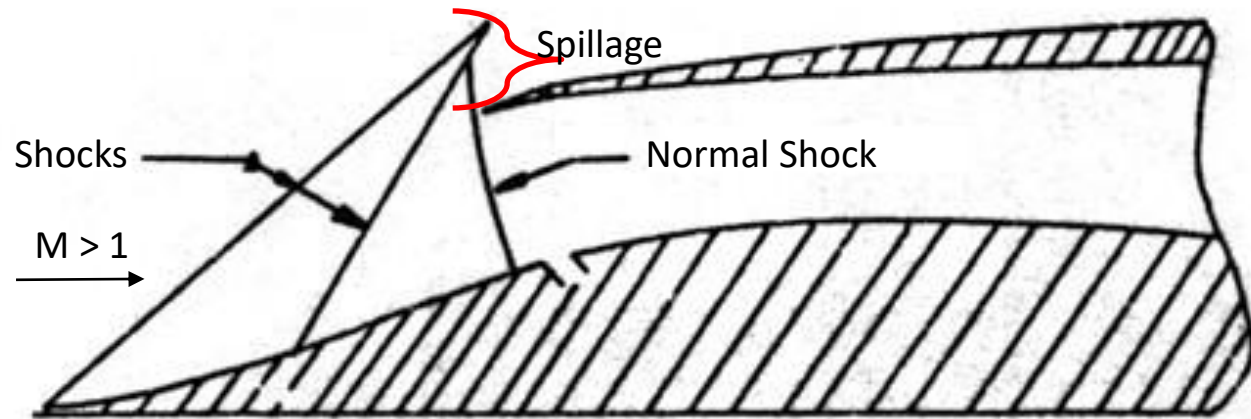
Type	<u>Drag</u>	<u>Pressure Oscillation</u>	<u>Inlet Start Mach Number</u>
 External Compression	—	●	●
 Internal Compression	●	—	—
 Mixed Compression	○	○	○

● Superior
 ◐ Good
 ○ Average
 — Poor

A Supersonic External Compression Inlet with Shock Wave(s) on Cowl Lip Prevents Spillage

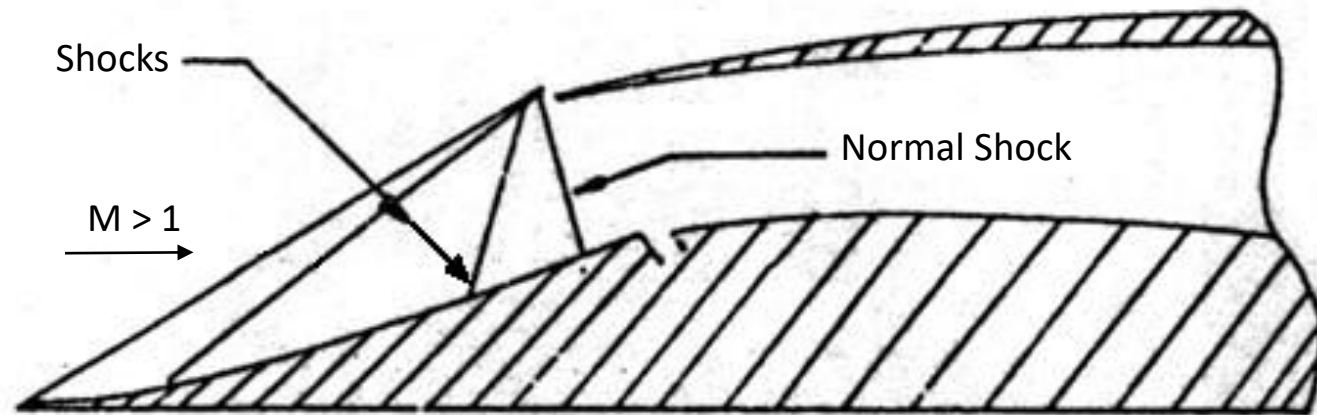
External Compression Inlet with Spillage

Shock Waves Converge Outside Inlet Cowl Lip (Results in Spillage Air)

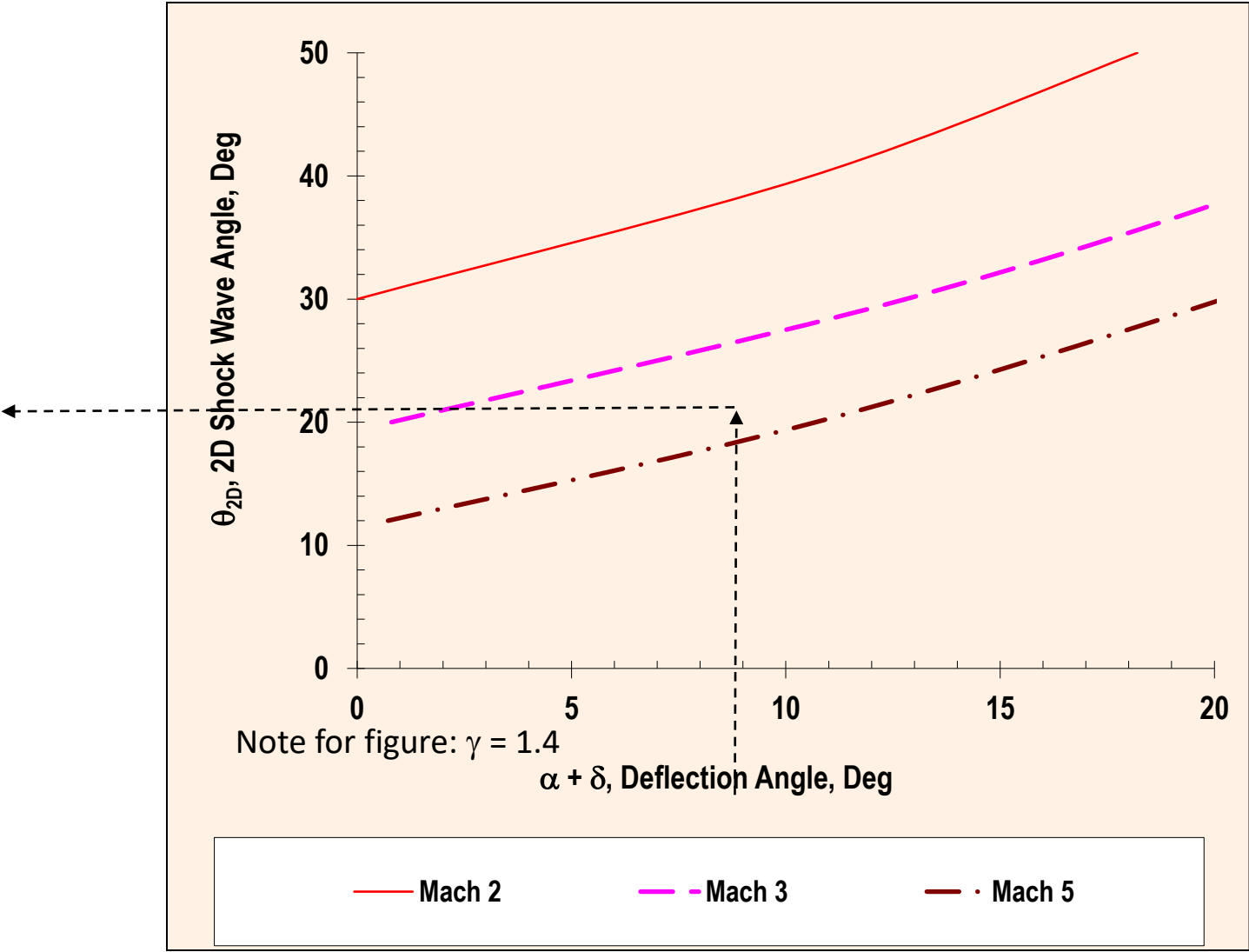


External Compression Inlet w/o Spillage

- Inlet Swallows 100% of the Free Stream Flow
- Shock Waves Converge at Inlet Cowl Lip (Inlet Captures Maximum Free Stream Flow)



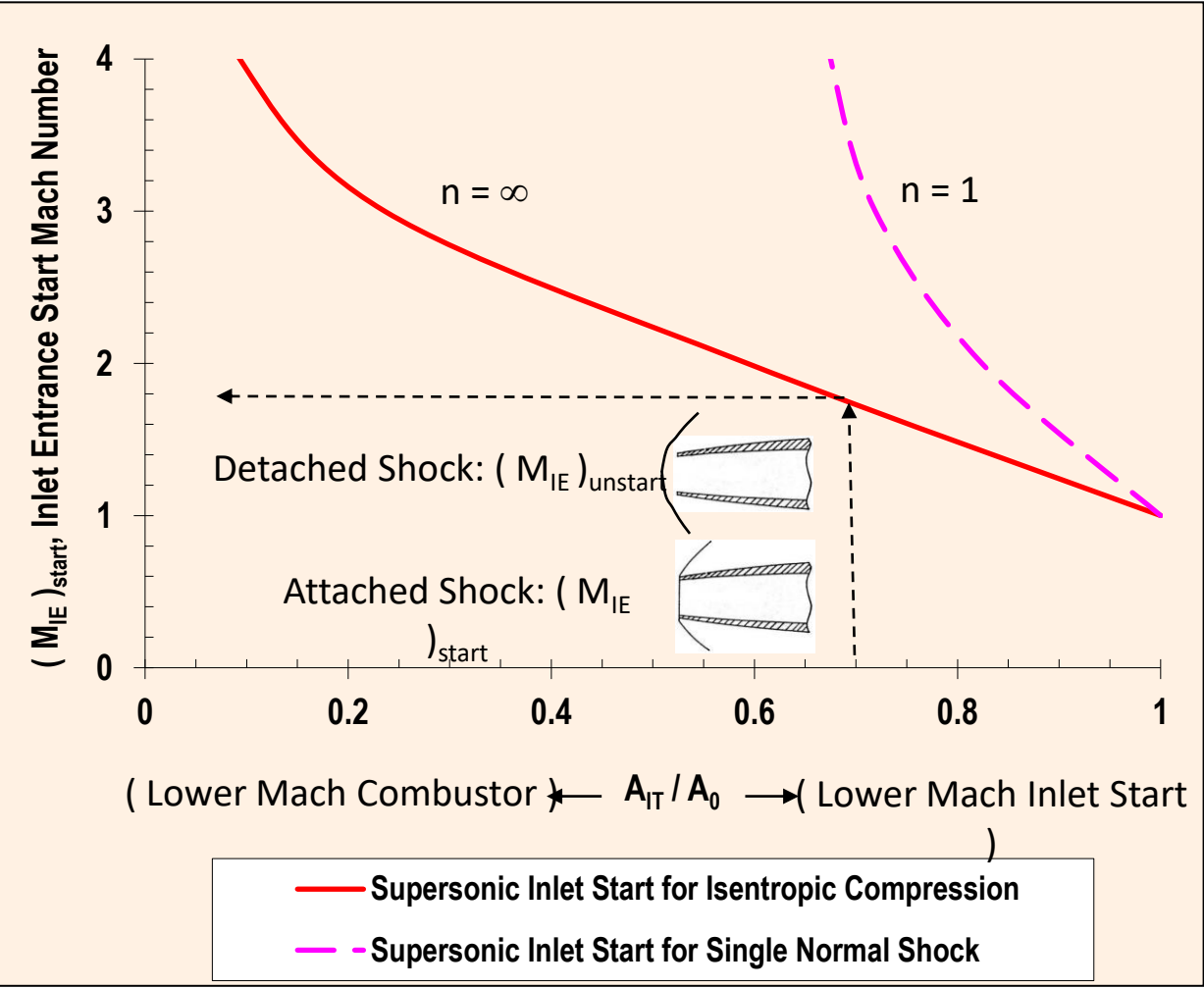
Shock Wave Angle Is Driven by Deflection Angle and Mach Number



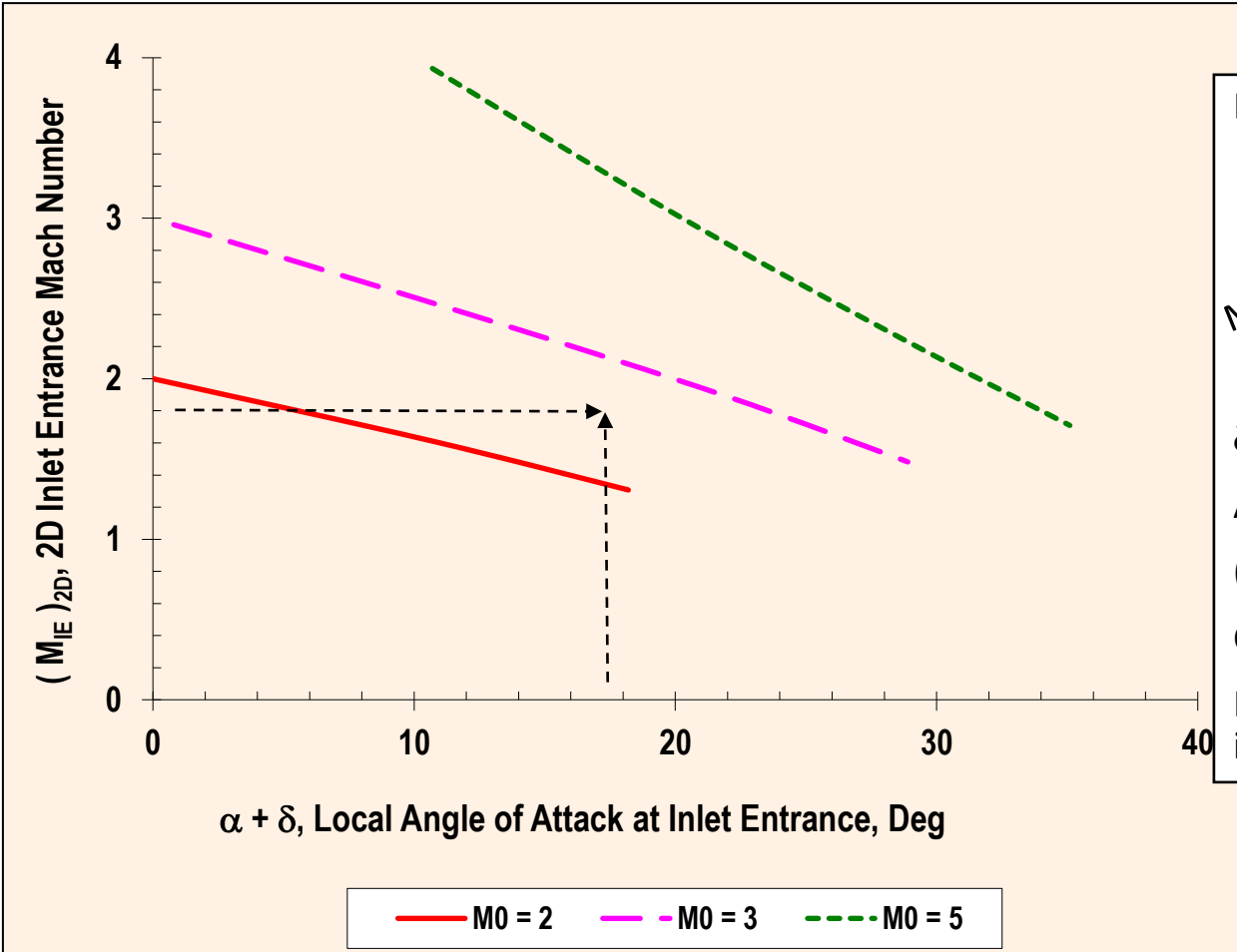
Deflection angle

In aerospace, a deflection angle refers to the angle at which a control surface (like an aileron, elevator, or rudder) is rotated from its neutral position. This rotation changes the shape of the airfoil and, consequently, the aerodynamic forces (lift, drag, etc.) acting on it, allowing the pilot to control the aircraft's movement in roll, pitch, and yaw

Isentropic Compression Allows Supersonic Inlet Start at Lower Mach Number



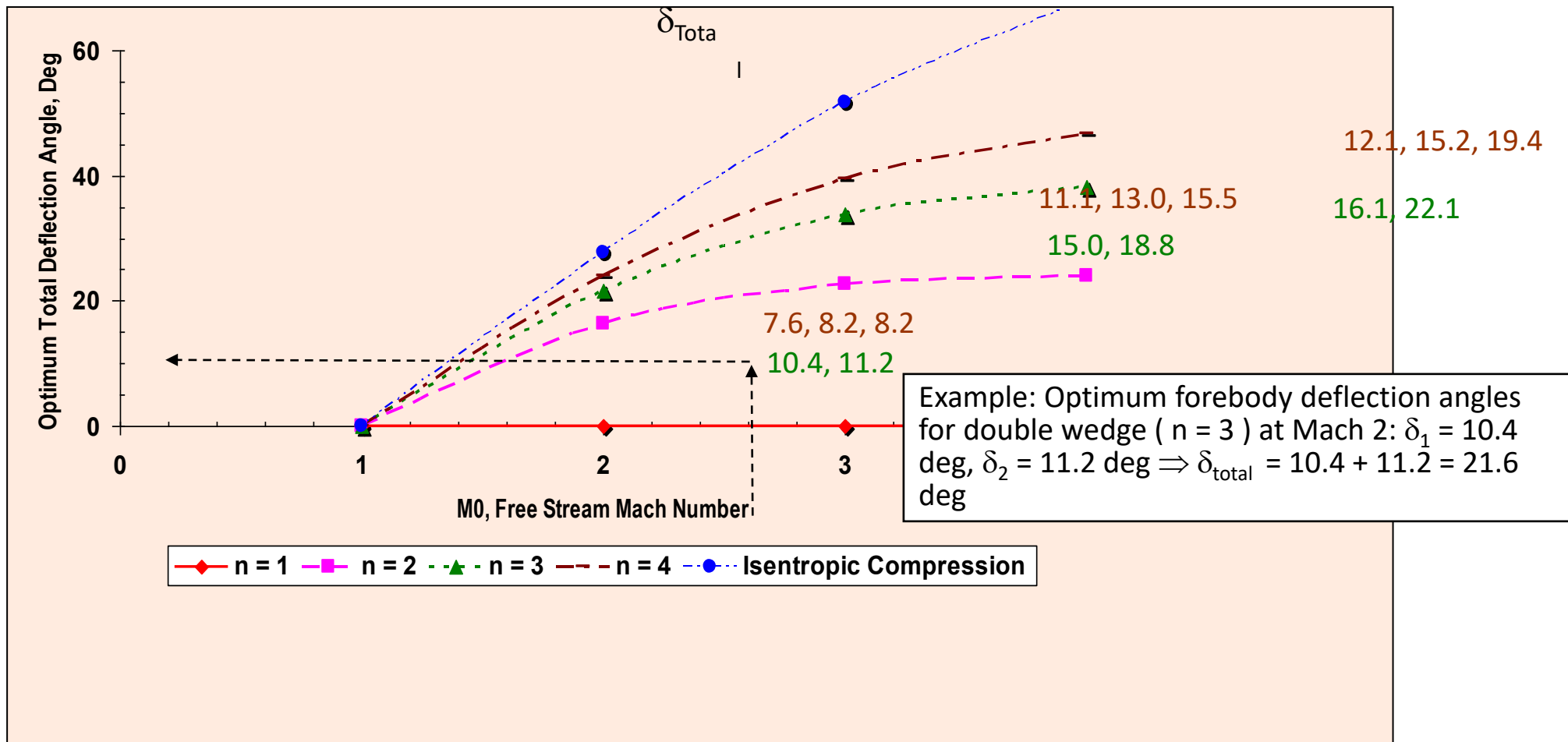
Forebody Shock Wave Compression Reduces the Inlet Entrance Mach Number



Example for ramjet baseline forebody

$\delta = 17.7$ deg
 Assume $\alpha = 0$ deg
 $(M_{IE})_{start} = 1.8$ (from prior example)
 Compute $M_0 = 2.55$
 Note: Ramjet baseline missile forebody is conical, not 2D


Optimum Forebody Deflection Angle(s) for Best Pressure Recovery Increases with Mach Number



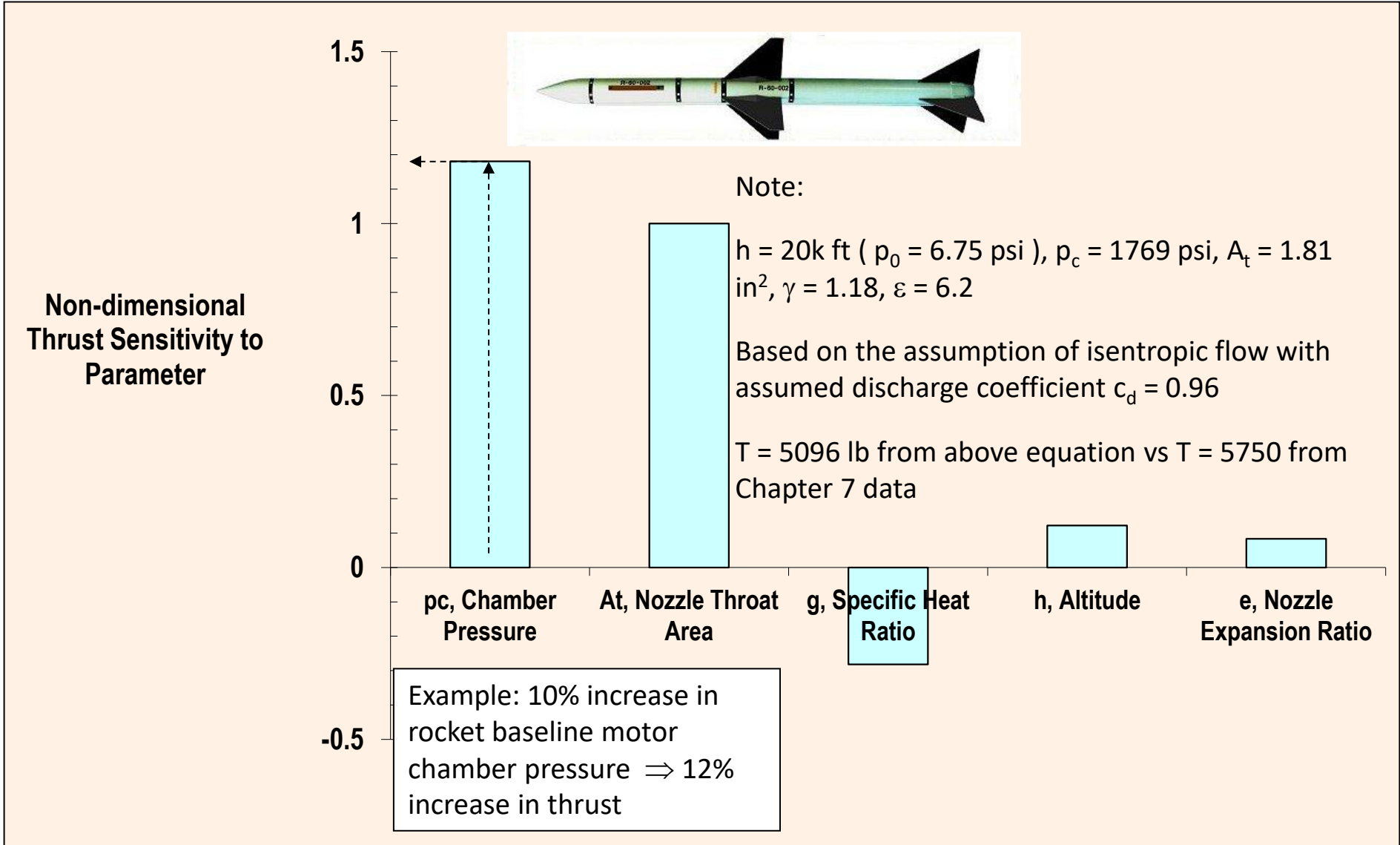
Reference: "Technical Aerodynamics Manual," North American Rockwell Corporation, DTIC AD 723823, June 1970.

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

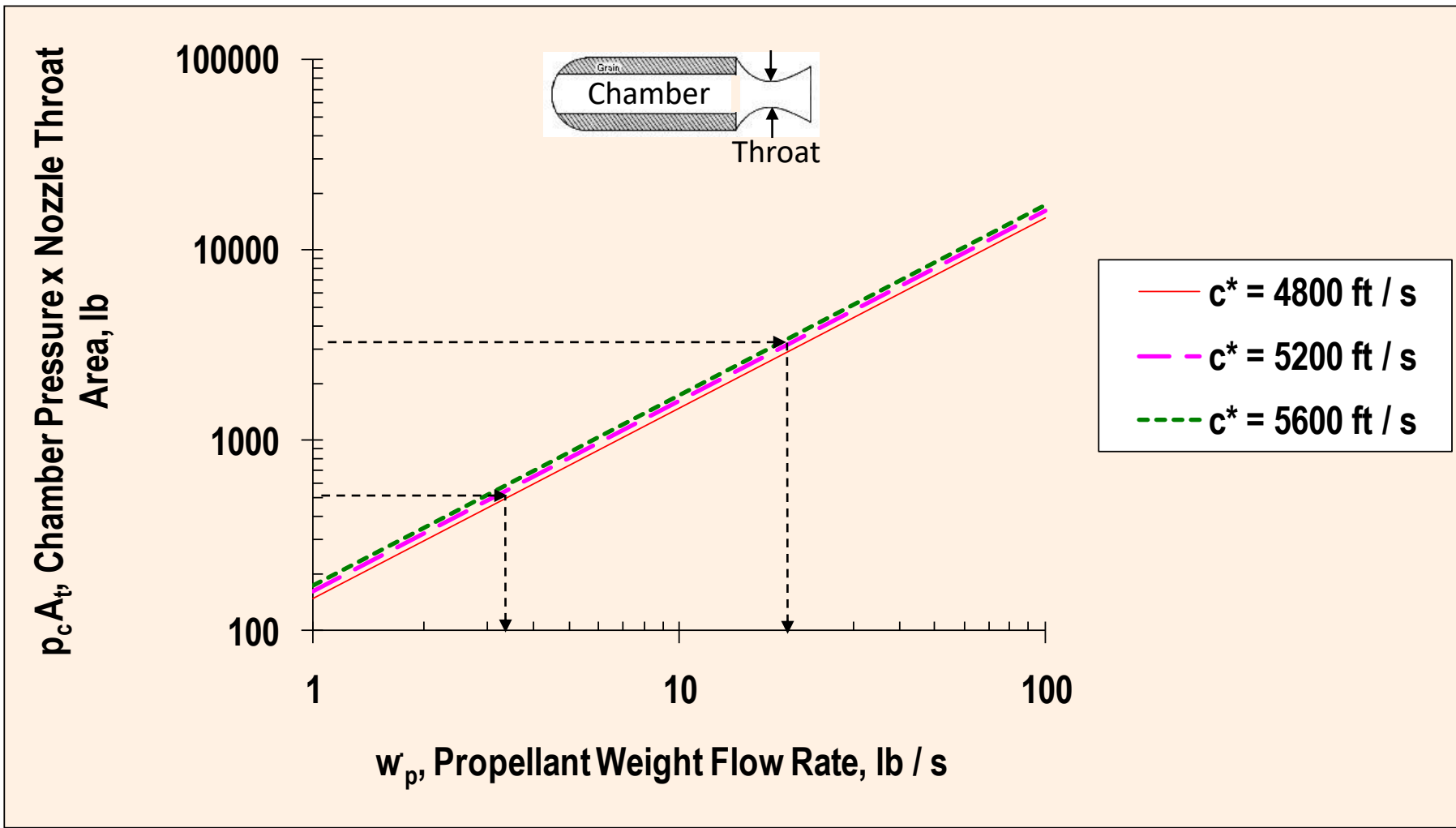
High Density Fuels Provide Higher Volumetric Performance, but Have Higher Observables

Type	Fuel	Density, lbm / in ³	Volumetric Performance, BTU / in ³
Hydrocarbon  Metal	Turbine (JP-4, JP-5, JP-7, JP-8, JP-10)	~ 0.031	~ 559
	Liquid Ramjet (RJ-4, RJ-5, RJ-6, RJ-7)	~ 0.037	≈ 648
	HTPB	~ 0.034	606
	Slurry (40% JP-10 / 60% carbon)	~ 0.049	801
	Solid Carbon (graphite)	~ 0.075	1132
	Slurry (40% JP-10 / 60% aluminum)	~ 0.072	866
	Slurry (40% JP-10 / 60% boron carbide)	~ 0.050	1191
	Solid Mg	~ 0.068	1200
	Solid Al	~ 0.101	1300
	Solid Boron	~ 0.082	2040

Rocket Baseline Pareto Shows Thrust Drivers Are Chamber Pressure and Nozzle Throat Area

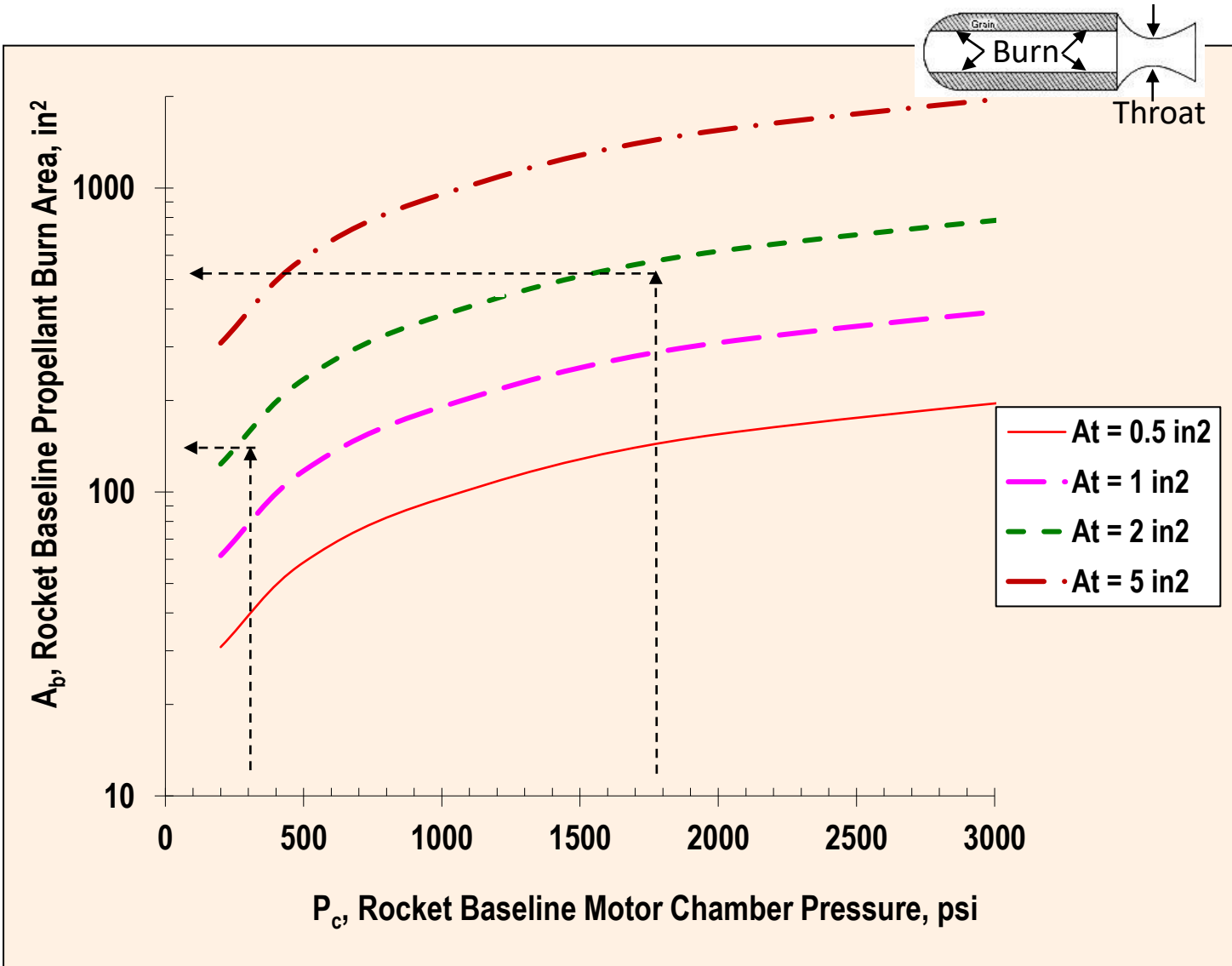


High Propellant Weight Flow Rate Is Driven by High Chamber Pressure and Nozzle Throat Area



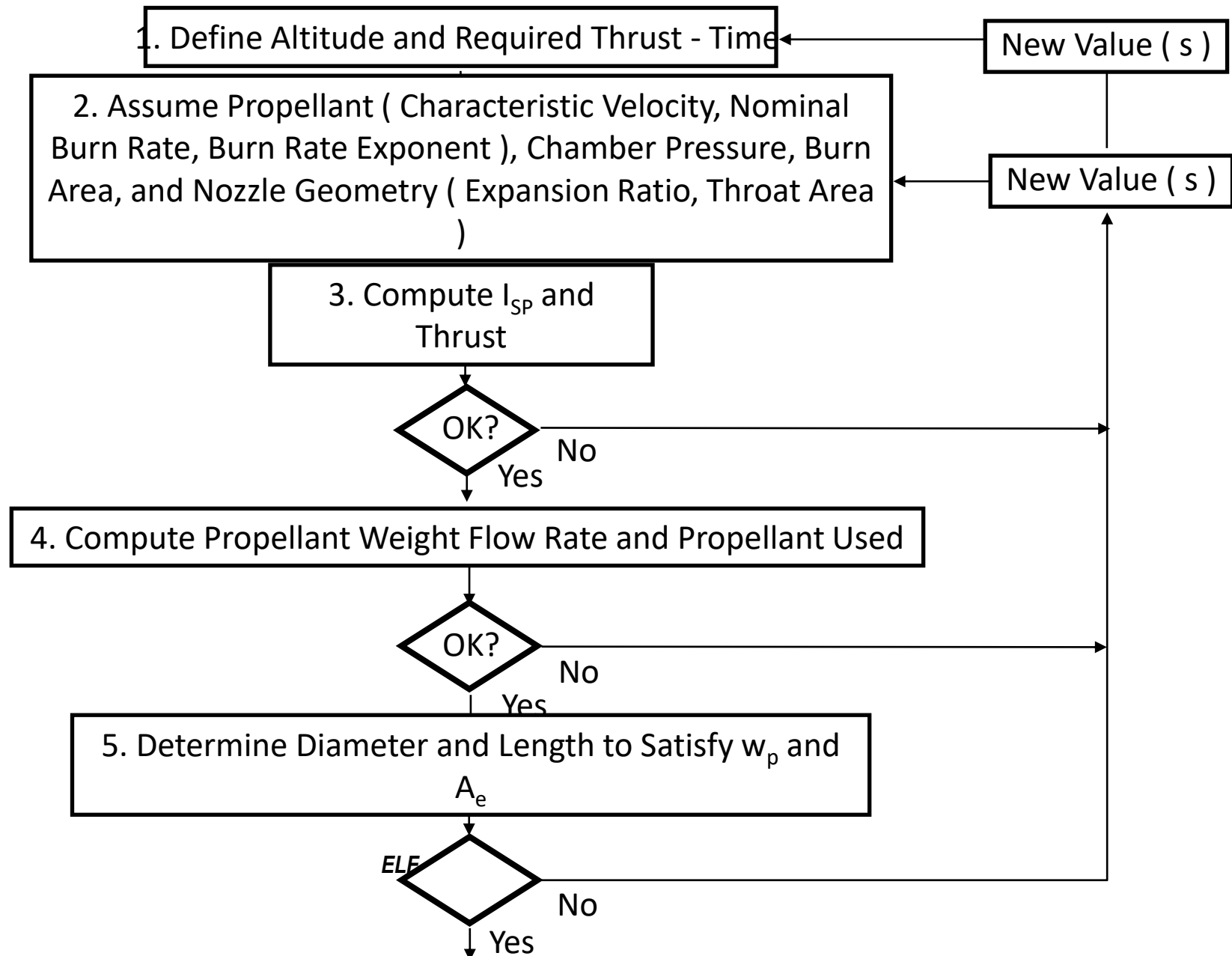
Note: A_t = nozzle throat area, c^* = characteristic velocity, w_p = propellant weight flow rate, g_c = gravitational constant = 32.2 lbf ft / (lbf s²), p_c = chamber pressure

Rocket Motor Chamber Pressure Is Driven by Propellant Burn Area and Nozzle Throat Area



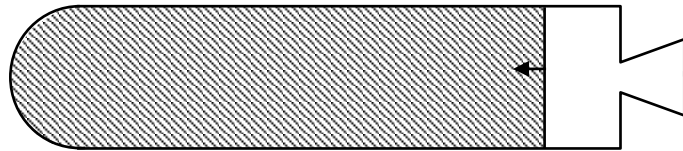
Note: A_b = propellant burn area, g_c = gravitational constant = 32.2 lbf ft./ (lbf s²), A_t = nozzle throat area, ρ = density of propellant, c^* = propellant characteristic velocity, r = propellant burn rate, $r_{p_c=1000 \text{ psi}}$ = propellant burn rate at $p_c = 1,000$ psi, p_c = chamber pressure, n = propellant burn rate exponent

Conceptual Design Sizing of a Solid Propellant Rocket Motor Is an Iterative Process

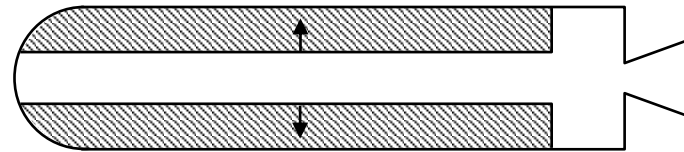


Thrust Magnitude Control Provides Flexibility of Missile Propulsion Energy Management

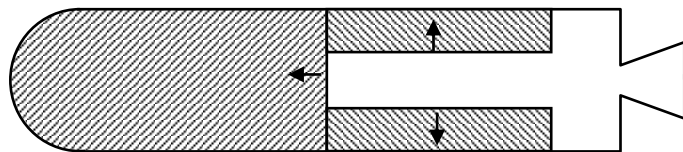
Examples of Conventional Fixed Burn Interval



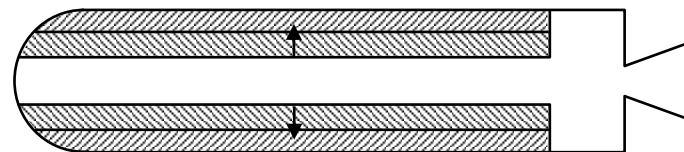
End Burning



Radial Burning

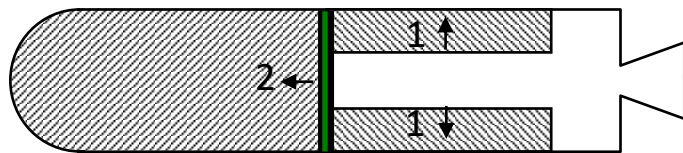


Radial Boost
End Burning Sustain
Simultaneous Burning

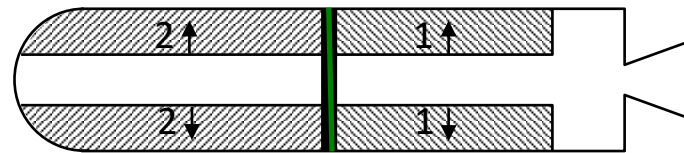


Concentric Radial Burning
High Burn Rate Boost
Low Burn Rate Sustain

Examples of Pulse Motor TMC Variable Burn Interval

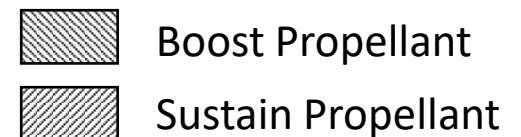


1st Pulse: Radial Boost
2nd Pulse: End Burning Sustain
Separate Burning (Pulsed Motor)



1st Pulse: Radial Boost
2nd Pulse: Radial Sustain / Boost
Separate Burning (Pulsed Motor)

Note: Each pulse increases motor cost approximately 40%.



Missile Rocket Motor Thrust Magnitude Control Alternatives and Tradeoffs

Solid Propellant Pulse

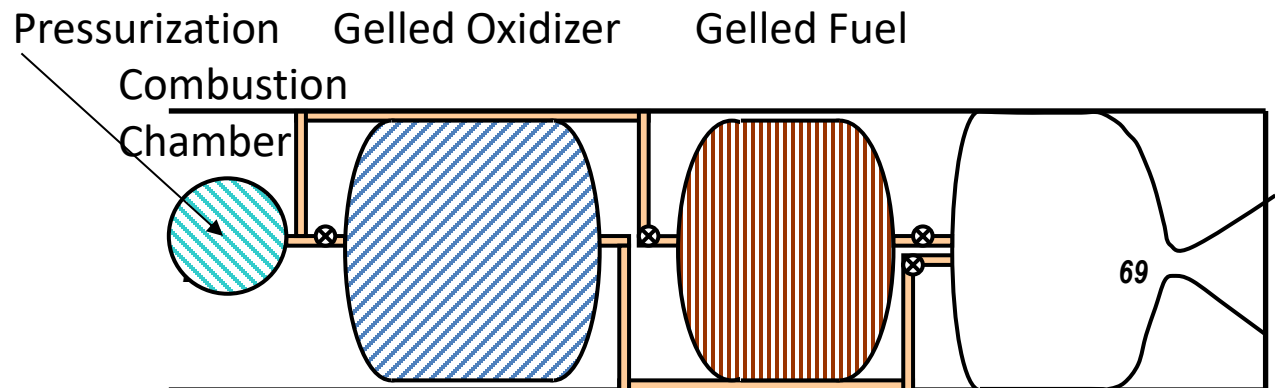
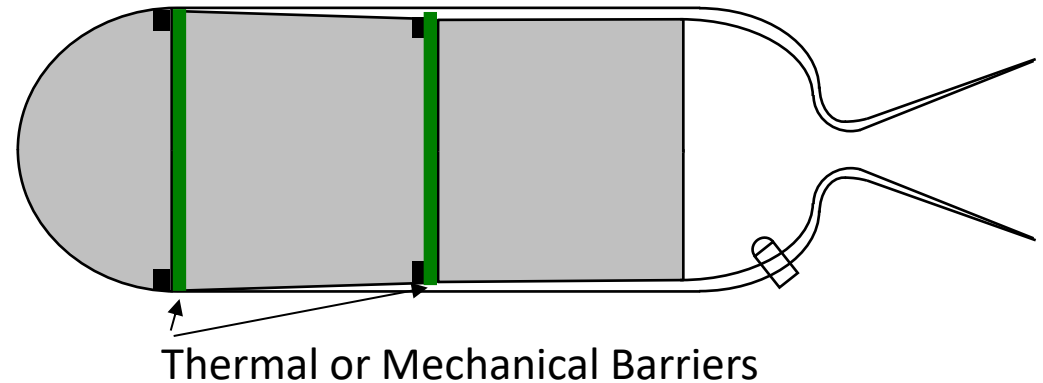
- 😊 High I_{sp}
- ☹️ Limited Pulses

Solid Propellant Pintle

- 😊 Continuously Select Up to 40:1 Variation in Thrust
- 😊 Can Reduce MEOP for Hot Day
- ☹️ Good I_{sp} at Lowest Thrust Only If Burn Rate Exponent $n \rightarrow 1$

Bi-propellant Gel

- 😊 High I_{sp}
- 😊 Duty Cycle Thrust
- 😊 Insensitive Munition
- ☹️ Lower Max Thrust
- ☹️ Toxicity

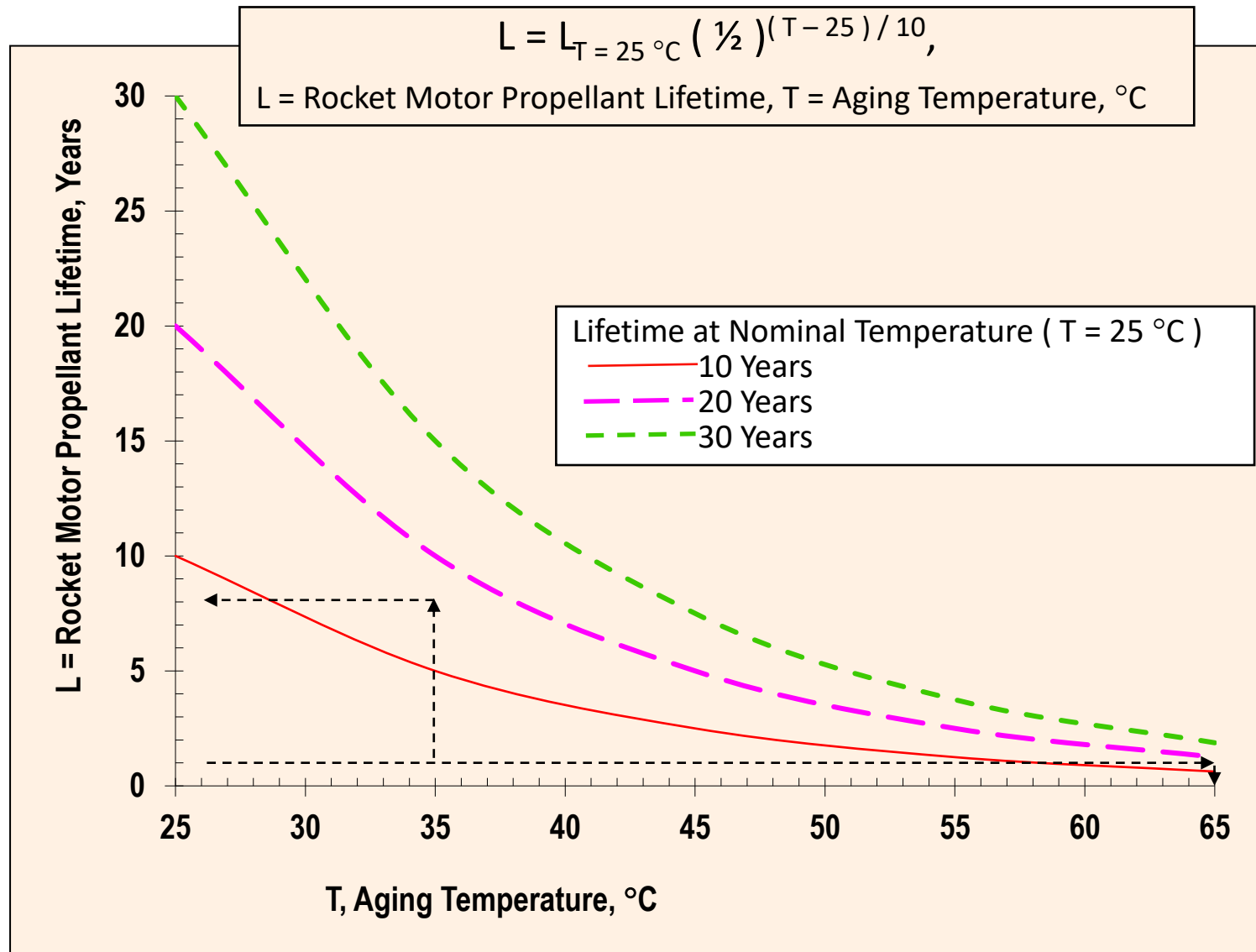


Solid Propellant Selection Requires Tradeoff of Performance, Safety, and Observables

Type	I_{SP} , Specific Impulse, s	ρ , Density, lbm / in ³	Burn Rate @ 1,000 psi, in / s	Safety	Observables
<ul style="list-style-type: none"> <u>Min Smoke</u>. No Al fuel or AP oxidizer. Either Composite with Nitramine Oxidizer (CL-20, ADN, HMX, RDX) or Double Base. Very low contrail (H₂O). 	— 220 - 255	— 0.055 - 0.062	○ 0.25 - 2.0	—	◐
<ul style="list-style-type: none"> <u>Reduced Smoke</u>. No Al (binder fuel). AP oxidizer. Low contrail (HCl). 	○ 250 - 260	○ 0.062	◐ 0.1 - 1.5	○	○
<ul style="list-style-type: none"> <u>High Smoke</u>. Al fuel. AP oxidizer. High smoke (Al₂O₃). 	◐ 260 - 265	◐ 0.065	● 0.1 - 3.0	◐	—




 Superior
  Good
  Average
  Poor

Solid Propellant Rocket Motor Lifetime Is Reduced by High Temperature Aging



Note: Elevated temperature tests, with accelerated aging, are used to verify rocket motor propellant lifetime.


Solid Propellant Rocket Motor Lifetime May Be Driven by Shock in Low Temp Environment

<u>Type of Storage</u>	<u>Typical Min Temp</u>	<u>Typical Max Temp</u>	<u>Typical Max Shock / Vibration @ Max / Min Temp</u>
Depot (e.g., Bunker) 	-9 deg F	120 deg F	100 g @ 10 ms (0.5 ft Drop)
Transportation 	-20 deg F	130 deg F	100 g @ 10 ms (0.5 ft Drop) 7 g @ 300 Hz, 10 g @1000 Hz)
Field 	-60 deg F	160 deg F	100 g @ 10 ms (0.5 ft Drop) 7 g @ 300 Hz, 10 g @1000 Hz)

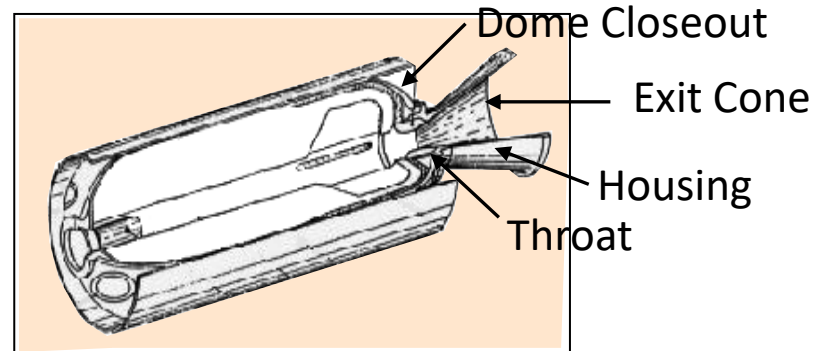
- Propellant Failure from Shock / Vibration @ T_{min}
 - Grain Cracking (From Δ Thermal Expansion: Grain / Case, Fuel / Oxidizer / Binder; Brittle Propellant)
 - Insulation Liner De-bond (From Δ Thermal Expansion of Grain / Case)
 - Voids (From Δ Thermal Expansion of Fuel / Oxidizer / Binder)
- Propellant Failure from Shock / Vibration @ T_{max}
 - Grain Cracking (From Low Modulus of Elasticity, Propellant Decomposition Gas Bubbles)
 - Does not satisfy IM requirements
- Note:
 - Propellant failure also caused by cycling at min / max temperature.
 - Propellant failure also caused by low / high humidity.

Steel and Aluminum Motor Cases Are Low Cost but a Composite Motor Case Is Light Weight

Type	Temperature	Volumetric Efficiency	Weight	IM	Attachment to Missile Airframe	Corrosion	Fatigue	Cost
◆ Steel	●	●	○ ●	○	●	○	●	● ●
◆ Aluminum	—	— ○	○ ●	○	●	●	—	● ●
◆ Strip Steel / Epoxy Laminate	○	●	○ ●	●	—	○	●	●
◆ Graphite Composite	○	○	●	●	—	●	●	—
◆ Titanium	●	●	●	○	—	●	●	—

 Superior
  Good
  Average
  Poor

Heat Transfer Drives Rocket Nozzle Materials, Weight, and Cost



<u>Rocket Nozzle Element</u>	<u>High Heating</u> (High Chamber Pressure or Long Burn) ⇒ High Cost / Heavy Nozzle	<u>Low Heating</u> (Low Chamber Pressure or Short Burn) ⇒ Low Cost / Light Weight Nozzle
<ul style="list-style-type: none"> ◆ Housing Material Alternatives ◆ Throat Material Alternatives ◆ Exit Cone, Dome Closeout, and Blast Tube Material Alternatives 	<ul style="list-style-type: none"> ◆ Steel ◆ Tungsten Insert ◆ Rhenium Insert ◆ Molybdenum Insert ◆ Silica / Phenolic Insert ◆ Graphite / Phenolic Insert ◆ Silicone Elastomer Insert 	<ul style="list-style-type: none"> ◆ Cellulose / Phenolic ◆ Aluminum ◆ Cellulose / Phenolic Insert ◆ Silica / Phenolic Insert ◆ Graphite Insert ◆ Carbon – Carbon Insert ◆ No Insert ◆ Glass / Phenolic Insert

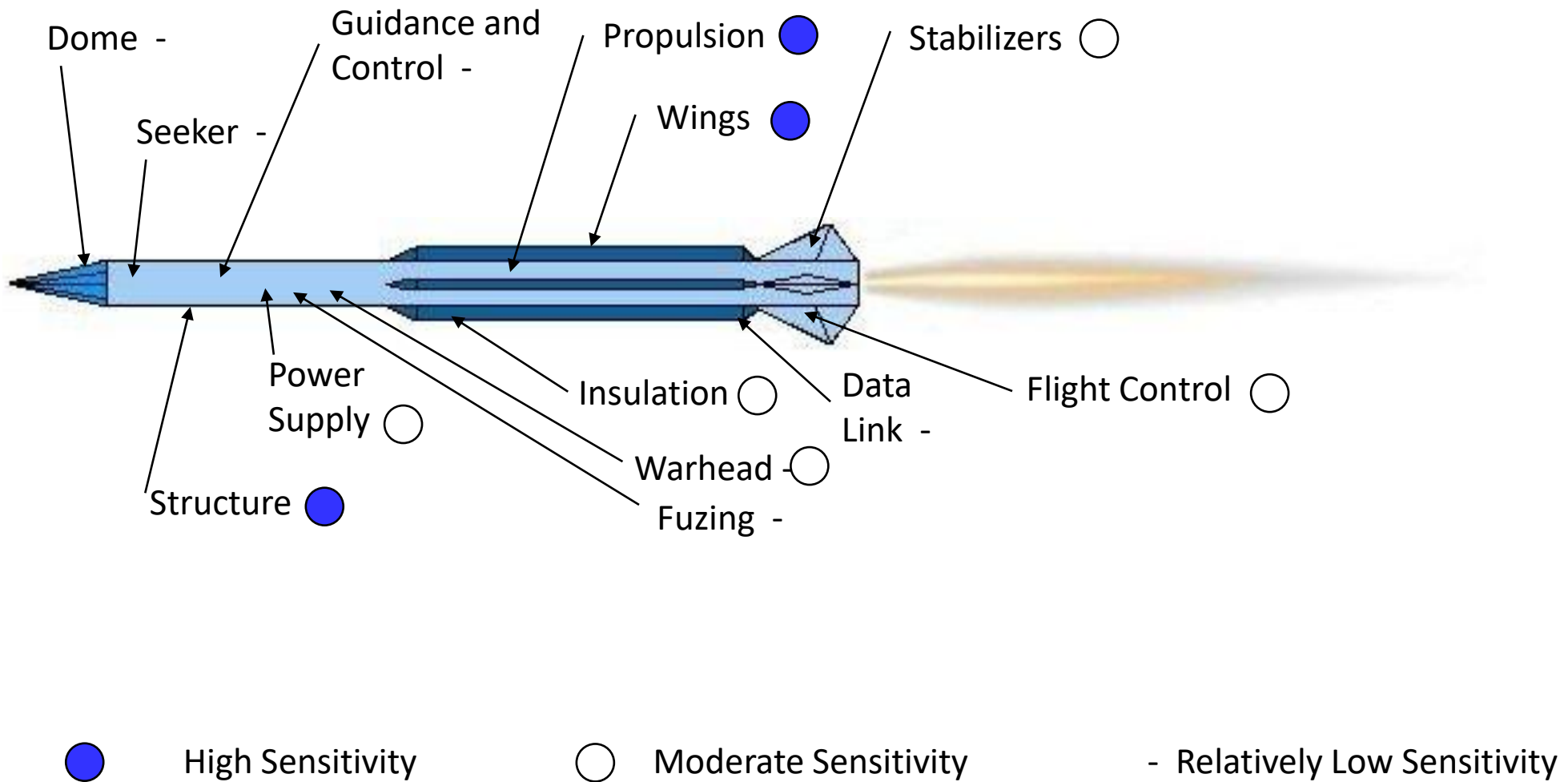
Summary of Propulsion

- Emphasis
 - Turbojet propulsion
 - Ramjet propulsion
 - Rocket propulsion
- Conceptual Design Prediction Methods
 - Thrust
 - Specific impulse
- Design and System Engineering Trades
 - Turbojet turbine material, compressor ratio, cycle, and inlet/launch platform integ
 - Ramjet combustion insulation
 - Ramjet engine / booster / inlet integration
 - Ramjet fuel
 - Rocket propellant burn area requirement
 - Nozzle throat area
 - Nozzle expansion ratio
 - Rocket motor propellant grain

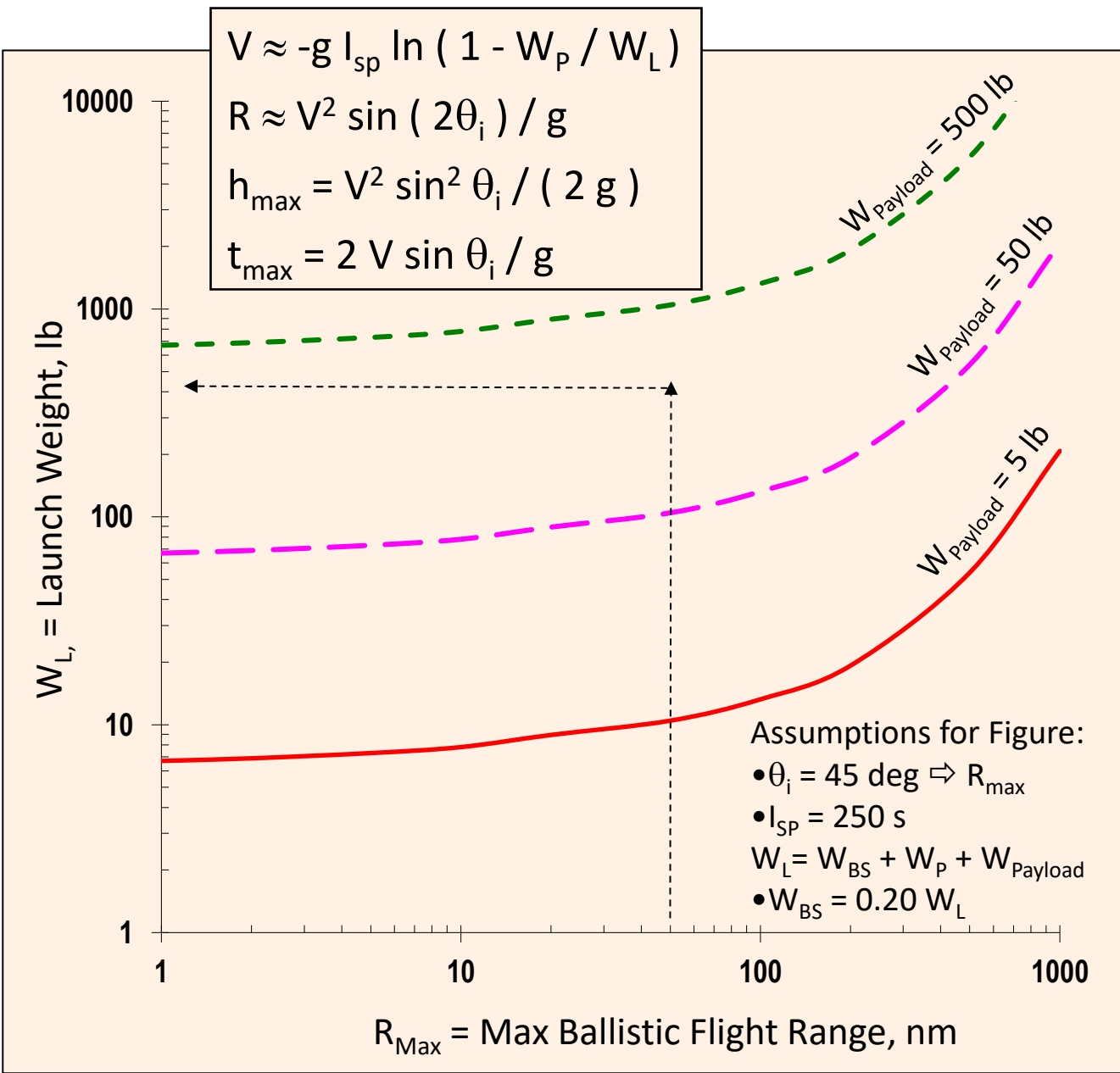
Summary of Propulsion

- Design and System Engineering Trades
 - Rocket thrust magnitude control
 - Solid propellant alternatives
 - Motor case material alternatives
 - Nozzle materials
- New Propulsion Technologies for Missiles
 - High temperature turbine materials
 - High stage pressure axial compressor
 - High temperature combustor
 - Optimum oblique shock airframe compression
 - Mixed compression supersonic inlet
 - Low drag inlet
 - High density fuel / propellant

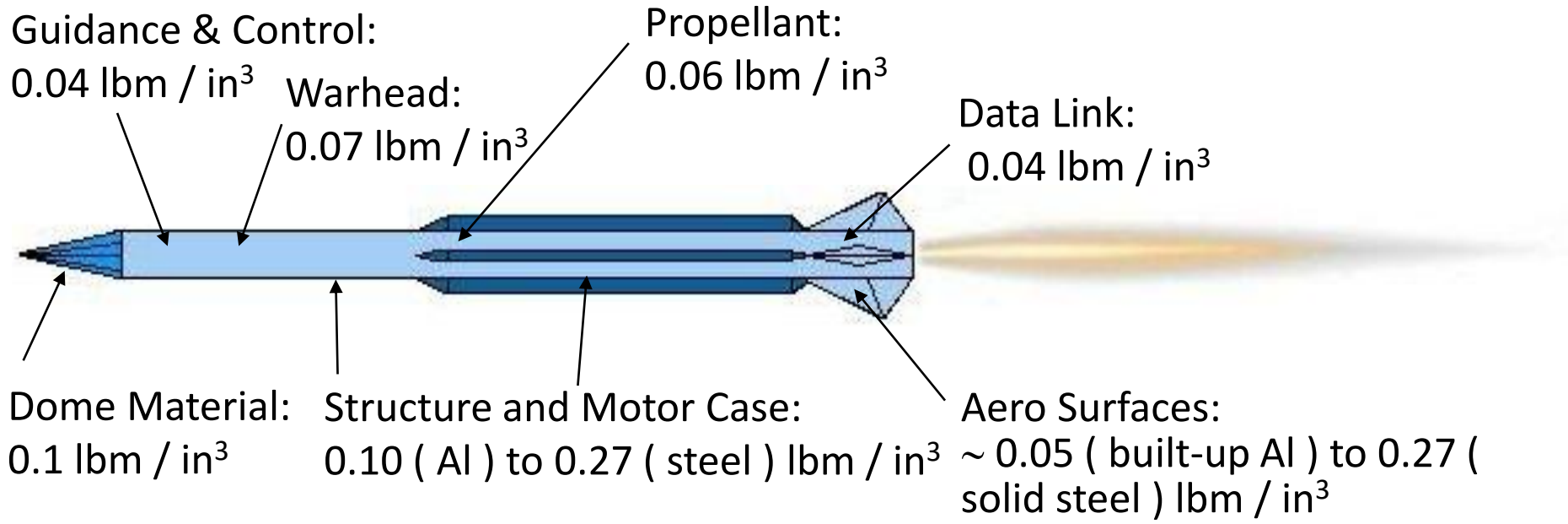
Weights of Missile Subsystems Are Often Sensitive to Flight Performance Requirements



Ballistic Missile Weight Driven by Range, Payload Weight, Propellant Weight, and Specific Impulse

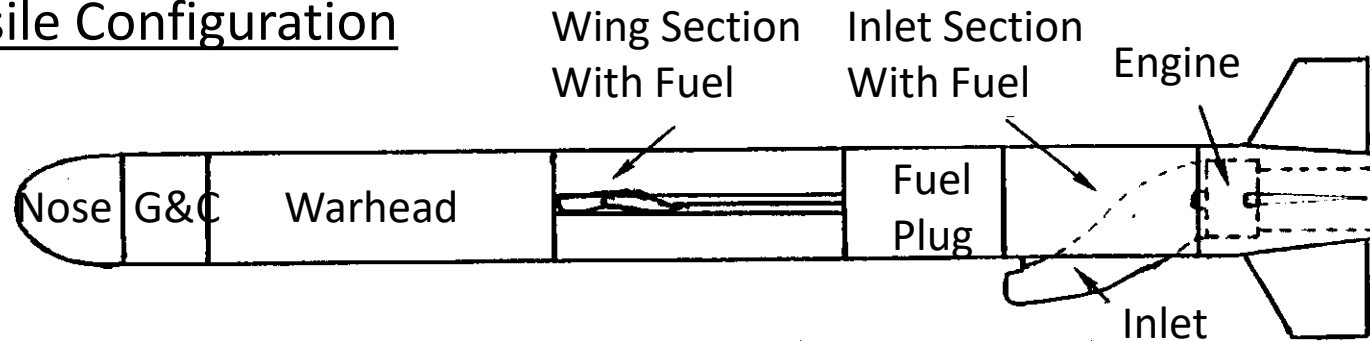


Most Subsystems for Missiles Have a Weight Density of about 0.05 lbm / in³

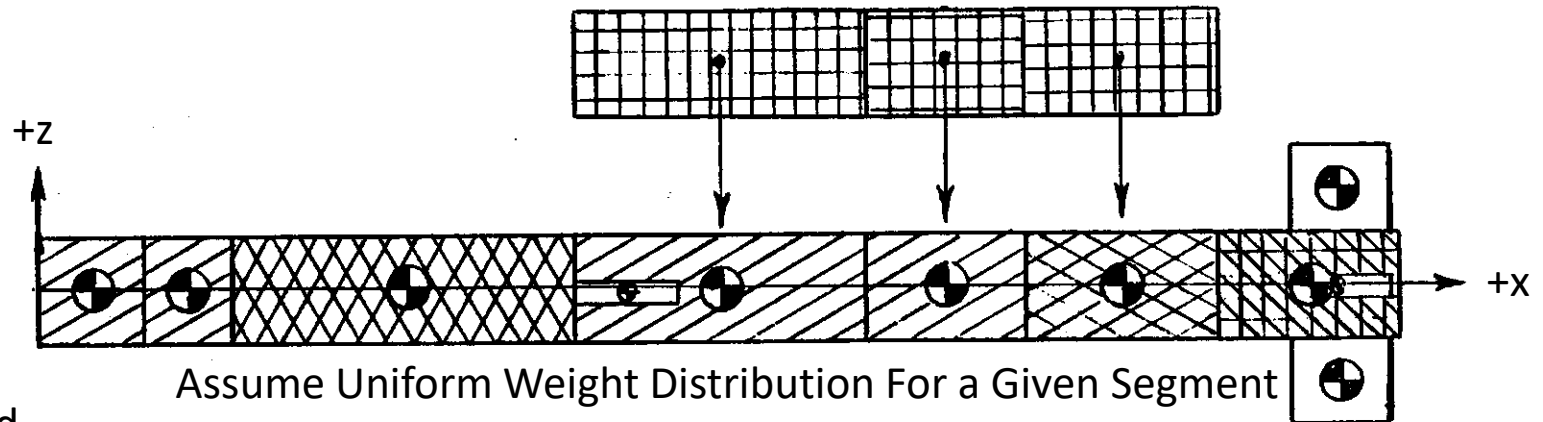


Modeling Missile Weight, Balance, and Moment-of-Inertia Is Based on a Build-up of Subsystems

Example Missile Configuration

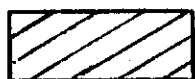







Model



Assume Uniform Weight Distribution For a Given Segment

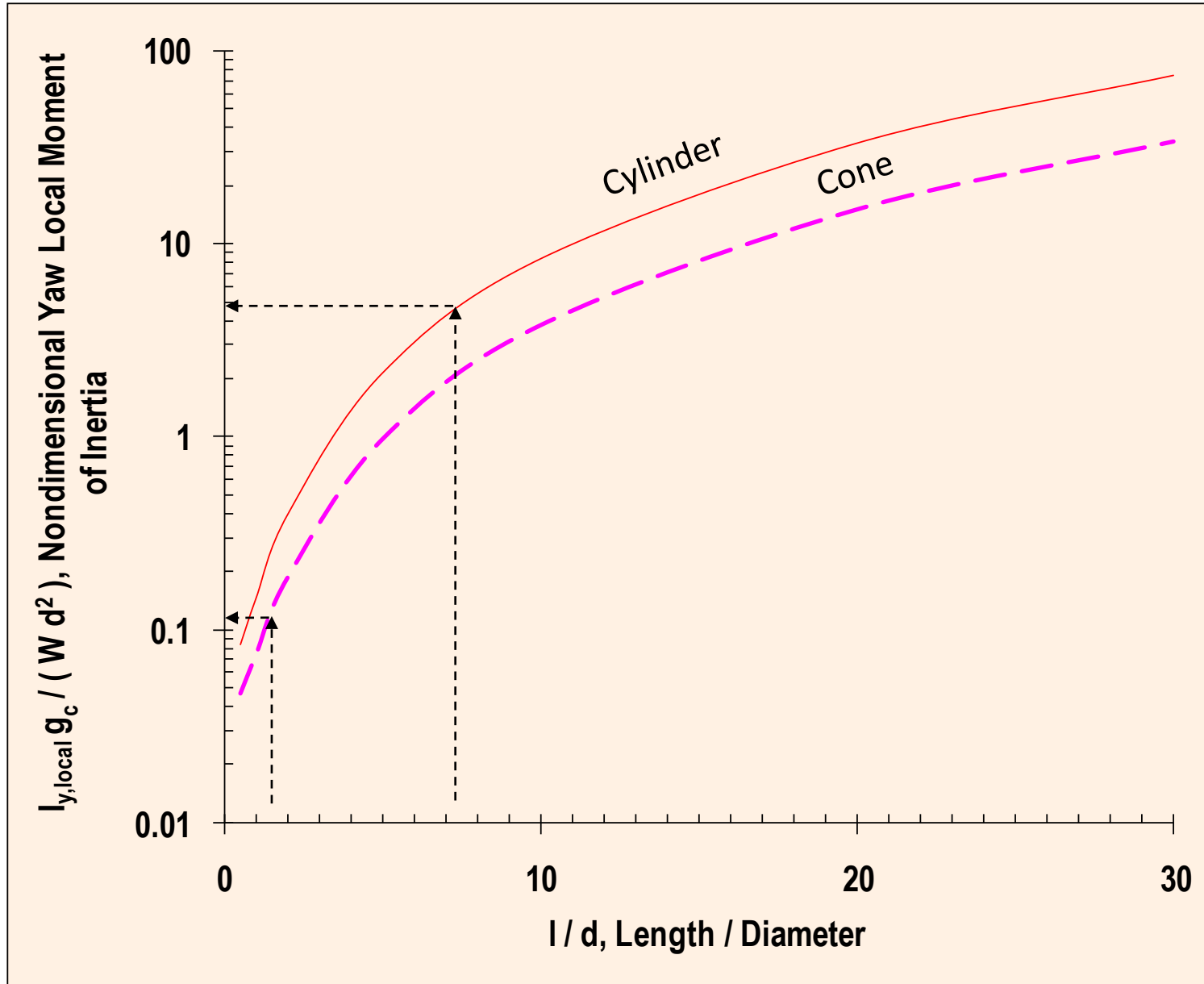
Legend

-  Structure and Subsystems
-  Warhead and Structure
-  Inlet Structure and Subsystems
-  Engine Structure and Subsystems
-  Fuel
-  Aero Surfaces

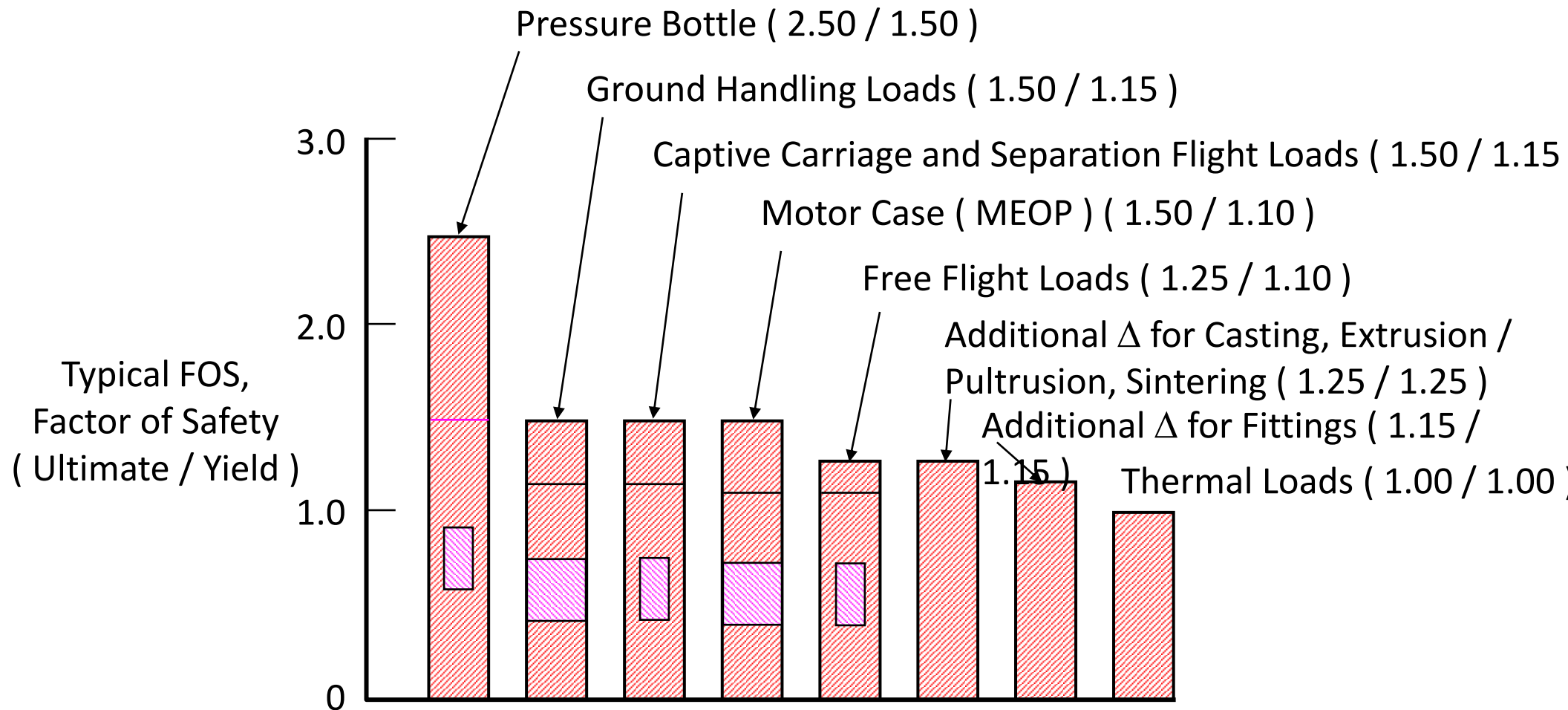
$$\bullet x_{CG} = \frac{\sum (x_{\text{subsystem1}} W_{\text{subsystem1}} + x_{\text{subsystem2}} W_{\text{subsystem2}} + \dots)}{W_{\text{total}}}$$

$$I_y = \sum [(I_{y,\text{subsystem1}})_{\text{local}} + W_{\text{subsystem1}} (x_{\text{subsystem1}} - x_{CG})^2 / g_c + (I_{y,\text{subsystem2}})_{\text{local}} + W_{\text{subsystem2}} (x_{\text{subsystem2}} - x_{CG})^2 / g_c + \dots]$$

A High Fineness Body Has a Larger Moment-of-Inertia



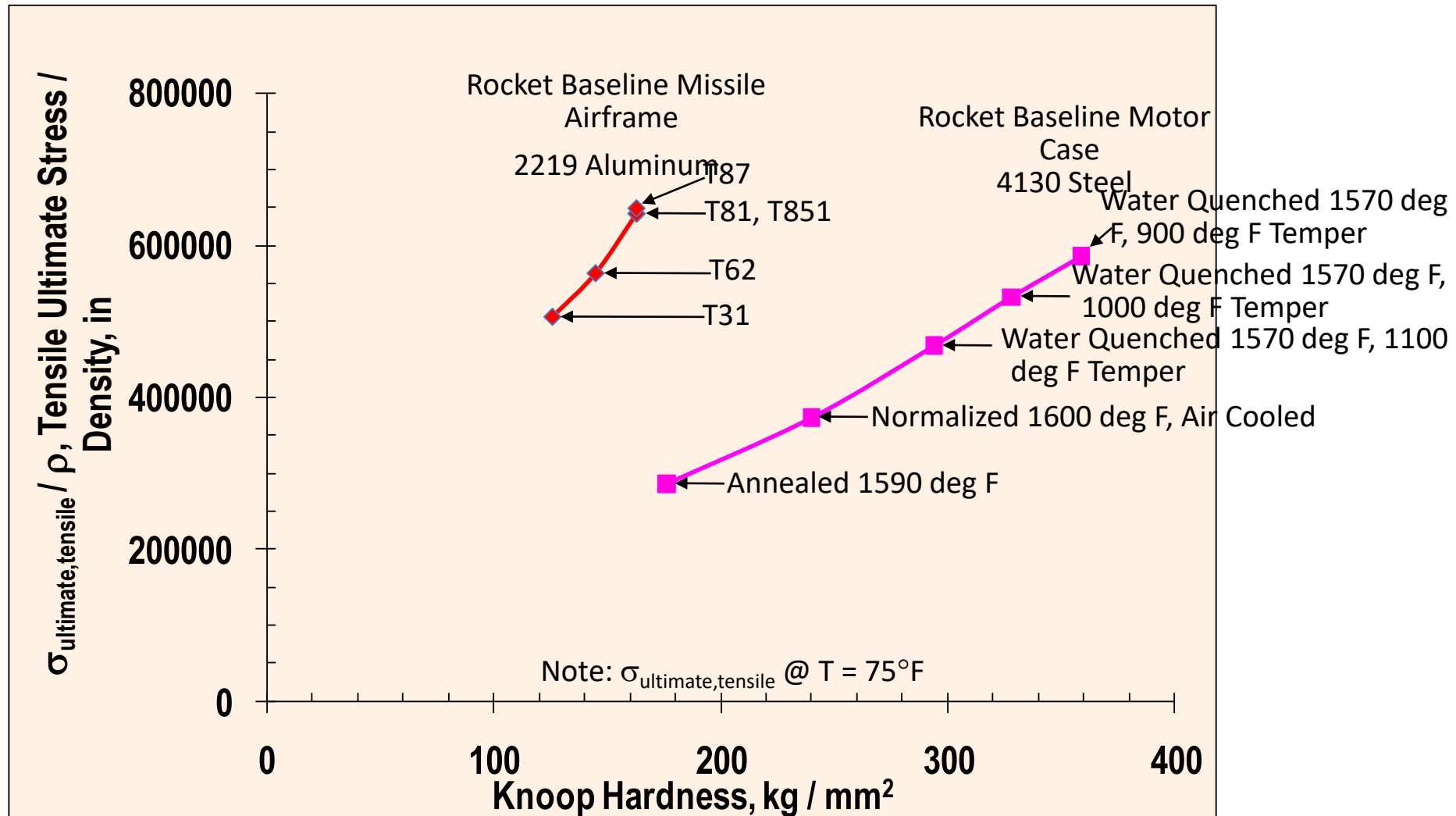
Structure Design Factor of Safety Must Be Greater for Hazardous Subsystems / Flight Conditions



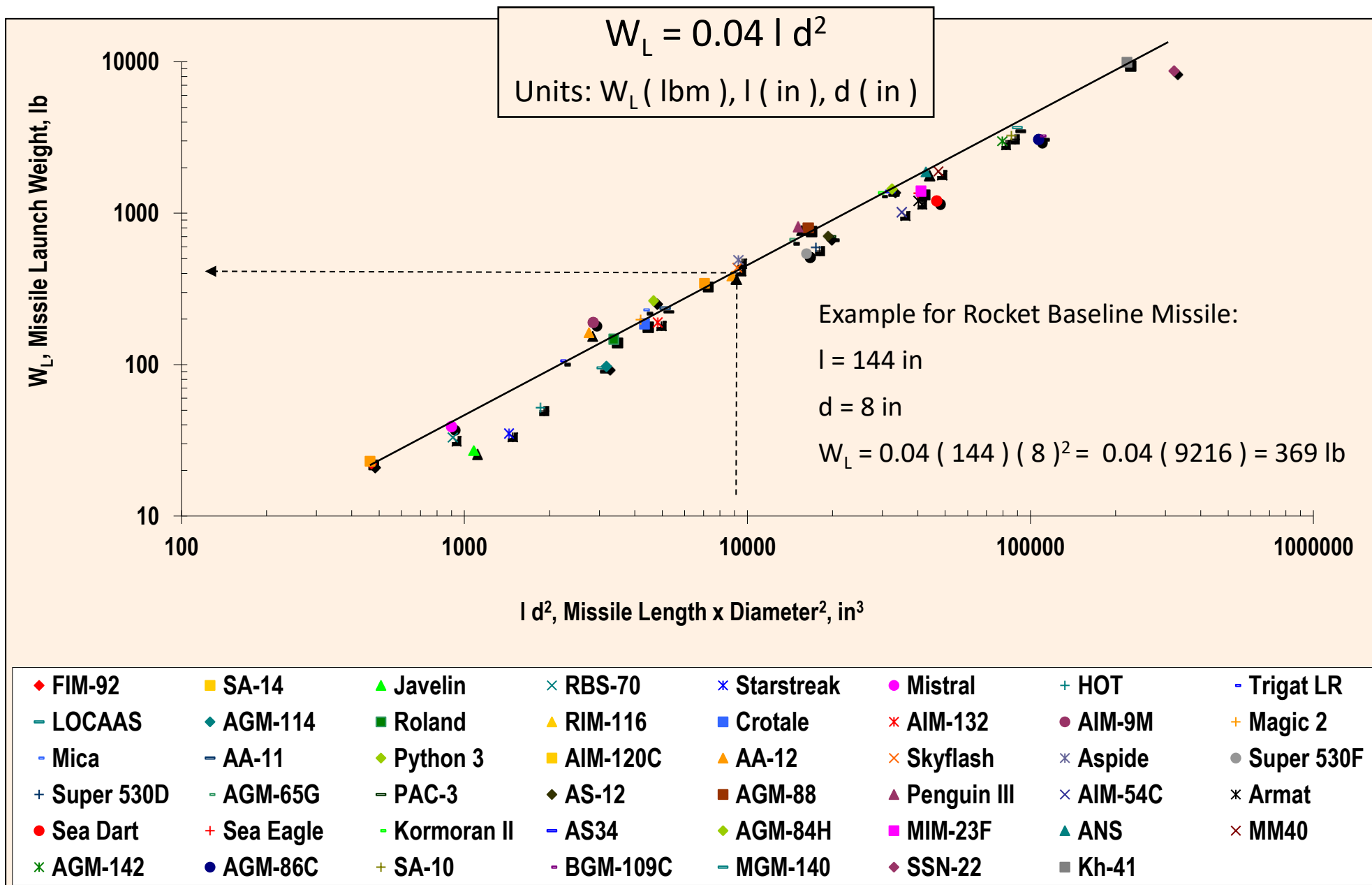
Note:

- MIL STDs include environmental (HDBK-310, NATO STANAG 4370, 810G, 1670A), strength and rigidity (8856), and captive carriage (8591).
- The entire environment (e.g., manufacturing, transportation, storage, ground handling, captive carriage, launch separation, post-launch maneuvering, terminal maneuvering) must be examined for driving conditions in structure design.
- Additional Δ FOS for casting, extrusion / pultrusion, and sintering is expected to be reduced in future as technologies mature.
- Reduction in required factor of safety is expected as analysis accuracy improves will result in reduced missile weight / cost.

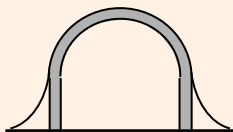
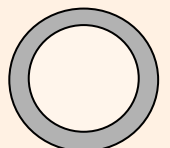
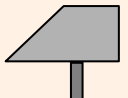
Increasing Metal Hardness Increases Strength, but Machining Is More Difficult / Expensive



A First-Order Estimate of Missile Weight Can Be Derived from Body Geometry Dimensions



Missile Airframe Parts Count Is Driven by the Manufacturing Process

Missile Airframe Geometry Alternatives	Missile Structure Concept Alternatives	Structure Manufacturing Process Alternatives									
		Graphite Composites						Metal			
		Vacuum Assist RTM	Compression Mold	Filament Wind	Pultrusion	Thermal Form	Vacuum Bag / Autoclave	Cast	High Speed Machine	Forming	Strip Laminating
Lifting Body Airframe 	Monocoque	●	◐	●	●	◐	◐	●		◐	
	Integrally Hoop Stiffened	●	◐				◐	●	—		
	Integrally Longitudinal Stiffened	●	◐		●		◐	●	—		
Axisymmetric Body Airframe 	Monocoque	●		●	●		●	●		●	●
	Integrally Hoop Stiffened	●					◐	●	◐		
	Integrally Longitudinal Stiffened	●			●		◐	●	◐		
Aerodynamic Surface 	Solid	●	●			●	●	●	●	●	
	Sandwich	◐	◐				◐		●	○	

Note: Very Low Parts Count Low Parts Count Moderate Parts Count High Parts Count

Missile Turbojet Engine Parts Are Often Castings (Lower Parts Count / Lower Cost)

Combustor and Turbine Housing Structure – Inconel 625 (an alloy of nickel containing chromium and iron, resistant to corrosion at high temperatures)

Nozzle – Cast Inconel 713

Compressor Bearings– BG-42 Steel

Compressor Housing Structure – Cast 355 Al

Nose – Cast C355 Al

Turbine – Cast Nickel Base Superalloy Mar-M-247

Centrifugal Compressor – Cast 17-4 PH Steel

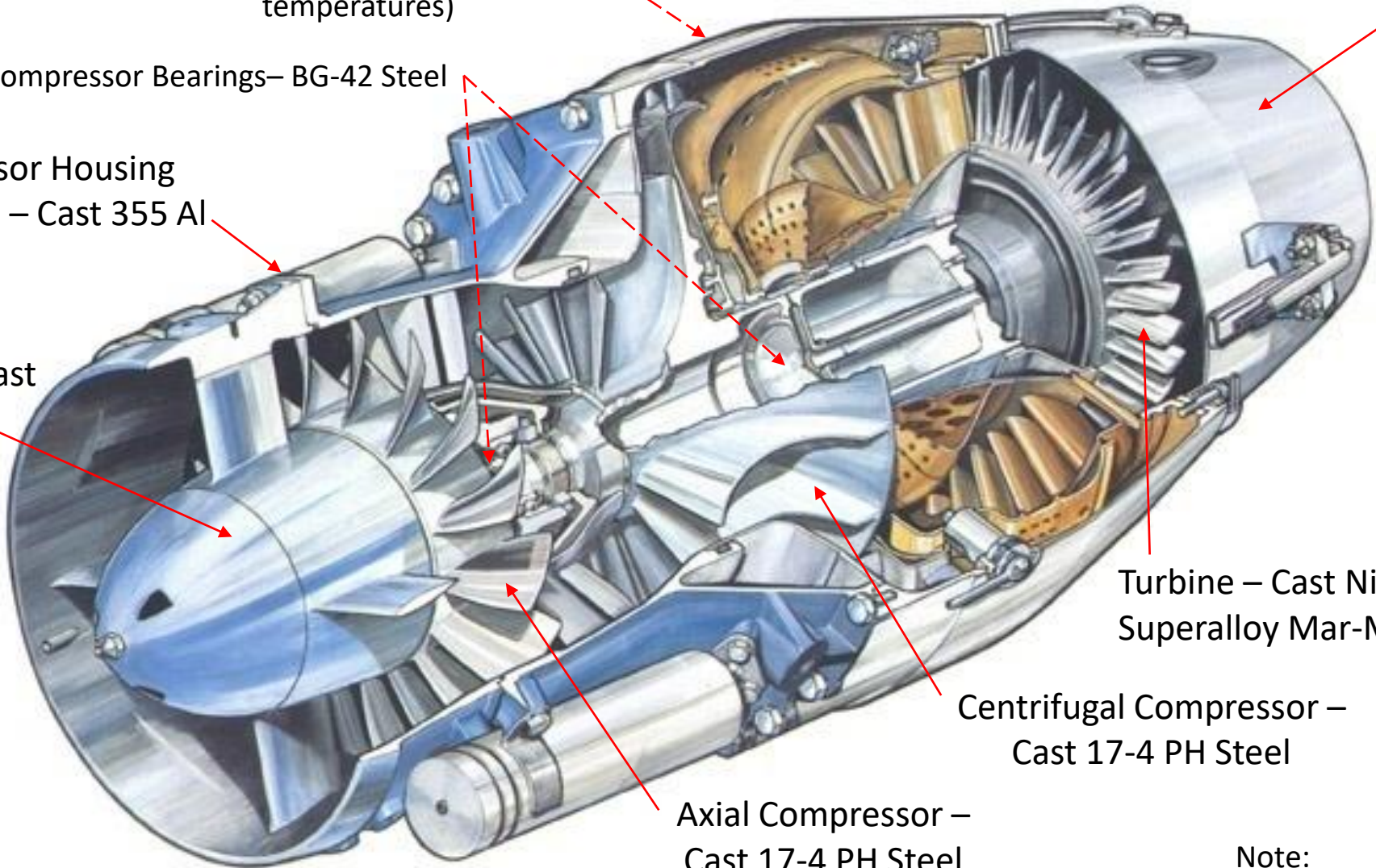
Axial Compressor – Cast 17-4 PH Steel

Note:

→ Cast Component

- - - → Machined Component

Example: Teledyne J402-CA-400

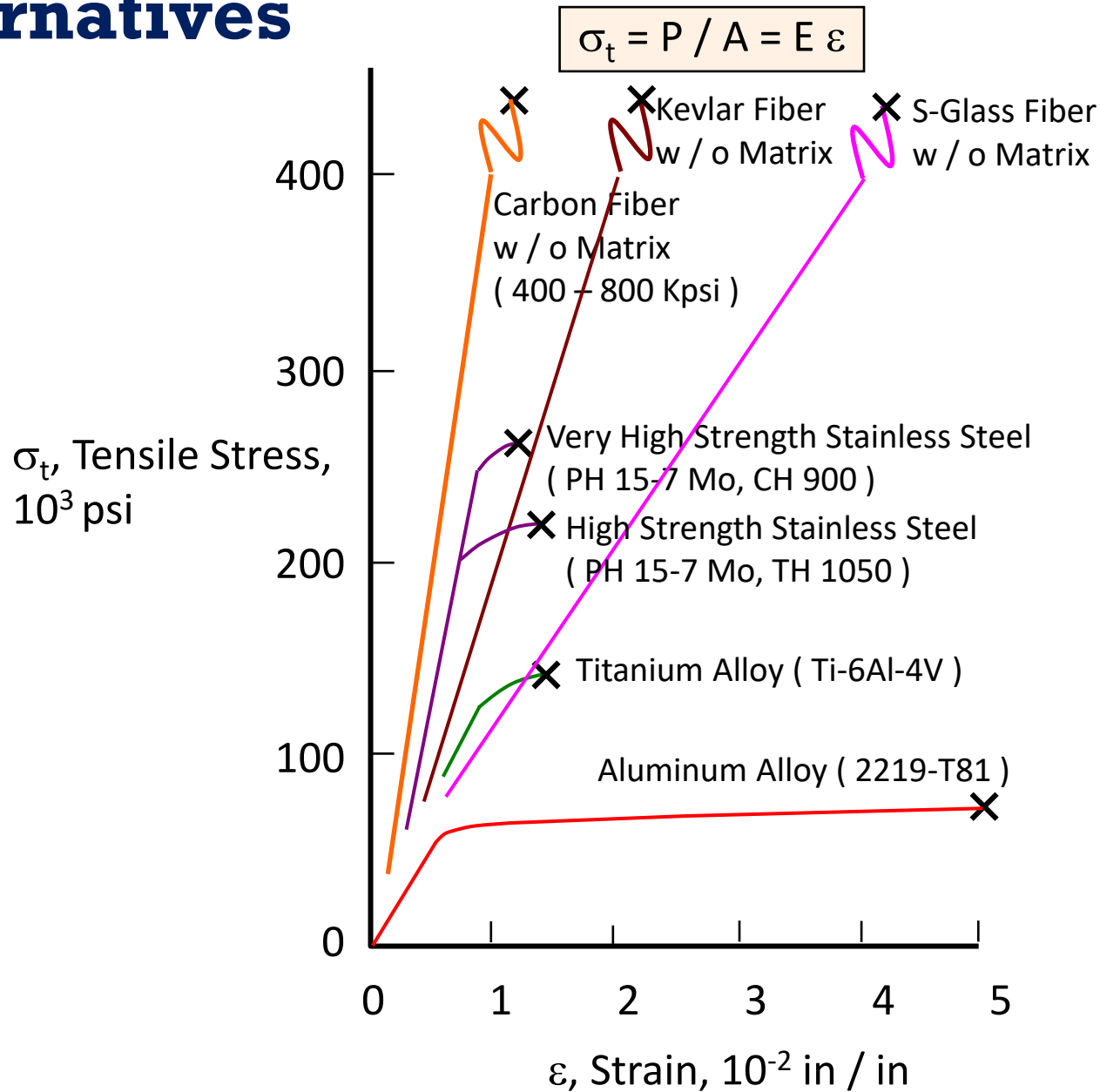


Missile Airframe Material Alternatives Include Aluminum, Steel, Titanium, and Composite

Type	Material	Tensile Stress (σ_{TU} / ρ)	Buckling Stability ($\sigma_{Buckling} / \rho$)	Max Short – Life Temp	Thermal Stress	Joining	Fatigue	Cost	Weight
Metallic ↓	Aluminum 2219	○	◐	– ○	–	◐	–	● ○	○
	Steel PH 15-7 Mo	◐	–	●	○	●	◐	● ○	–
	Titanium Ti-6Al-4V	◐	○	●	◐	○	◐	–	○
Composite ↓	S994 Glass / Epoxy and S994 Glass / Polyimide	◐	– ○	○	◐	○	●	●	◐
	Glass or Graphite Reinforce Molding	–	– ○	○	◐	○	●	○	◐
	Graphite / Epoxy and Graphite Polyimide	●	○	○ ◐	●	–	●	–	●

Note: ● Superior ◐ Good ○ Average – Poor

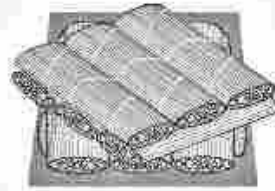
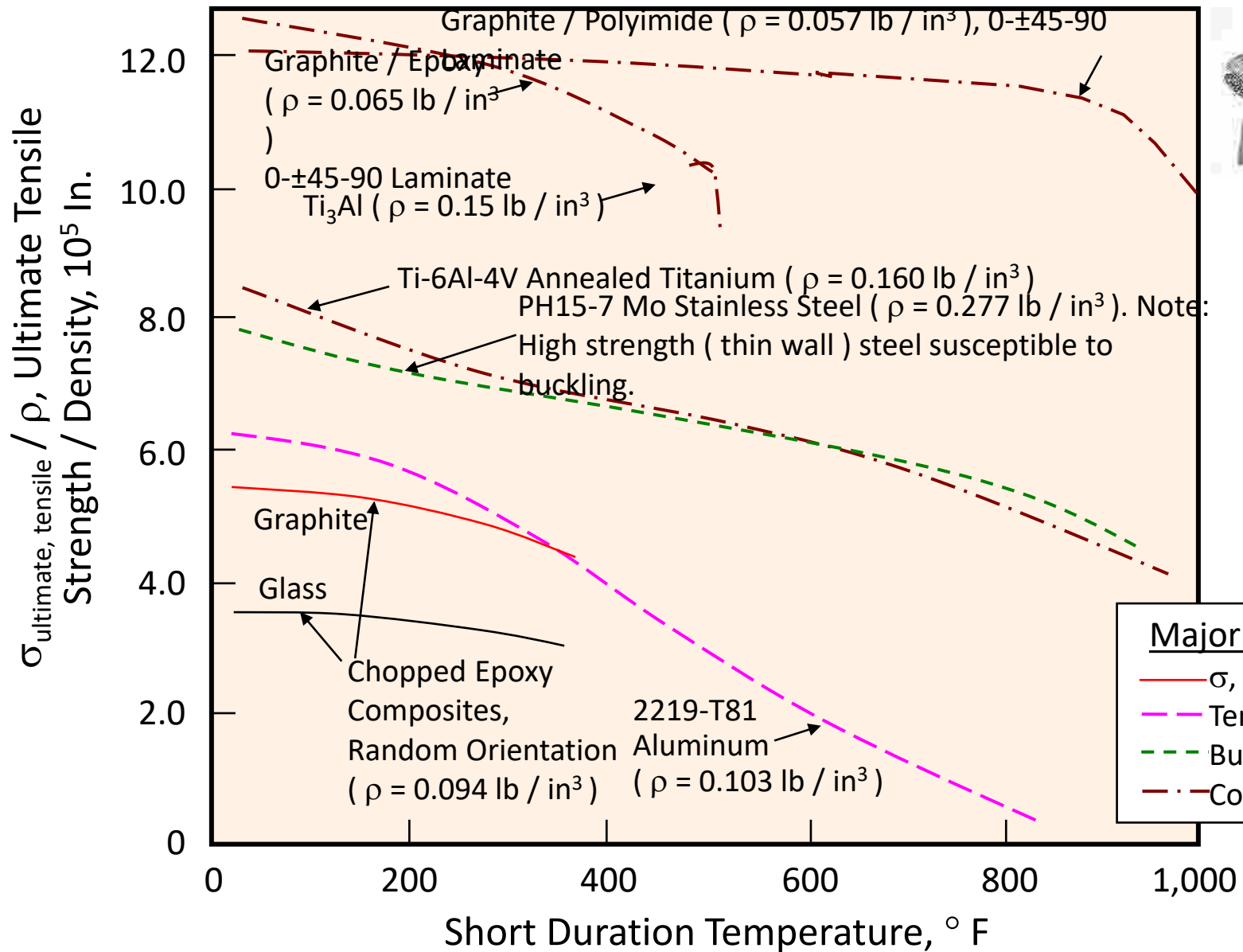
Strength – Elasticity Comparison of Missile Airframe Example Material Alternatives



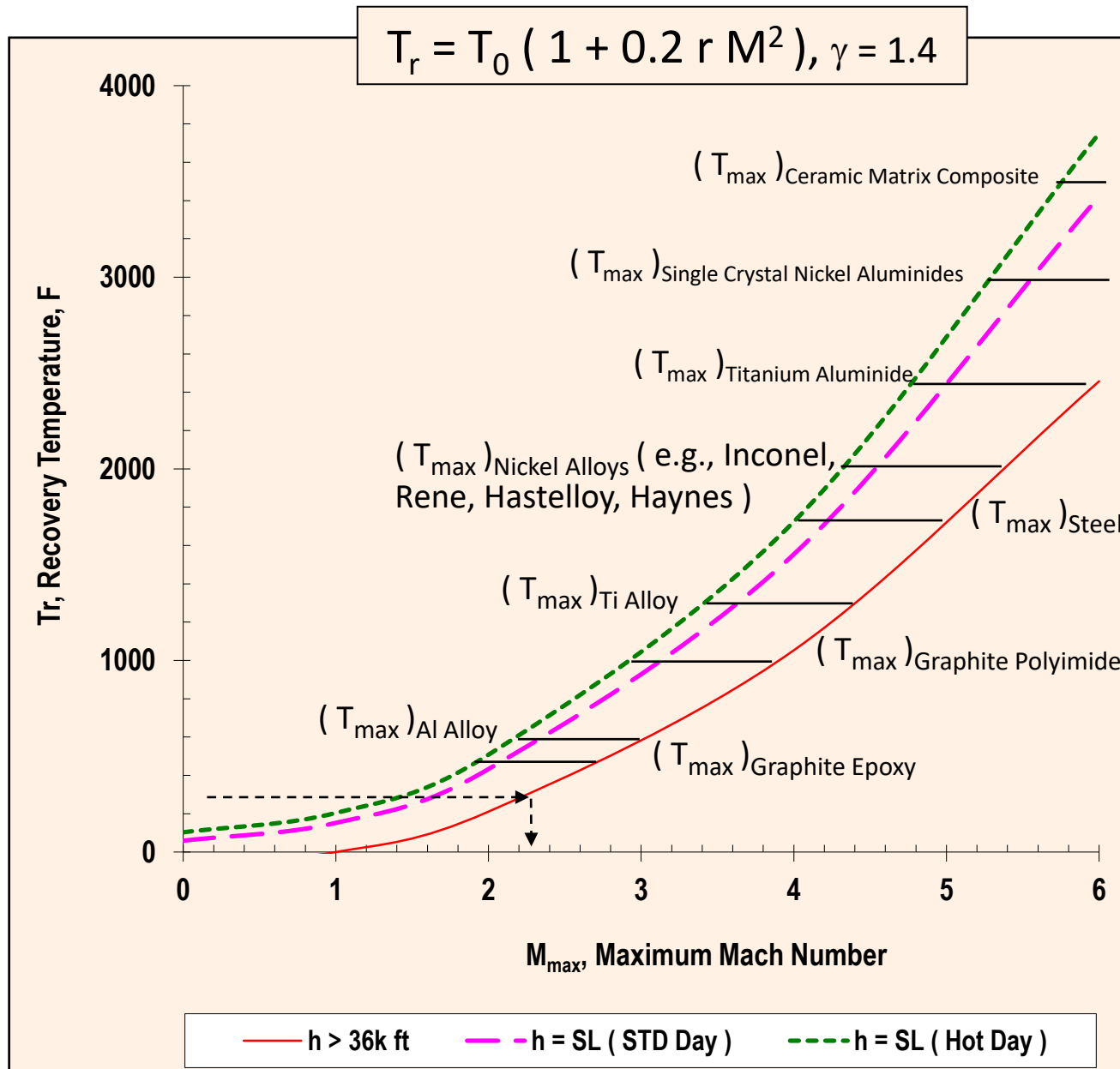
- Note:
- High strength fibers are:
 - Very small diameter
 - Unidirectional
 - High modulus of elasticity
 - Very elastic
 - No yield before failure
 - Non forgiving failure
 - Metals:
 - More ductile, yields before failure
 - Allow adjacent structure to absorb load
 - Resist crack formation
 - Resist impact loads
 - More forgiving failure

E, Young's modulus of elasticity, psi
 P, Load, lb
 ε , Strain, in / in
 A, Area, in²
 Room temperature

Laminate Graphite Composite Provides a High Strength-to-Weight Airframe



A High Speed Missile without External Insulation Requires High Temperature Structure



Note for Equation:

- T_r = Recovery Temperature, R
- T_0 = Free Stream Temperature, R
- r = Recovery Factor
 - Laminar Boundary Layer $\Rightarrow r \approx 0.85$
 - Turbulent Boundary Layer $\Rightarrow r \approx 0.9$
 - Stagnation $\Rightarrow r \approx 1$
- M = Free Stream Mach Number

Assumptions for Figure:

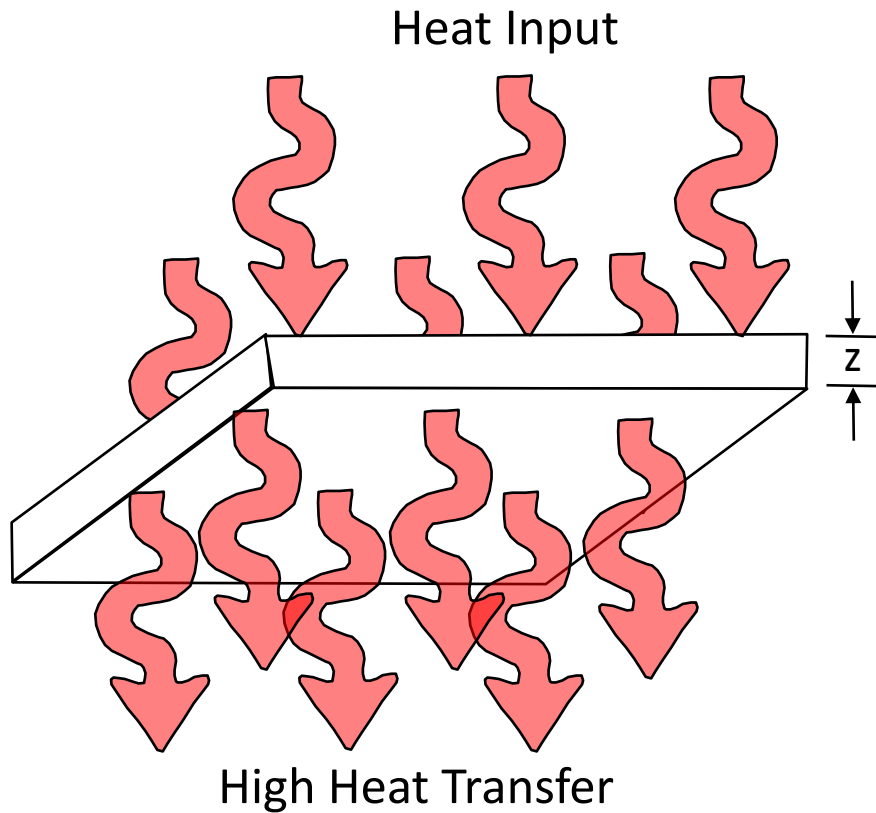
- No External Insulation
- Thermal Soak ($T_r \approx T_{structure}$)
- T_{max} = Max Temperature of Material
- $h > 36k$ ft $\Rightarrow T_0 = 390$ R = - 70° F
- $h =$ SL (STD day) $\Rightarrow T_0 = 519$ R = 59° F
- $h =$ SL (Hot Day) $\Rightarrow T_0 = 563$ R = 103° F
- Turbulent Boundary Layer $r = 0.9$

Example for Hot (Thermal Soak) Al

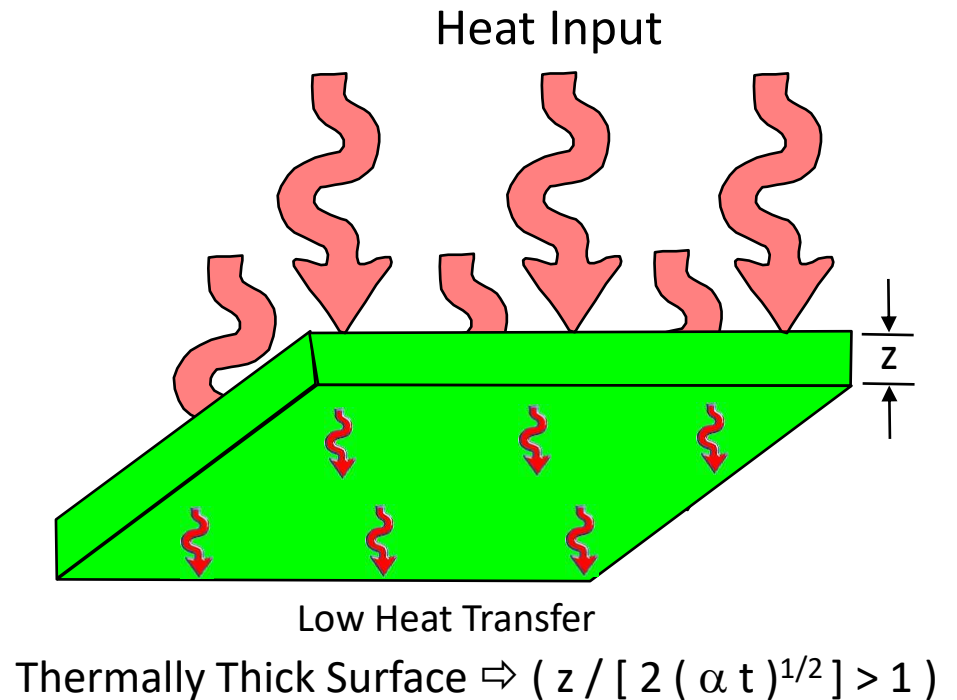
Alloy Airframe with $T_{max} = 300^\circ$ F = 760 R, $h > 36k$ ft ($T_0 = 519$ R), Turbulent Boundary Layer ($r = 0.9$)

- $M_{max} = \{ 5 [(T_r / T_0) - 1] / r \}^{1/2} = \{ 5 [(760 / 519) - 1] / 0.9 \}^{1/2} = 2.3$

A Thermally Thin Surface \Rightarrow High Heat Transfer
A Thermally Thick Surface \Rightarrow Low Heat Transfer

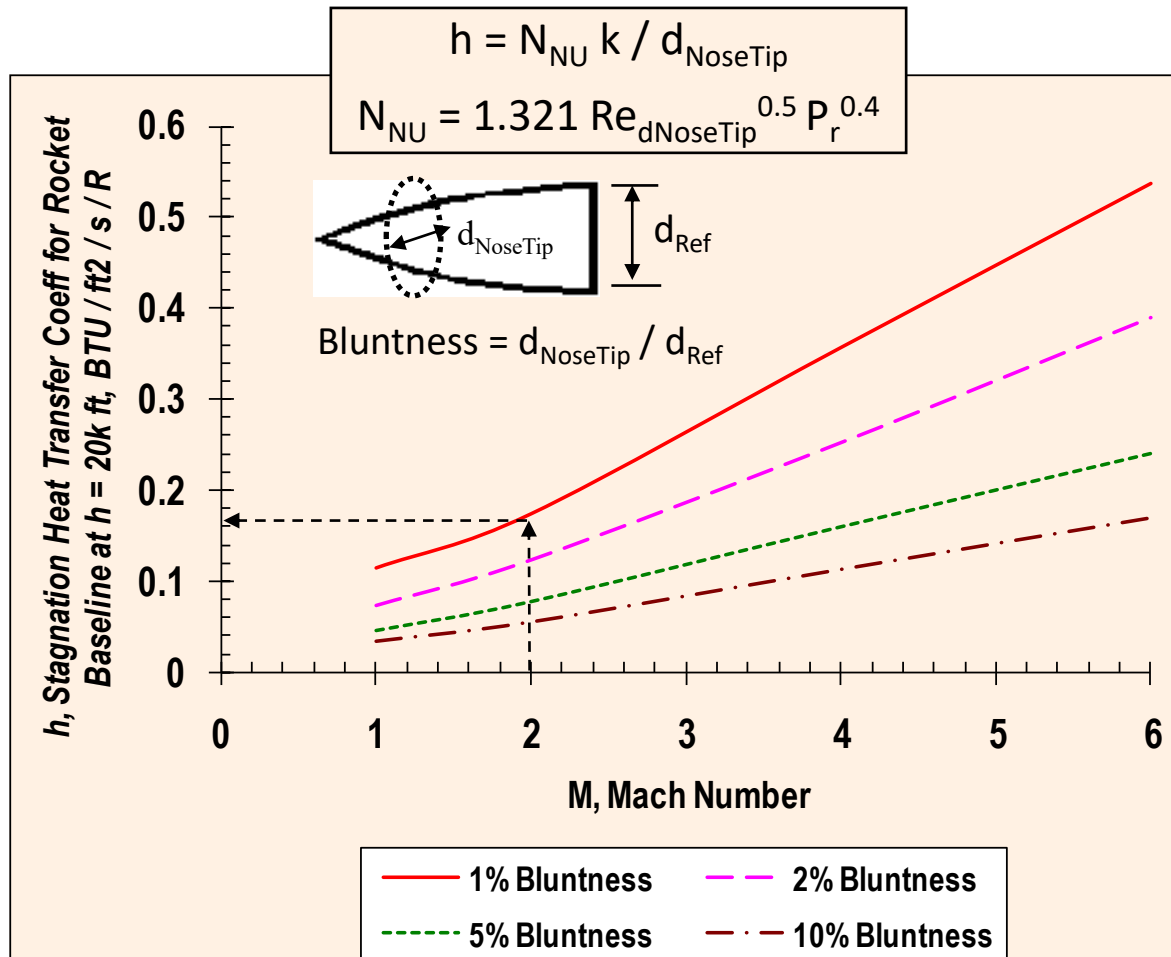


Thermally Thin Surface $\Rightarrow h (z / k)_{\text{surface}} < 0.1, T (0, t) \approx T (z, t)$



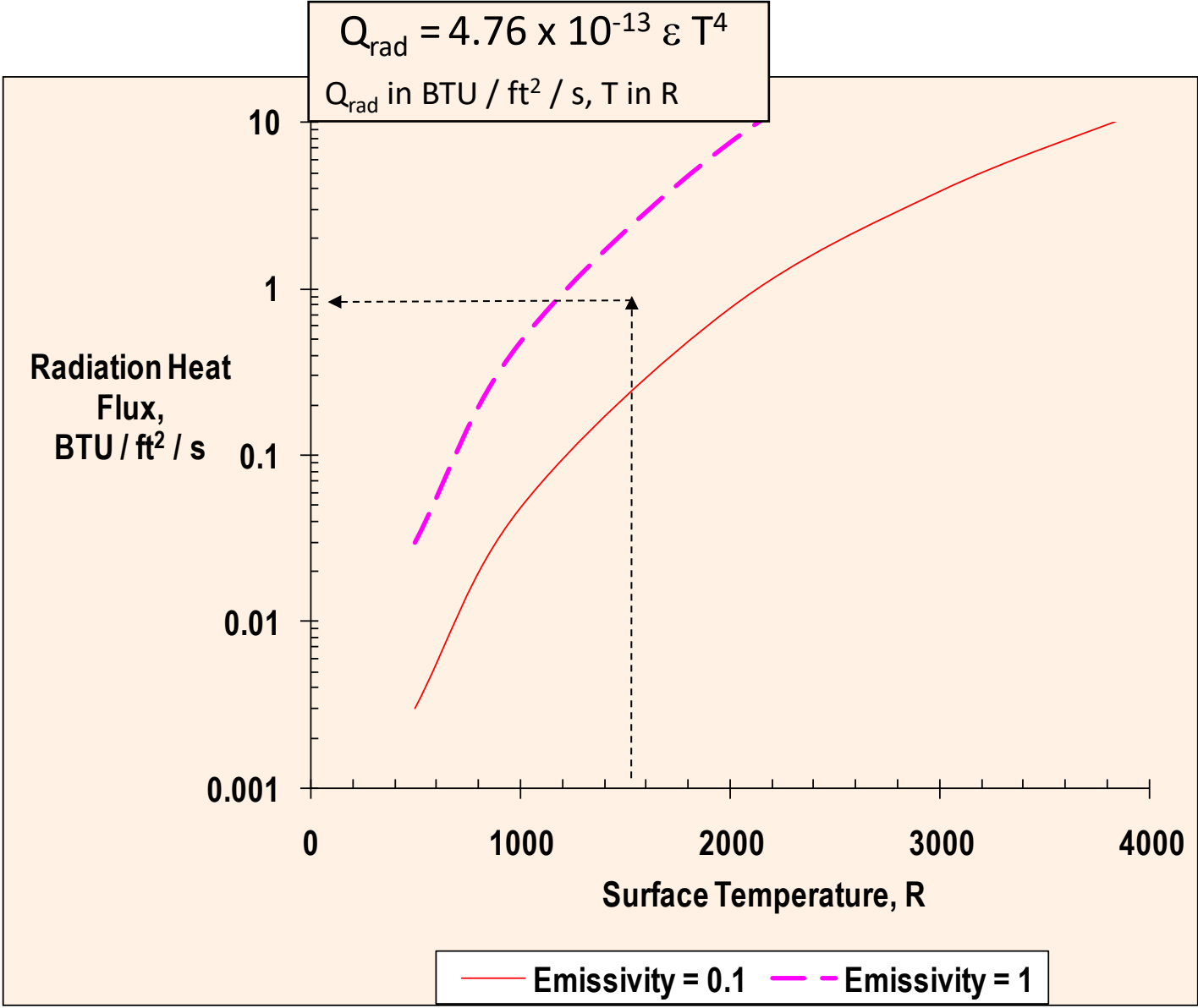
Note: T = Temperature, t = time, h = Convection heat transfer coefficient, z = Thickness ; k = Conductivity, α = Diffusivity

A Sharp Nose Tip / Leading Edge Has High Aerodynamic Heating in Hypersonic Flight



Note: 1-D conduction heat transfer; Laminar boundary layer; Stagnation heating; Radiation neglected; h = Convection heat transfer coefficient for stagnation recovery, BTU / s / ft² / R; N_{NU} = Nusselt number for stagnation recovery; k = Air thermal conductivity at stagnation recovery (total) temperature, BTU / s / ft / R; $d_{NoseTip}$ = Nose tip diameter, ft; $Re_{dNoseTip}$ = Reynolds number based on nose tip diameter, P_r = Prandtl number

Missiles Have Relatively Low Radiation Heat Loss at Moderate Temperature / Mach Number

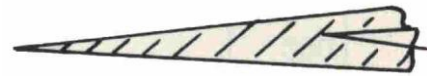


Missile Design Concerns for Localized Aerodynamic Heating and Thermal Stress



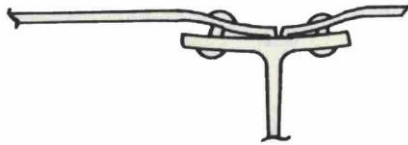
IRdome / Radome

- ◆ Large temp gradients due to low thermal conduction
- ◆ Thermal stress at attachment
- ◆ Low tensile strength
- ◆ Dome fails in tension



Sharp Leading Edge / Nose Tip

- ◆ Hot stagnation temperature on leading edge
- ◆ Small radius prevents use of external insulation
- ◆ Cold heat sink material as chord increases in thickness leads to leading edge warp
- ◆ Shock wave interaction with adjacent body structure



Body Joint

- ◆ Hot missile shell
- ◆ Cold frames or bulkheads
- ◆ Causes premature buckling

Note: σ_{TS} = Thermal stress from restraint in compression or tension = $\alpha E \Delta T$

α = coefficient of thermal expansion, E = modulus of elasticity, $\Delta T = T_2 - T_1$ = temperature difference.

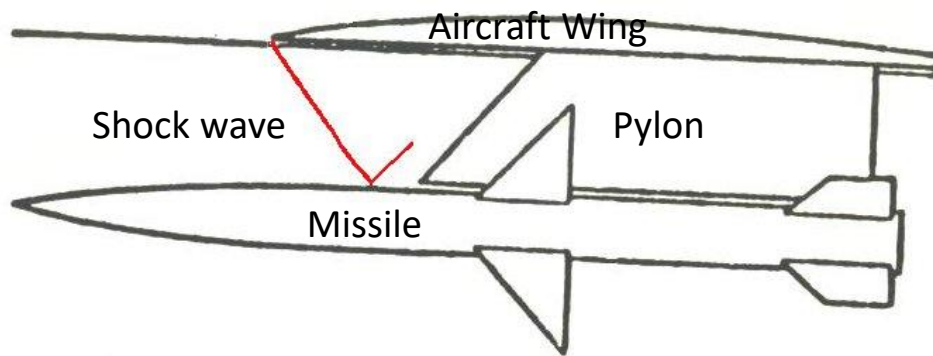
Example: Thermal Stress for Rocket Baseline Missile Pyroceram Dome ($\alpha = 3 \times 10^{-6} / R$, $E = 13.3 \times 10^6$ psi , $\sigma_{max} = 25,000$ psi)

Assume $M = 2$, $h = 20k$ ft alt, $t = 10$ s. Based on prior figures: $\Delta T = T_{OuterWall} - T_{InnerWall} = 575 - 479 = 96$ R (Jerger Reference), $\Delta T = 769 - 531 = 238$ R (Carslaw Reference)

Then $\sigma_{TS} = 3 \times 10^{-6} (13.3 \times 10^6) (96) = 3,830$ psi (Jerger), $\sigma_{TS} = 3 \times 10^{-6} (13.3 \times 10^6) (238) = 9,500$ psi (Carslaw)

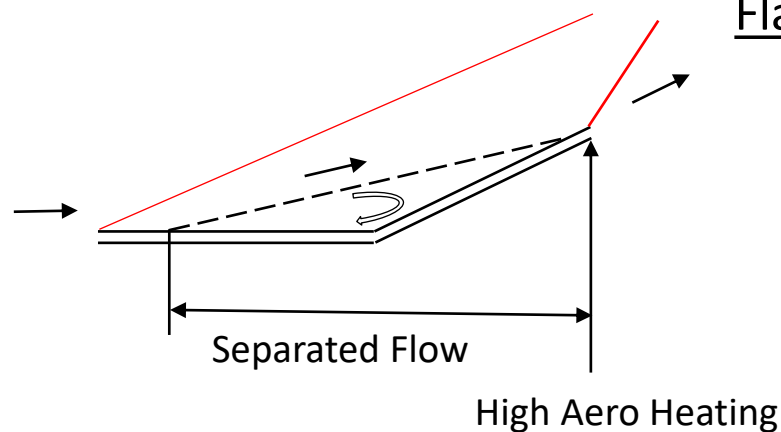
Design Concerns for Localized Aerodynamic Heating and Thermal Stress (cont)

Shock Wave – Boundary layer Interaction



Shock Wave from Surface Leading Edge Intercepts Another Surface

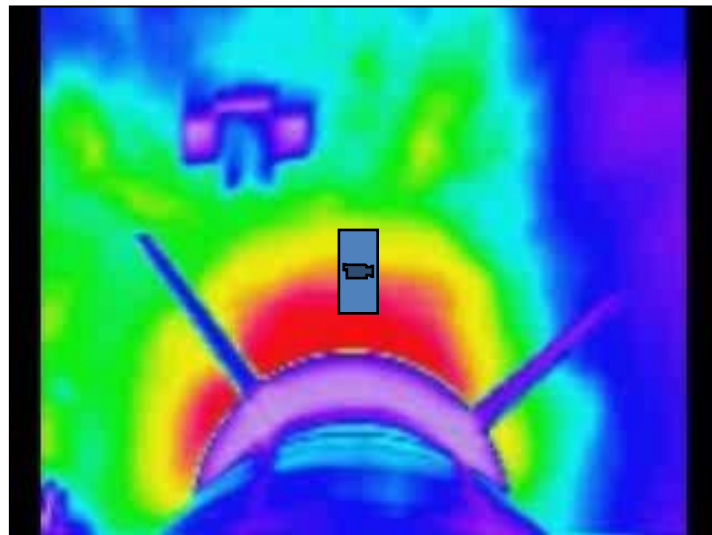
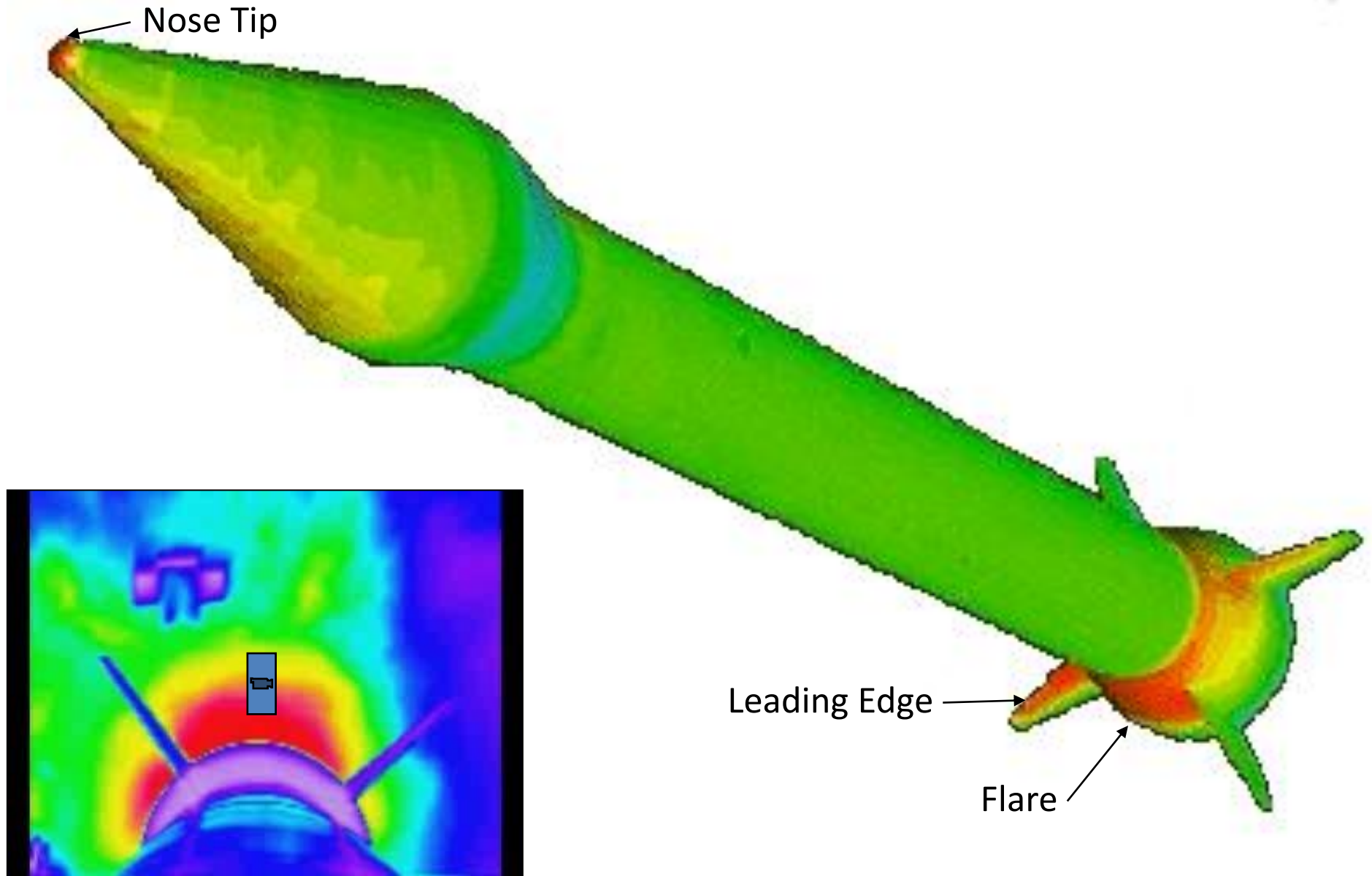
- ◆ High localized heating
- ◆ Example: shock wave from aircraft wing intercepts store



Flare / Wedge Corner Flow

- ◆ Separated flow at corner
- ◆ Shock wave at reattachment
- ◆ High heating at reattachment ($r \approx 1$)
- ◆ Example: flare

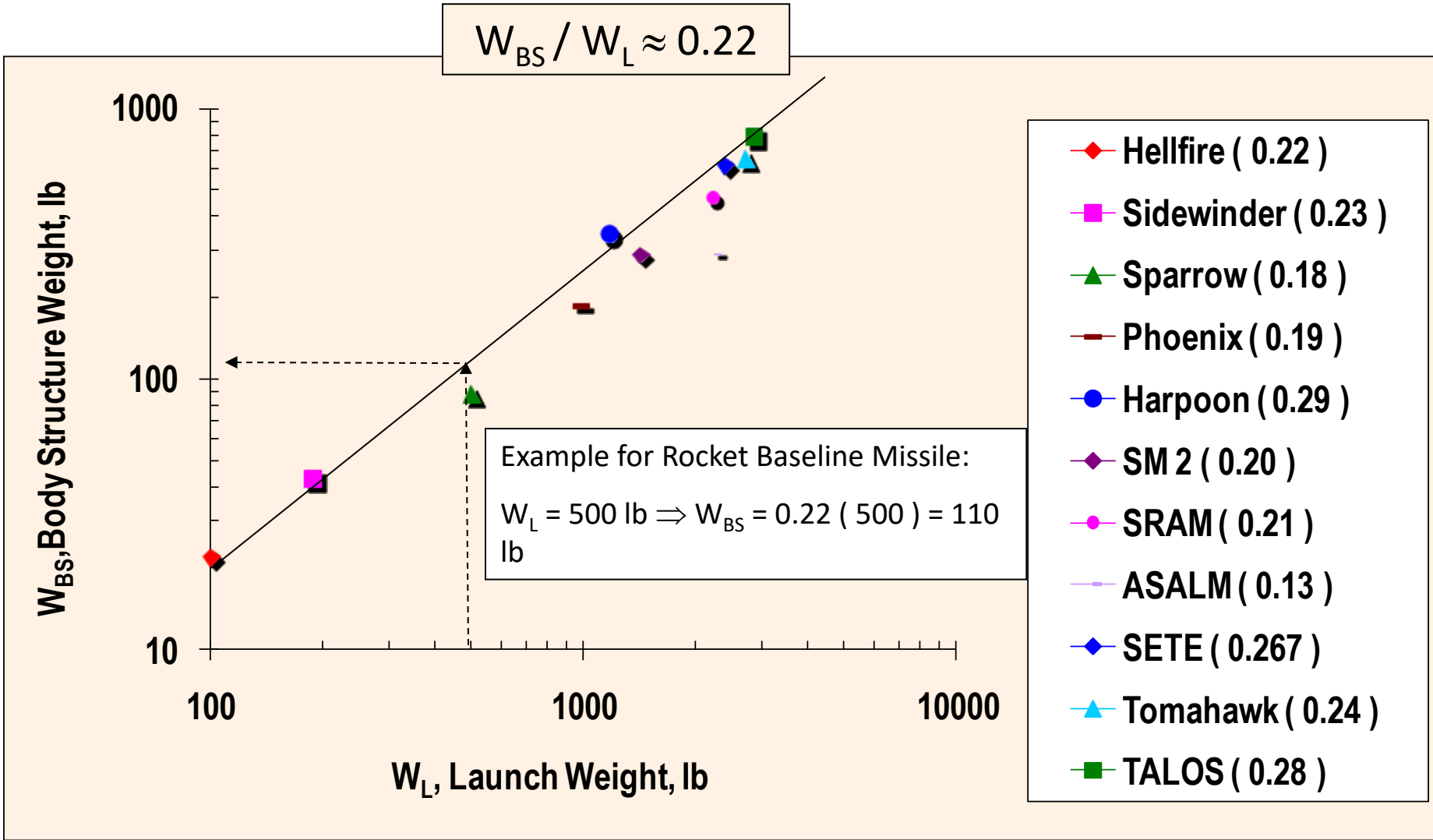
Examples of Aerodynamic Hot Spots



Video of Radiometric Imagery – SM-3

Flight

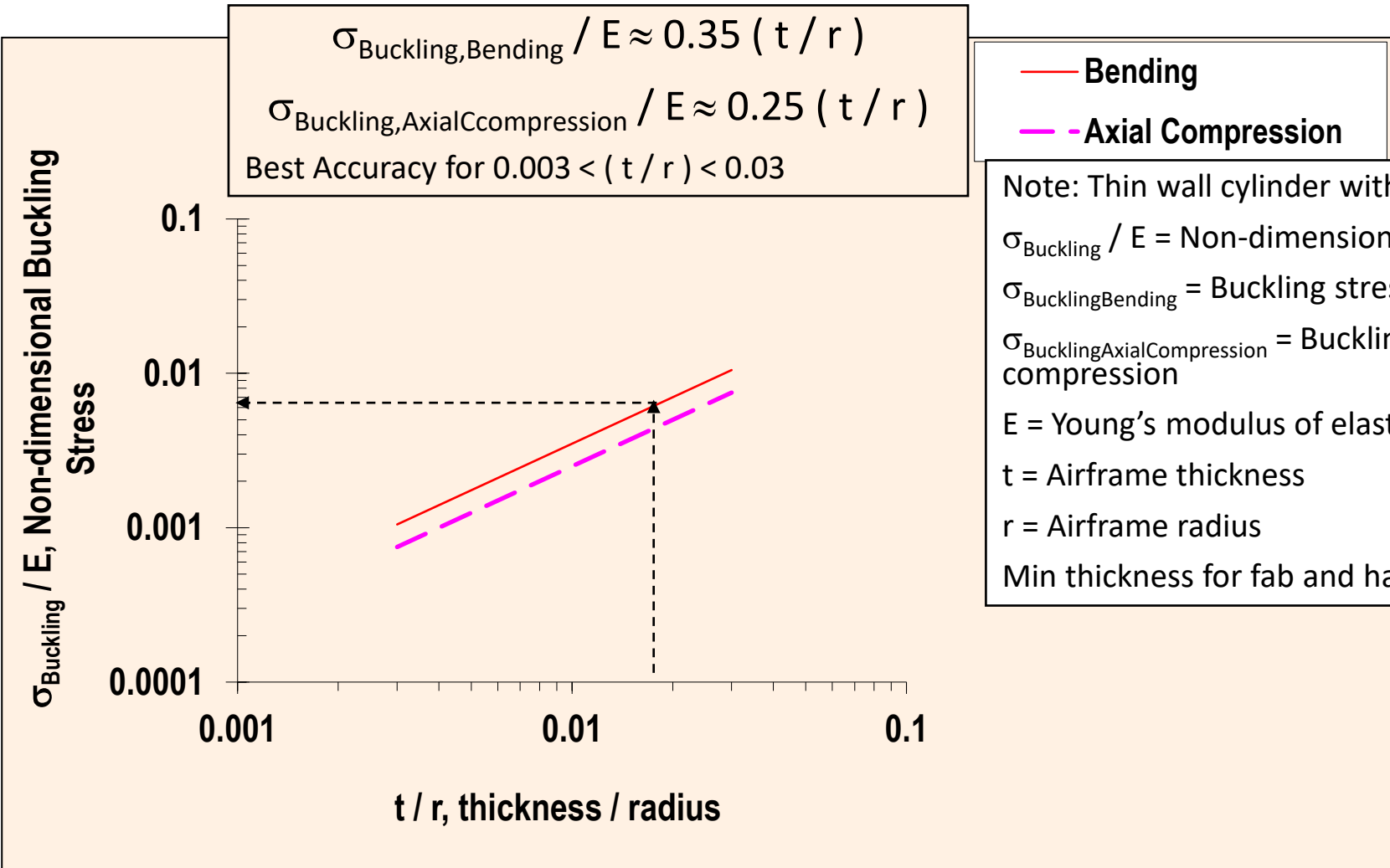
Missile Metal Body Structure Weight Is about 22% of the Launch Weight



Note: W_{BS} includes all load carrying body structure. If motor case, engine, or warhead case carry external loads then they are included in W_{BS} . W_{BS} does not include tail, wing, or other surface weight.

Note: Above based on metal structure. Graphite composite structure would result in lower weight fraction.

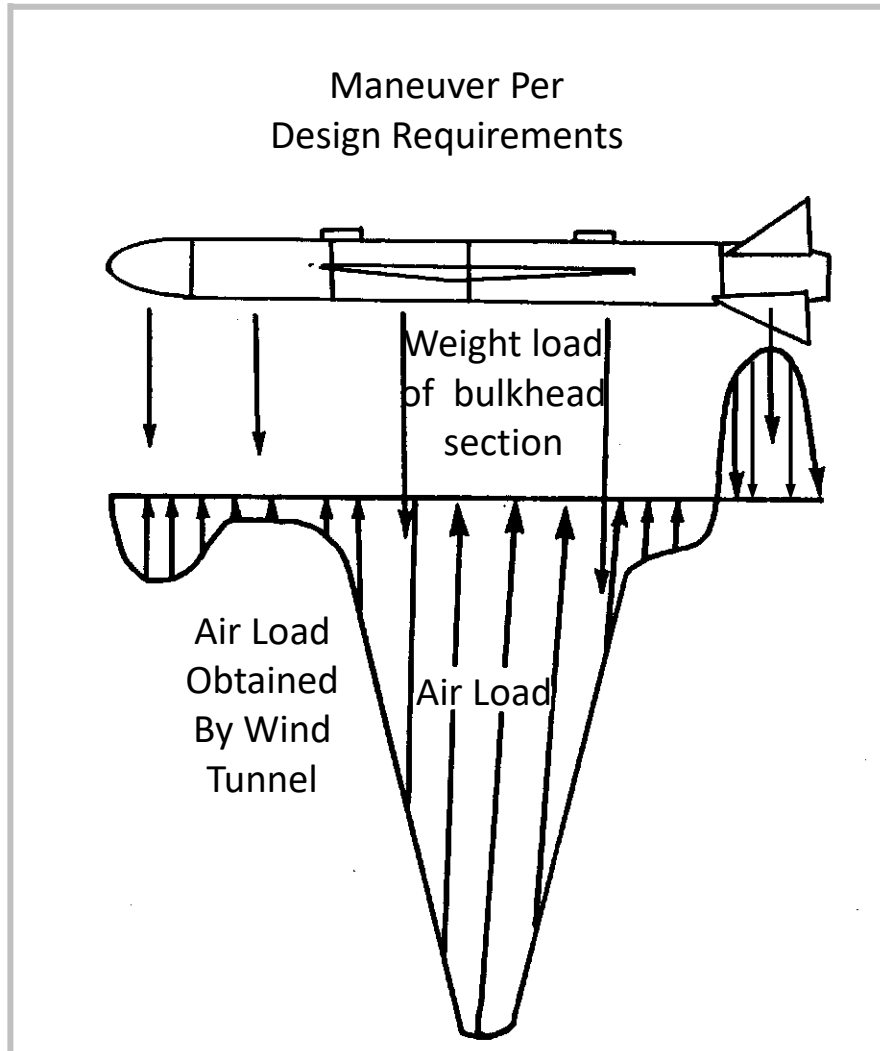
Localized Buckling May Be a Concern for a Thin Wall Structure



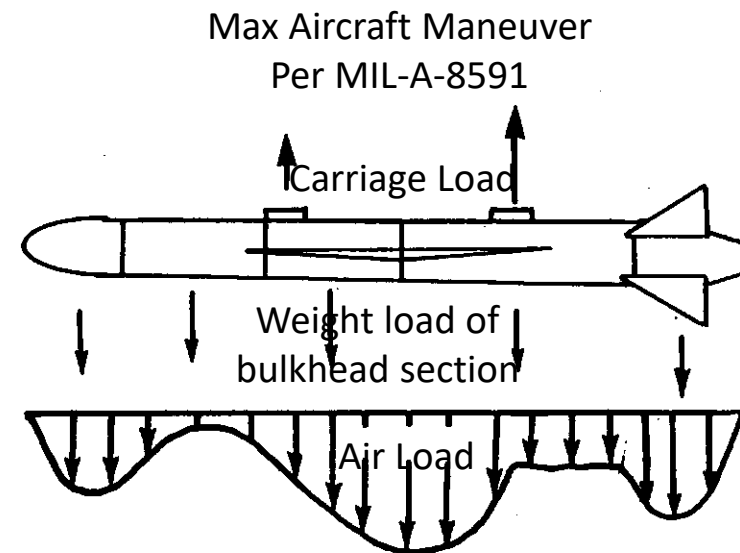
Note: Actual compression buckling stress can vary +/- 50%, depending upon typical imperfections in geometry and the loading symmetry.

Conceptual Design Procedure for Captive Flight Carriage and Free Flight Loads Calculation

Free Flight



Captive Flight



Note: MIL-A-8591 Procedure A assumes a worst case where the max air loads flight condition combines with the max g forces flight condition, regardless of different angles of attack.

Example of α_{\max} Calculated by MIL-A-8591 Using Procedure A for F-18 Aircraft Carriage:

$$\alpha_{\max} = 1.5 \left[n_{z,\max} W_{\max} / (C_{L\alpha} q S_{\text{Ref}}) \right]_{\text{aircraft}}$$

$$\alpha_{\max} = 1.5 (7.5) (49200) / [0.05 (1481) (400)]$$

$$= 18.7 \text{ deg}$$

Maximum Body Bending Moment Depends Upon Load Distribution

Example for Rocket Baseline Missile Body: 

① $c = 4$, ejection load

② $l = 144$ in

⇒ --- ③

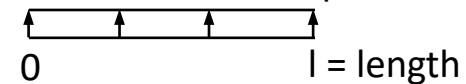
④ $N = 10,000$ lb (20 g)

⇒ - · - · ⑤ $M_B = 360,000$ in-lb

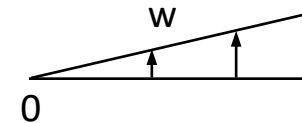
$$M_B = \frac{N l}{C}$$

$C = 8$ for uniform loading

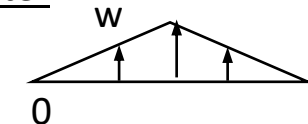
$w = dN / dx =$ load per unit length



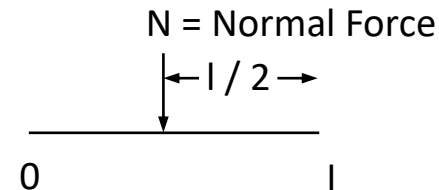
$C = 7.8$ for linear loading



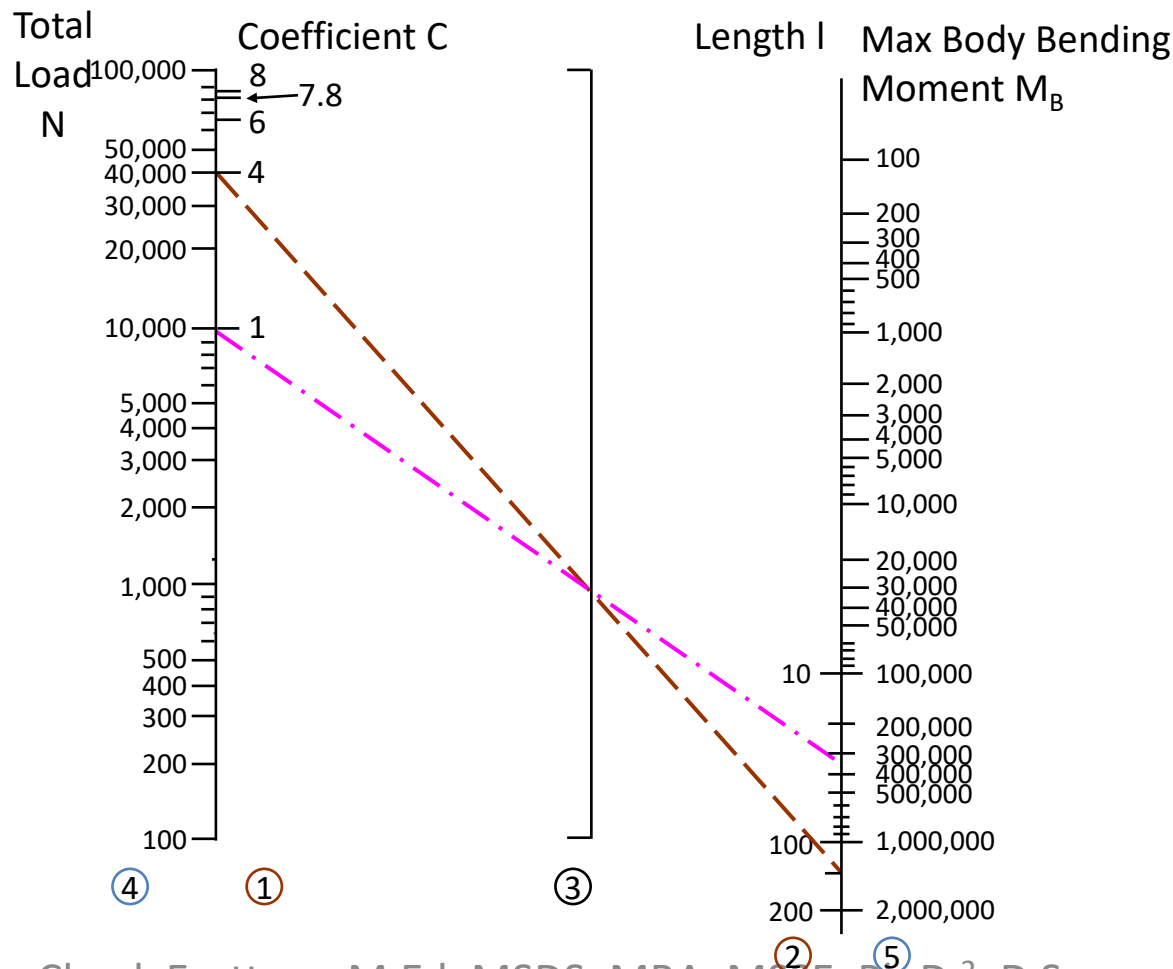
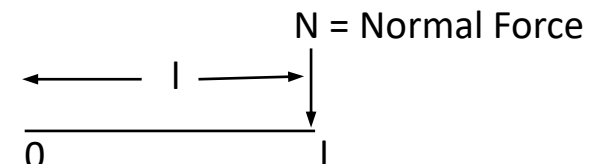
$C = 6$ for linear loading to center



$C = 4$ for load at center (e.g., ejection load)



$C = 1$ for load at end (e.g., flight control force)



Maximum Body Bending Moment Depends Upon Load Distribution

Example for Rocket Baseline Missile Body: 

① $c = 4$, ejection load

② $l = 144$ in

⇒ --- ③

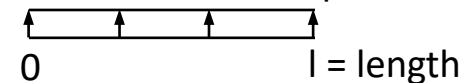
④ $N = 10,000$ lb (20 g)

⇒ - · - · ⑤ $M_B = 360,000$ in-lb

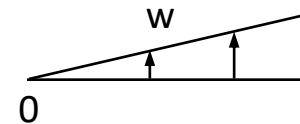
$$M_B = N l / C$$

$C = 8$ for uniform loading

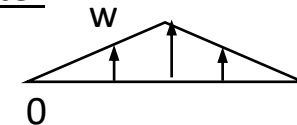
$w = dN / dx =$ load per unit length



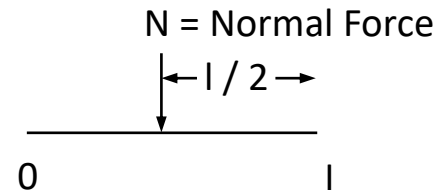
$C = 7.8$ for linear loading



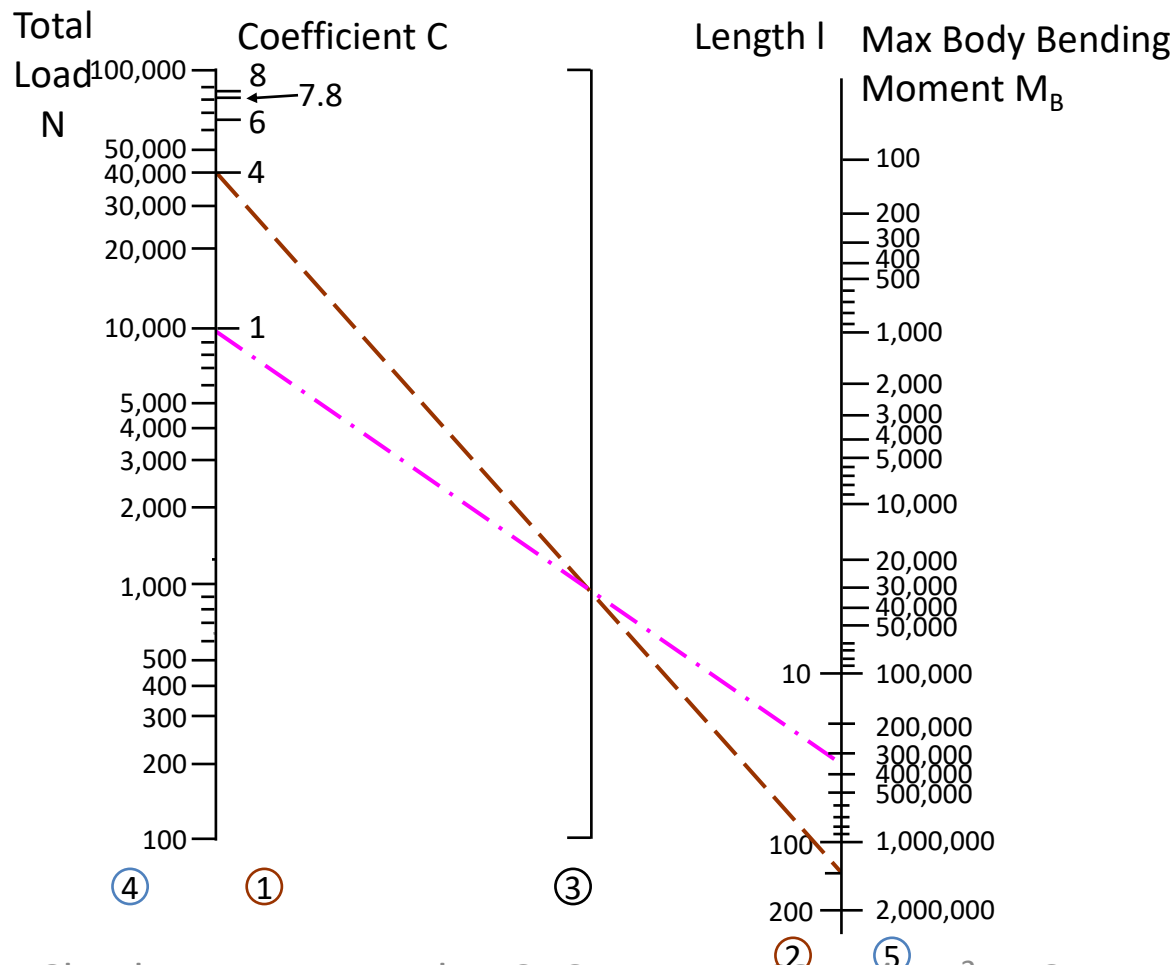
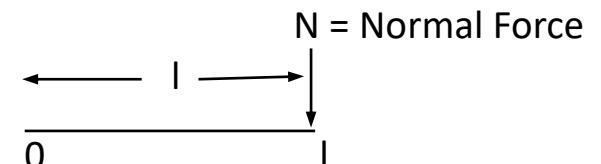
$C = 6$ for linear loading to center



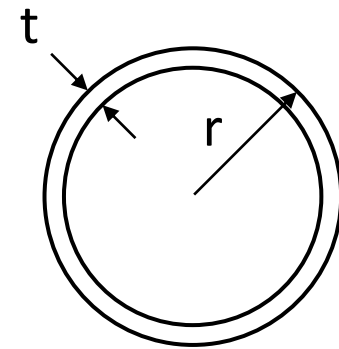
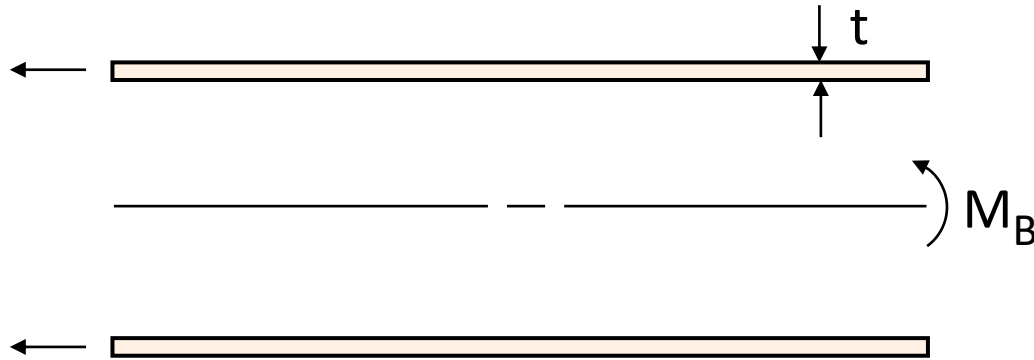
$C = 4$ for load at center (e.g., ejection load)



$C = 1$ for load at end (e.g., flight control force)



Body Bending Moment May Drive Body Structure Thickness / Weight



$$A = 2 \pi r t$$

$$I_z = I_y = \pi r^3 t$$

$$t = M_B (FOS) / [\pi r^2 \sigma_{max}]$$

Note / Assumptions:

Thin cylinder

Circular cross section

Solid skin

Longitudinal strength

Axial load stress and thermal stress assumed small compared to bending moment stress

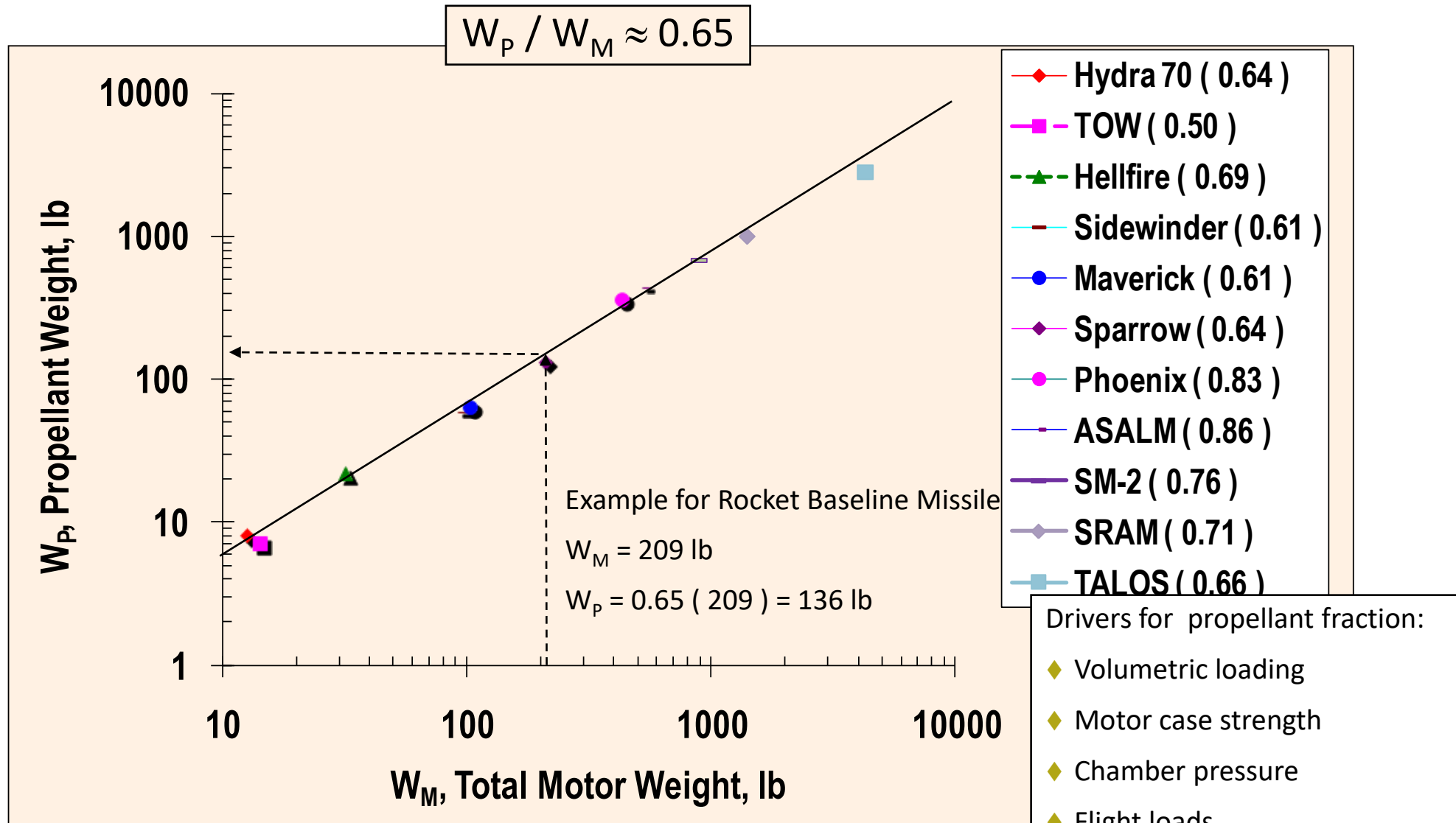
$$\sigma = M_B r / I_z = M_B r / (\pi r^3 t)$$

$$= M_B / (\pi r^2 t)$$

Example for Rocket Baseline Missile: 

- Body has circular cross section
- 2219-T81 aluminum skin ($\sigma_{ultimate,tensile} = 65,000$ psi)
- $r = 4$ in
- Ejection load = 10,000 lb (20 g)
- $M_B = 360,000$ in · lb
- FOS = 1.5
- $t = 360,000 (1.5) / [\pi (4)^2 (65,000)] = 0.16$ in

For a Typical Solid Propellant Rocket Motor, about 65% of the Weight Is Propellant



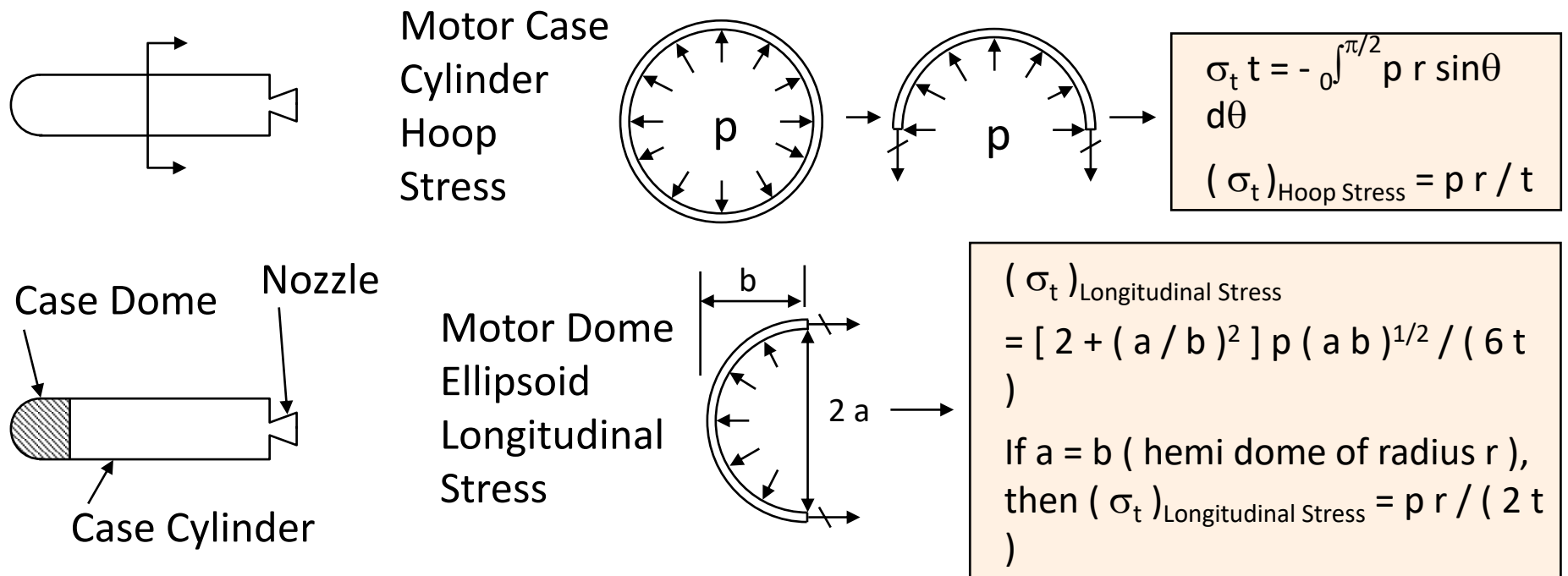
Note: Correlation base on solid propellant rocket

W_M includes propellant, motor case, nozzle, and insulation.

Based on metal motor case (composite case would have higher propellant weight fraction)

Rocket Motor Case Weight Is Usually Driven by Stress from Internal Pressure

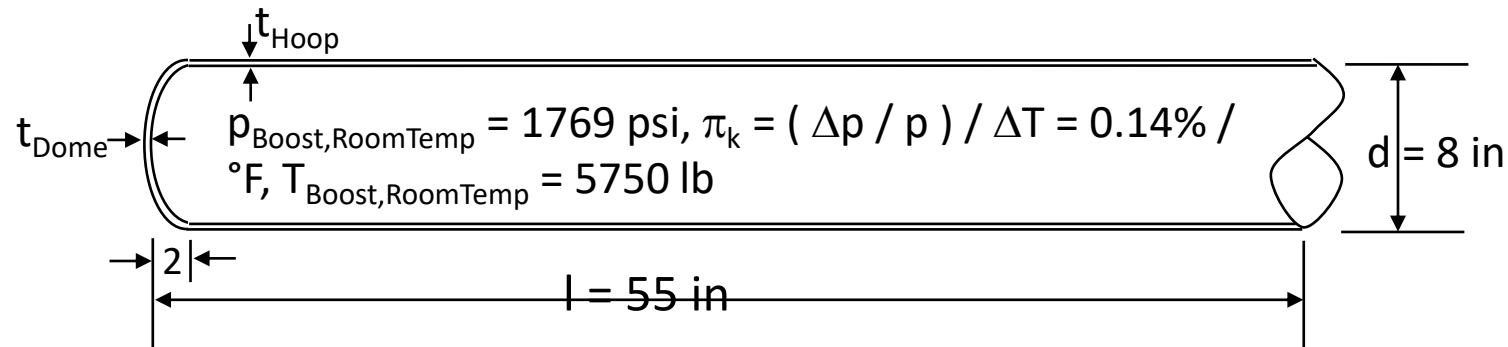
- ◆ Assume motor case is axisymmetric, with a front ellipsoid dome and an aft cylinder body



- ◆ With metals – the material also reacts body bending loads (e.g., maneuver loads)
- ◆ In composite motor designs, extra (longitudinal) fibers must usually be added to accommodate body bending loads

Solid Propellant Rocket Motor Case Thickness and Weight Are Driven by Internal Pressure

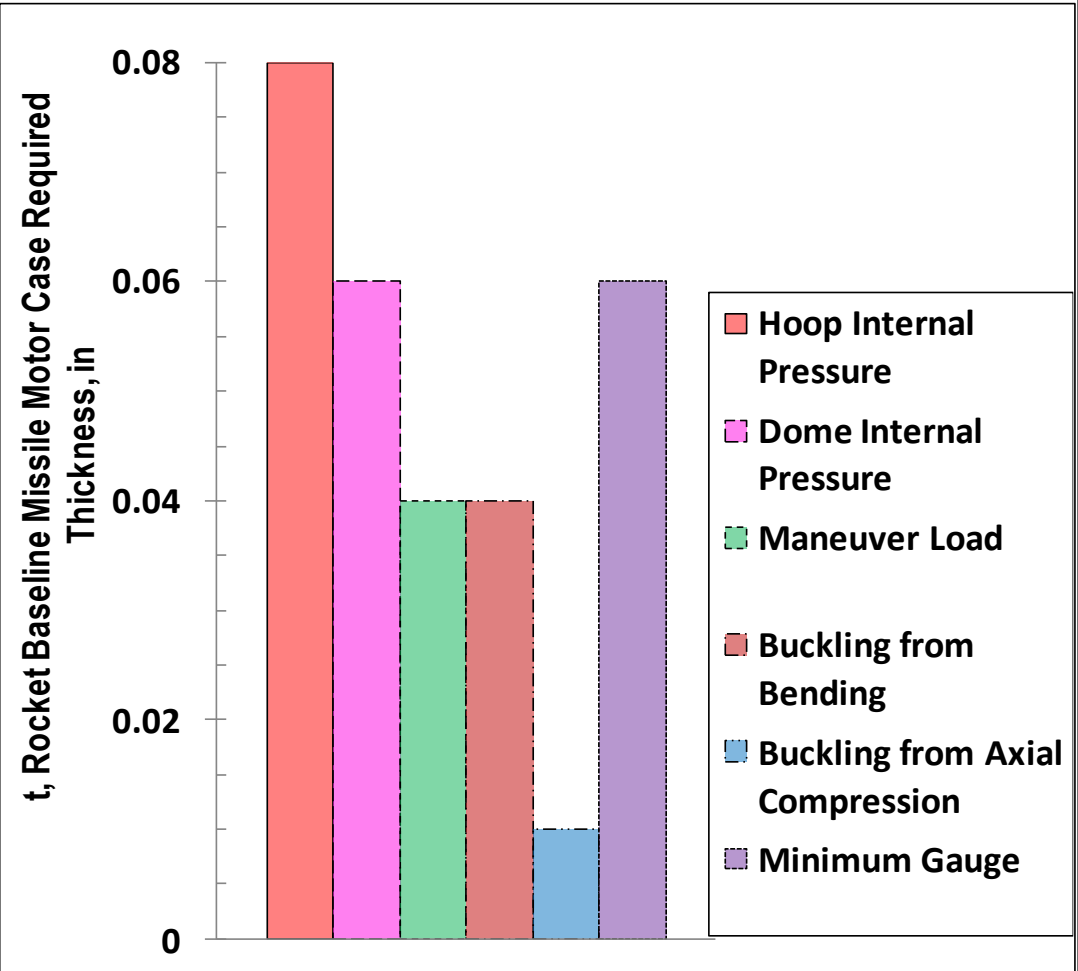
- ◆ Compare Rocket Baseline Steel Motor Case with a Graphite Composite Motor Case



- ◆ Maximum Effective Operating Pressure (MEOP) Propellant Pressure Sensitivity to Temperature (π_k) Is Driver for Rocket Baseline Missile Motor Case Thickness
- ◆ Assume Hot Day ($T = 160 \text{ Deg F}$), Ambient Propellant Temp ($T = 70 \text{ Deg F}$), $\pi_k = 0.14\% / \text{Deg F}$)
 - ◆ $p_{\text{MEOP}} = p_{\text{Boost, RoomTemp}} \times e^{\pi_k \Delta T} = 1769 \times e^{0.0014 (160 - 70)} = 2007 \text{ psi}$
- ◆ Must Design Burst Pressure p_{Burst} Greater Than Nominal p_{MEOP}
 - ◆ Ignition Spikes
 - ◆ Welds
 - ◆ Other Uncertainty
- ◆ Assume $p_{\text{burst}} \approx p_{\text{Boost, RoomTemp}} (p_{\text{MEOP}} / p_{\text{Boost, RoomTemp}})^3 = 1769 (2007 / 1769)^3 = 2,582 \text{ psi}$
- ◆ Next, Calculate Required Thickness of Motor Case

Rocket Baseline Missile Motor Case Thickness Is Driven by Internal Pressure

Example for Rocket Baseline Missile Steel Motor Case



Required Thickness for Rocket Baseline Missile Steel Motor Case ($\rho = 0.283 \text{ lb / in}^3$, $(\sigma_t)_{ult} = 190,000 \text{ psi}$)

$$t_{Hoop} = (FOS) p_{burst} r / \sigma_t$$
 Calculate $t_{Hoop} = 1.5 (2582) (4.0) / 190000 = 0.08 \text{ in}$

$$t_{Dome} = (FOS) p_{burst} (ab)^{1/2} [2 + (a/b)^2] / (6 \sigma_t) = 1.5 (2582) (4 \times 2)^{1/2} (2 + 2^2) / [6 (190000)] = 0.06 \text{ in}$$

$$t_{ManeuverBending} = (FOS) M_B / (\pi \sigma r^2)$$

Assume 30 g maneuver at launch ($W_L = 500 \text{ lb}$) with uniform loading ($c = 8$) over length of missile (144 in) and FOS = 1.5. Then

$$N = n W = 30 (500) = 15,000 \text{ lb}$$

$$M_B = N l / c = 15000 (144) / 8 = 270,000 \text{ in-lb}$$

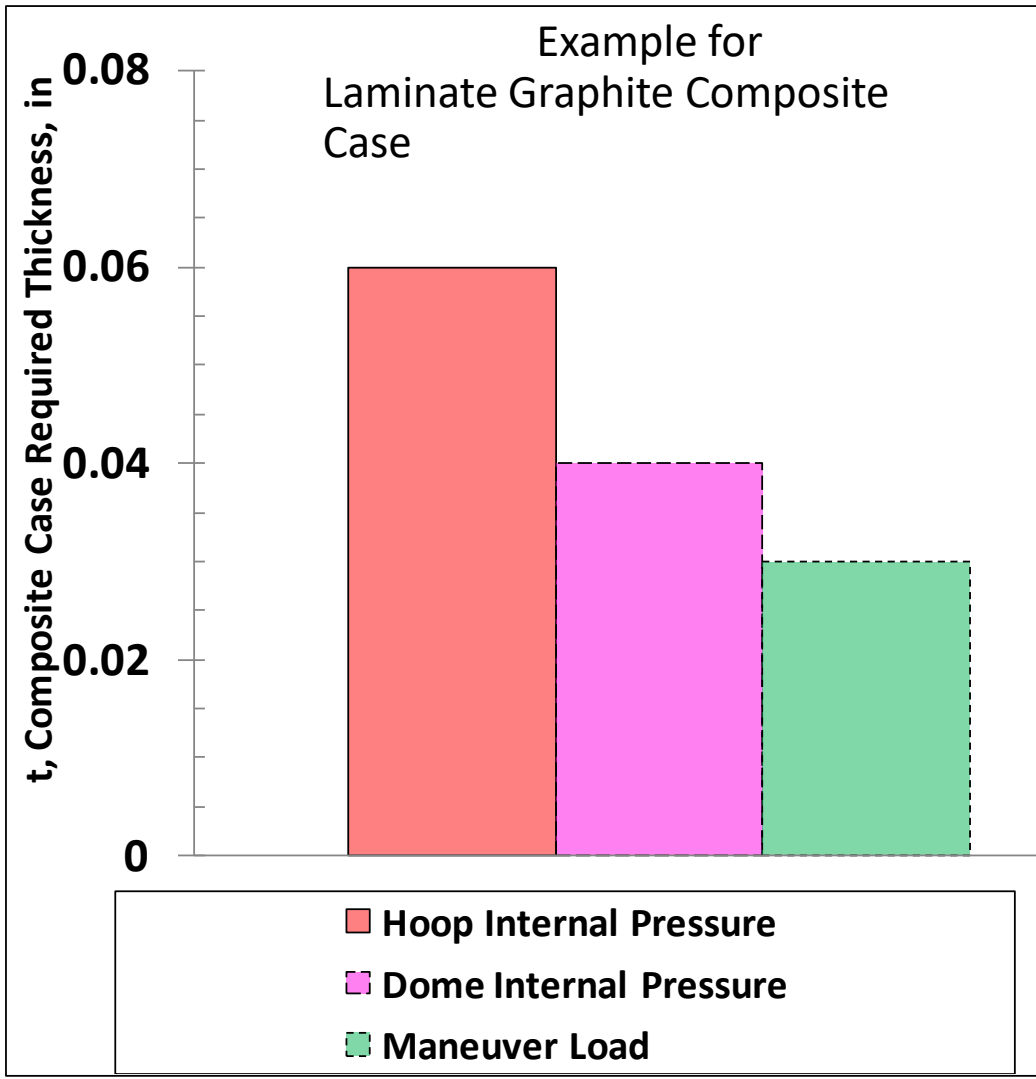
$$t_{ManeuverBending} = 1.5 (270000) / [\pi (190000) 4^2] = 0.04 \text{ in}$$

◆ Total Required Thickness Under Combined Loads of Internal Pressure + Maneuver Load Is

$$t_{Hoop} = t_{ManeuverBending} + t_{InternalPressure} = 0.04 + 0.08 = 0.12 \text{ in}$$

$$t_{Dome} = t_{ManeuverBending} + t_{InternalPressure} = 0.04 + 0.06 = 0.10 \text{ in}$$

Rocket Baseline Missile Motor Case Thickness Is Driven by Internal Pressure (cont)



Assume 60% Graphite / 40% Polyimide Composite Motor Case ($\rho = 0.057 \text{ lb / in}^3$, $(\sigma_t)_{ultimate} = 270,000 \text{ psi}$)

◆ $(t_{Hoop})_{InternalPressure} = (FOS) p_{burst} r / \sigma_t$
 Calculate $(t_{Hoop})_{InternalPressure} = 1.5 (2582) (4.0) / 270000 = 0.06 \text{ in @ } 90 \text{ deg orientation (radial fibers)}$

◆ Also, $(t_{Dome})_{InternalPressure} = (FOS) p_{burst} (ab)^{1/2} [2 + (a/b)^2] / (6 \sigma_t) = 1.5 (2582) (4 \times 2)^{1/2} (2 + 2^2) / [6 (270000)] = 0.04 \text{ in}$

◆ For the Motor Case in Maneuver Bending Moment:
 $t_{ManeuverBending} = (FOS) M_B / (\pi \sigma r^2) = 1.5 (270000) / [\pi (270000)^2] = 0.03 \text{ in @ } 0 \text{ deg orientation (longitudinal fibers)}$

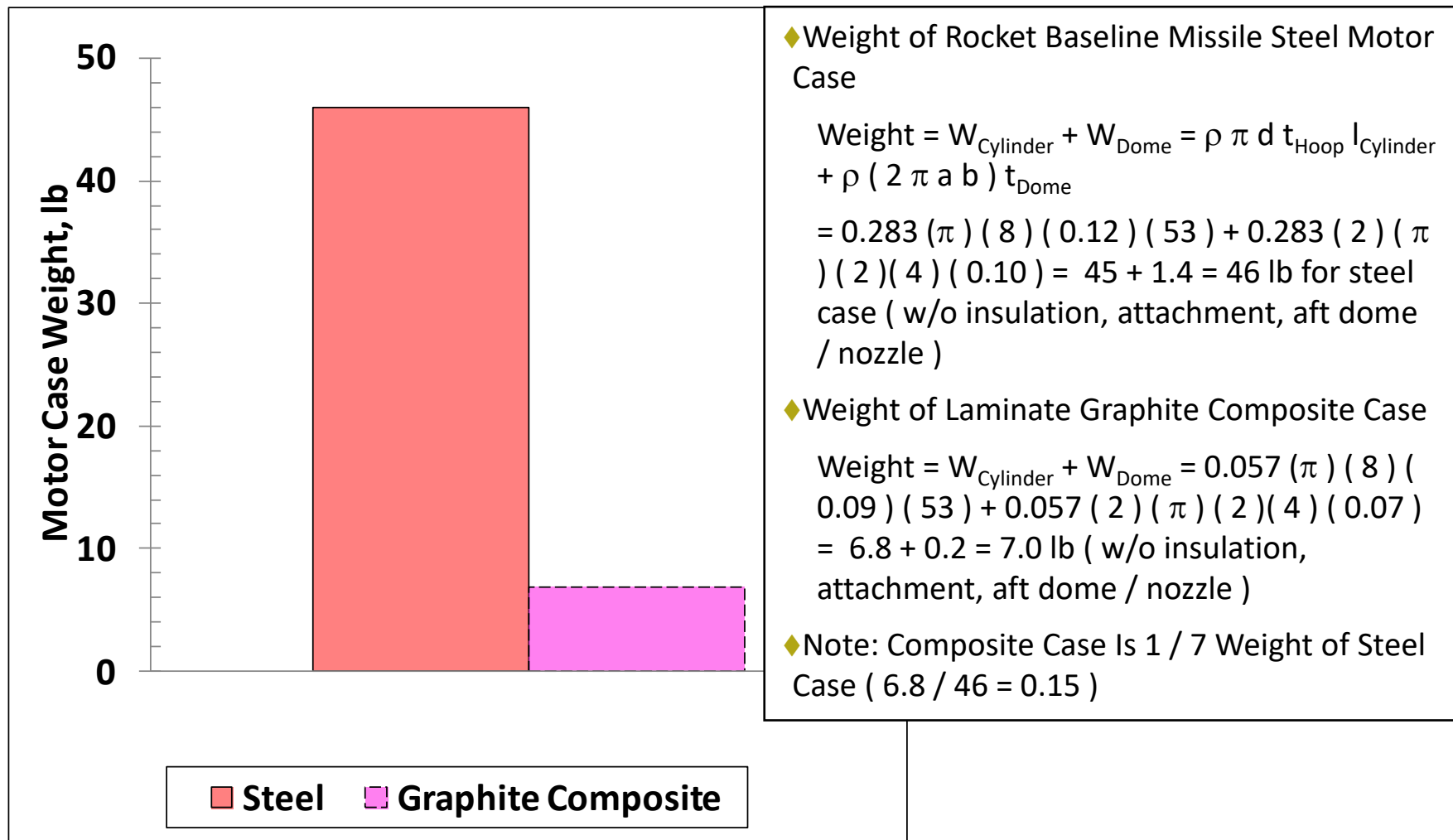
◆ Total Required Composite Case Thickness Under Combined Loads of Internal Pressure + Maneuver Load:

$t_{Hoop} = t_{ManeuverBending} + t_{InternalPressure} = 0.03 \text{ @ } 0 \text{ deg} + 0.06 \text{ @ } 90 \text{ deg} = 0.09 \text{ in total}$

$t_{Dome} = t_{ManeuverBending} + t_{InternalPressure} = 0.03 \text{ longitudinal fibers} + 0.04 \text{ radial fibers} = 0.07 \text{ in total}$

Note: Composite case hoop thickness is 75% of steel thickness (0.09 / 0.12). Composite case dome thickness is 70% of steel thickness (0.07 / 0.10)

Laminate Graphite Composite Rocket Motor Case Is Lighter Weight



Multi-mode Seeker Dome Material Is Driven by RF / IR Transmission and Flight Environment

Multi-Mode Seeker Dome Material	Density (g / cm ³)	Dielectric Constant	MWIR / LWIR Bandpass	Transverse Strength (10 ³ psi)	Thermal Expansion (10 ⁻⁶ / °F)	Erosion, Knoop (kg / mm ²)	Max Short-Duration Temp (°F)
Zinc Sulfide (ZnS)	4.05	8.4 ○	● ○	18 ○	4 ○	350 ○	700 ○
Zinc Selenide (ZnSe)	5.16	9.0 U	● ●	8 U	4 ○	150 ○	600 ○
Sapphire / Spinel (Al ₂ O ₃)	3.68	8.5 U	● -	28 U	3 ○	1650 ●	1800 ●
Quartz / Fused	2.20	3.7 ●	○ -	8 U	0.3 ●	600 ○	2000 ●
Silica (SiO ₂) Silicon Nitride (Si ₃ N ₄)	3.18	6.1 ○	U -	90 ●	2 ○	2200 ●	2700 ●
Diamond (C)	3.52	5.6 ○	U U	400 ●	1 ●	8800 ●	3500 ●
Pyroceram	2.55	5.8 ○	U U	25 ○	3 ○	700 ○	2200 ●
Polyimide	1.54	3.2 ●	U U	17 ○	40 U	70 U	700 ○
Mag. Fluoride (MgF ₂)	3.18	5.5 ○	● U	7 U	6 U	420 ○	1000 ○
Alon (Al ₂₃ O ₂₇ N ₅)	3.67	9.3 U	○ U	44 U	3 U	1900 ●	1800 ●

● Superior
 ○ Good
 ○ Average
 U Poor
 - Very Poor

Infrared Seeker Dome Material Is Driven by MWIR / LWIR Transmission and Flight Environment

Infrared Seeker Dome Material	Density (g / cm ³)	MWIR / LWIR Bandpass	Transverse Strength (10 ³ psi)	Thermal Expansion (10 ⁻⁶ / ° F)	Erosion, Knoop (kg / mm ²)	Max Short-Duration Temp (° F)
Zinc Sulfide (ZnS)	4.05	● ●	18 ○	4 ○	350 ○	700 ○
Zinc Selenide (ZnSe)	5.16	● ●	8 U	4 ○	150 ○	600 ○
Mag. Fluoride (MgF ₂)	3.18	● U	7 U	6 U	420 ●	1000 ●
Germanium (Ge)	5.33	● ●	15 U	4 U	780 ●	200 U
Sapphire / Spinel (Al ₂ O ₃)	3.68	● -	28 ○	3 ○	1650 ●	1800 U
Diamond (C)	3.52	- U	400 ●	1 ●	8800 ●	3500 ●
Alon (Al ₂₃ O ₂₇ N ₅)	3.67	● U	44 ●	3 ○	1900 ●	1800 ●
Quartz / Fused Silica (SiO ₂)	2.20	○ -	8 U	0.3 ●	600 ●	2000 ●


 Superior (blue circle) Poor (white circle) Good (half-blue circle) Average (white circle) Poor (U-shape) Very (dash symbol)

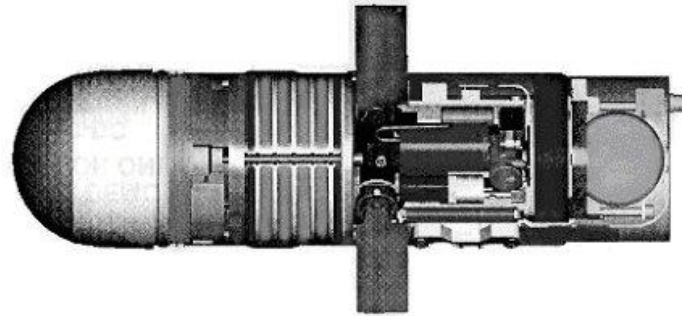
Radar Seeker Radome Material Is Driven by RF Transmission and Flight Environment

Radar Seeker Dome Material	Density (g / cm ³)	Dielectric Constant	Transverse Strength (10 ³ psi)	Thermal Expansion (10 ⁻⁶ / °F)	Erosion, Knoop (kg / mm ²)	Max Short-Duration Temp (°F)
Quartz / Fused Silica (SiO ₂)	2.20	3.7	8	0.3	600	2000
Silicon Nitride (Si ₃ N ₄)	3.18	6.1	90	2	2200	2700
Diamond (C)	3.52	5.6	400	1	8800	3500
Pyroceram	2.55	5.8	25	3	700	2200
Polyimide	1.54	3.2	17	40	70	700
Mag. Fluoride (MgF ₂)	3.18	5.5	7	6	420	1000

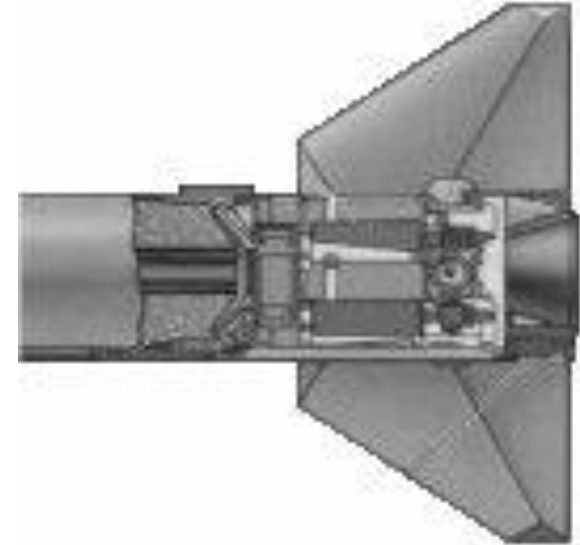
Superior
 Average
 Poor - Very
 Good

An Electromechanical Actuator Allows Efficient Packaging

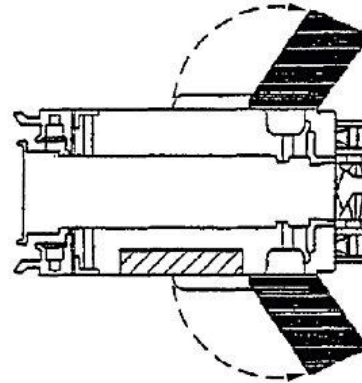
Canard (Stinger)



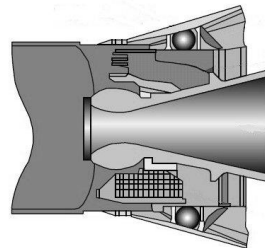
Tail (AMRAAM)



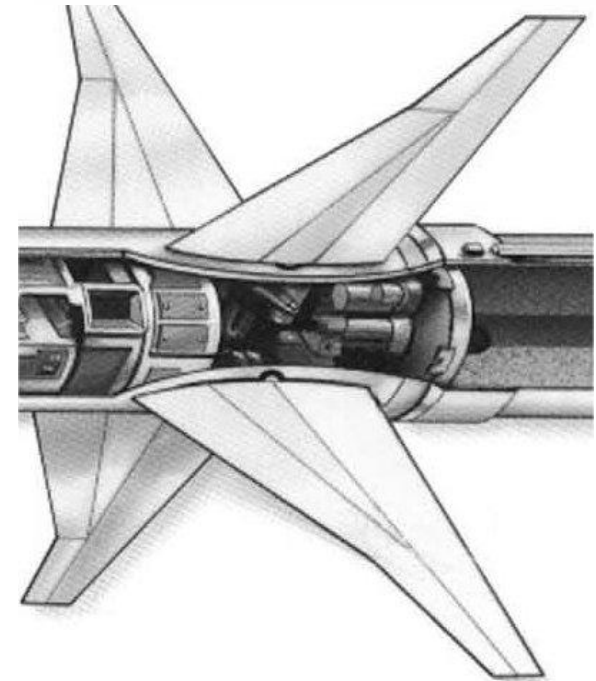
Jet Vane / Tail (Javelin)



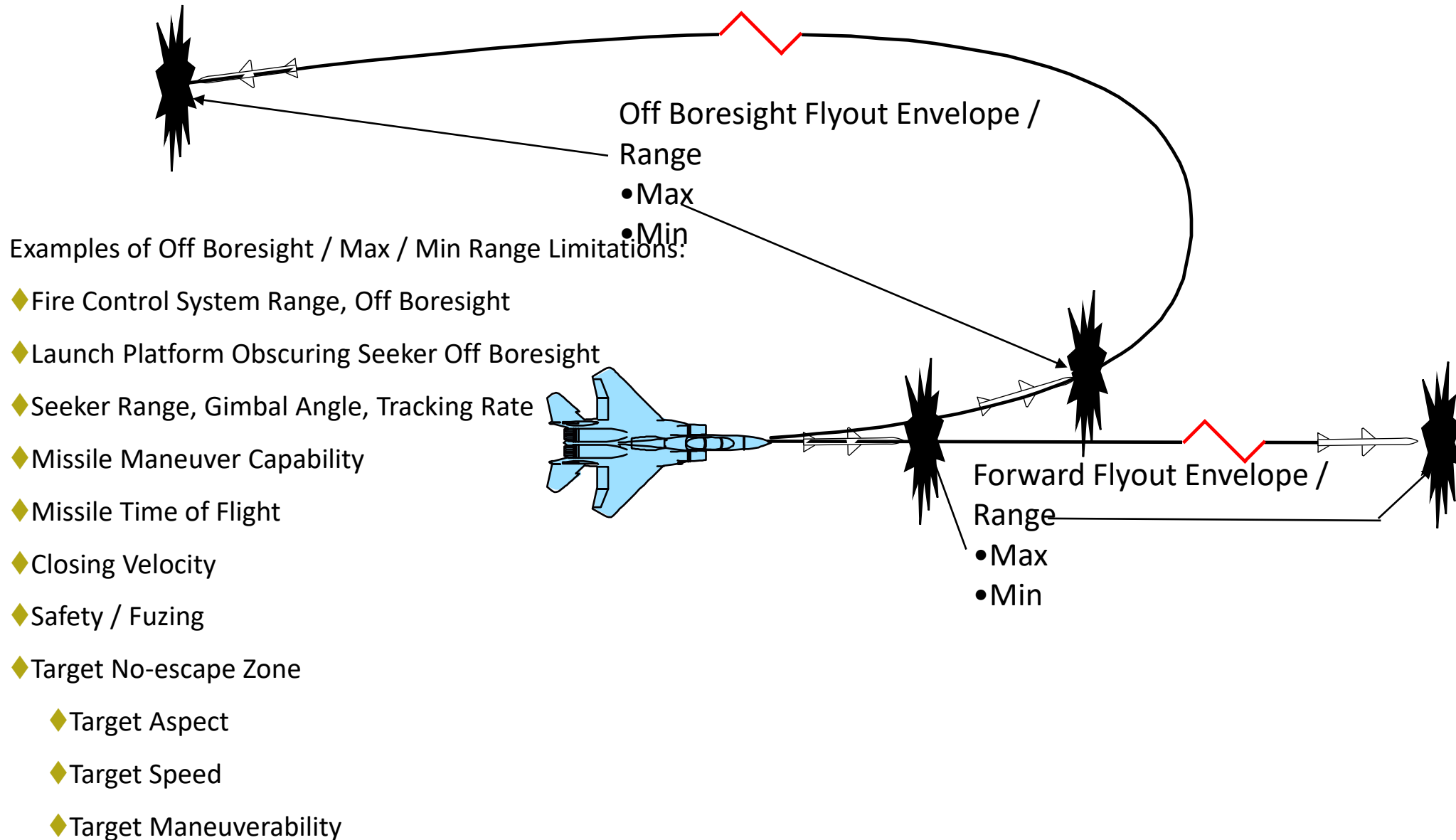
Movable Nozzle (THAAD) ...



Wing (HARM)



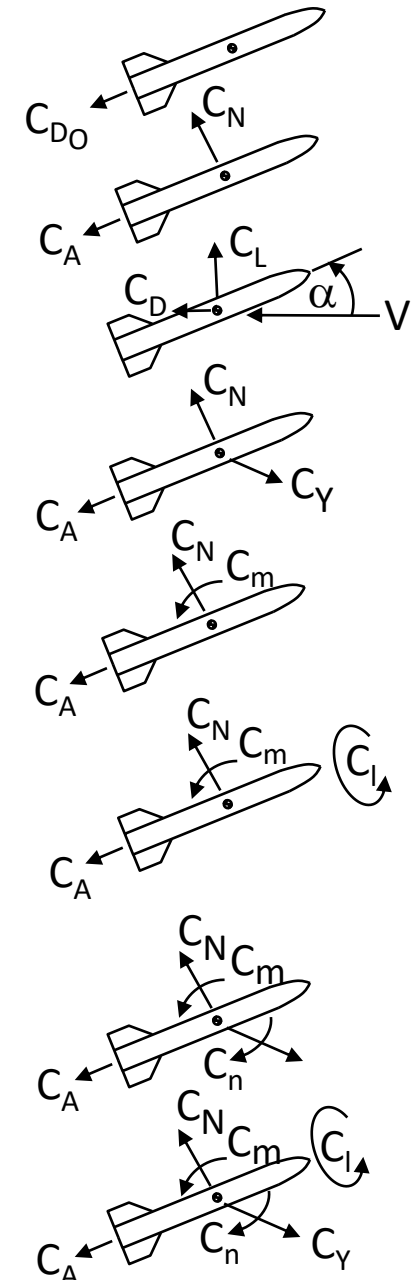
Missile Flight Envelope Should Have Large Max Range, Small Min Range, and Large Off Boresight



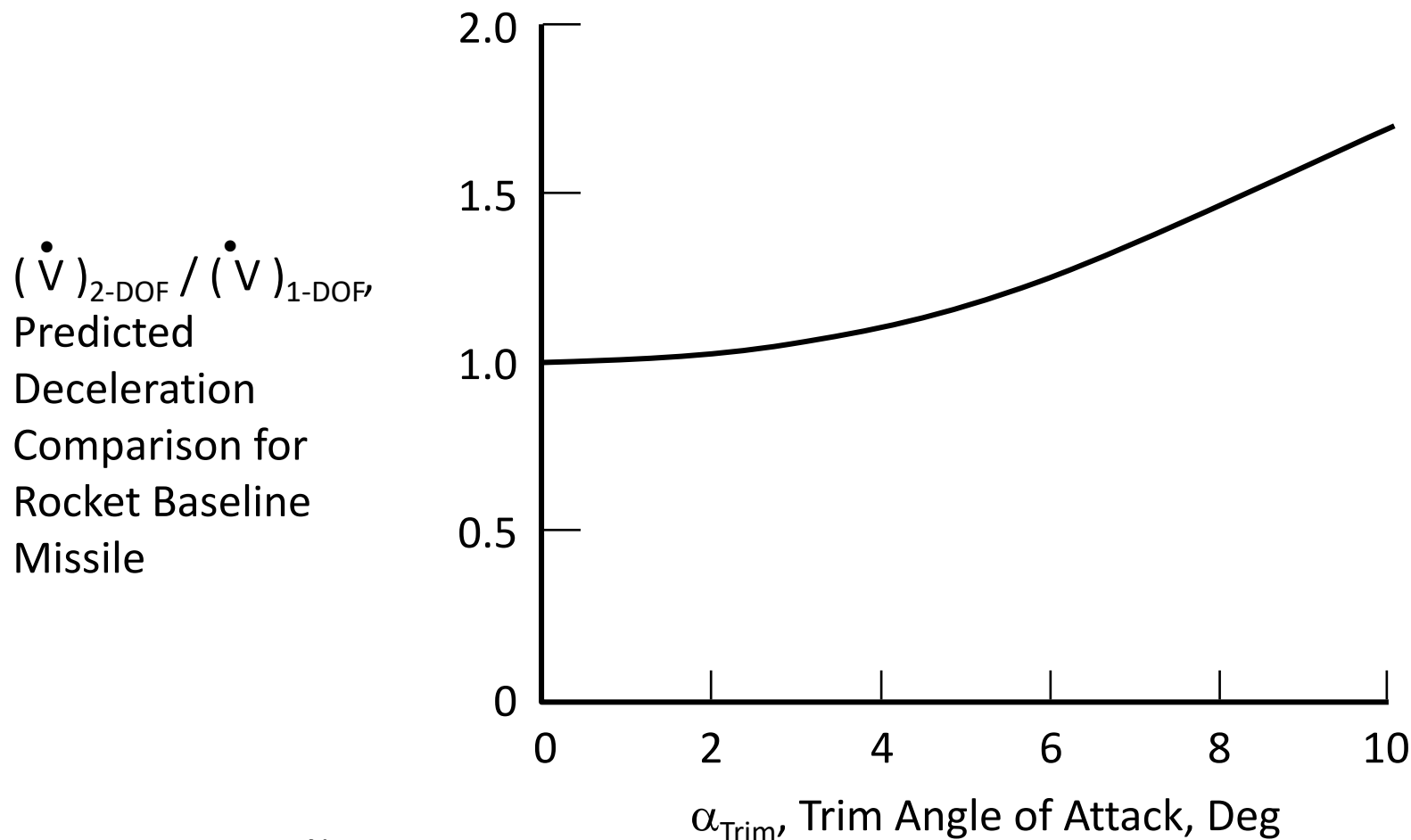
Comparison of Conceptual Design vs Preliminary Design Flight Trajectory Modeling of DOF

Aero Forces & Moments


- Conceptual Design Force and Moment Modeling
 - 1-DOF [axial force (C_{D0}), thrust, weight]
 - 2-DOF [normal force (C_N), axial force, thrust, weight]
 - 2-DOF [lift force (C_L), drag (C_D), thrust, weight]
 - 3-DOF point mass [3 aero forces (normal, axial, side), thrust, weight]
 - 3-DOF pitching [2 aero forces (normal, axial), 1 aero moment (pitching), thrust, weight]
 - 4-DOF [2 aero forces (normal, axial), 2 aero moments (pitching, rolling), thrust, weight]
- Preliminary Design Force and Moment Modeling
 - 5-DOF [3 aero forces (normal, axial, side), 2 aero moments (pitching, yawing), thrust, weight]
 - 6-DOF [3 aero forces (normal, axial, side), 3 aero moments [pitching, rolling, yawing), thrust, weight]



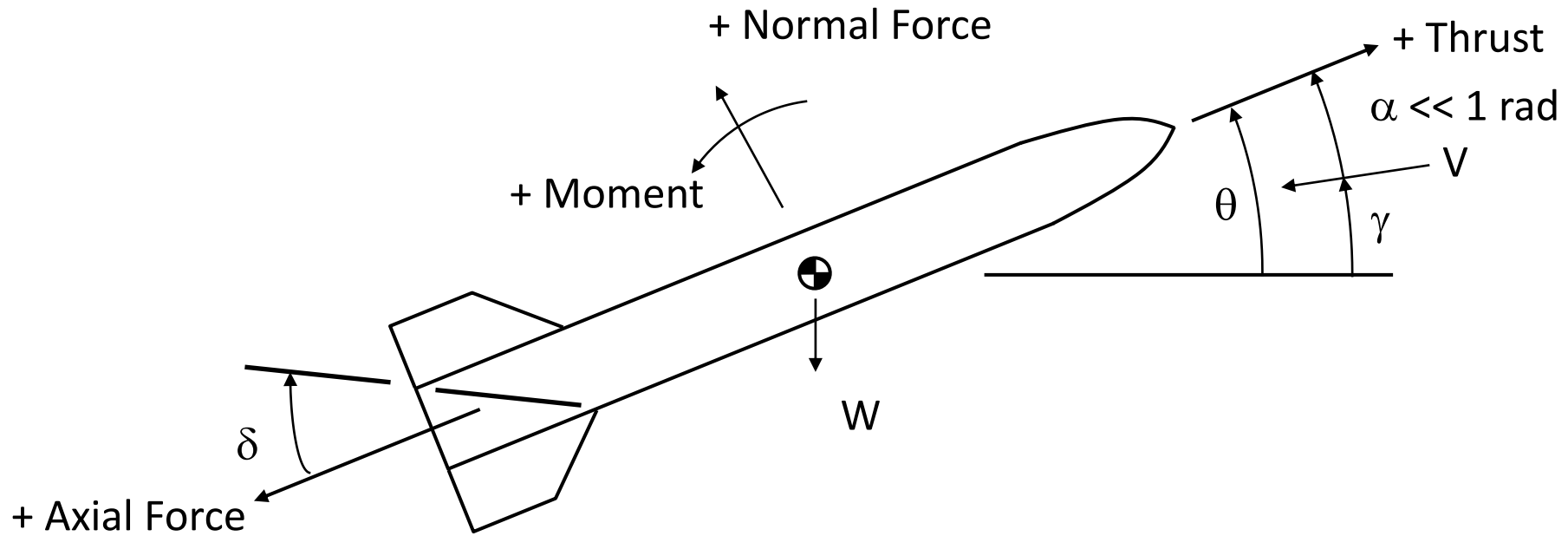
1-DOF Coast Equation Has Good Accuracy if the Missile Fly-out Is at Low Angle of Attack



Note:

- $(\dot{V})_{2-DOF}$ = Two-degrees-of-freedom deceleration
- $(\dot{V})_{1-DOF}$ = One-degree-of-freedom deceleration
- Rocket baseline missile during coast 
- Mach 2, h = 20,000 ft
- $\alpha_{Trim} \approx 0.3$ deg for 1-g flyout

3-DOF Simplified Equations of Motion Show Drivers for Missile Configuration Sizing



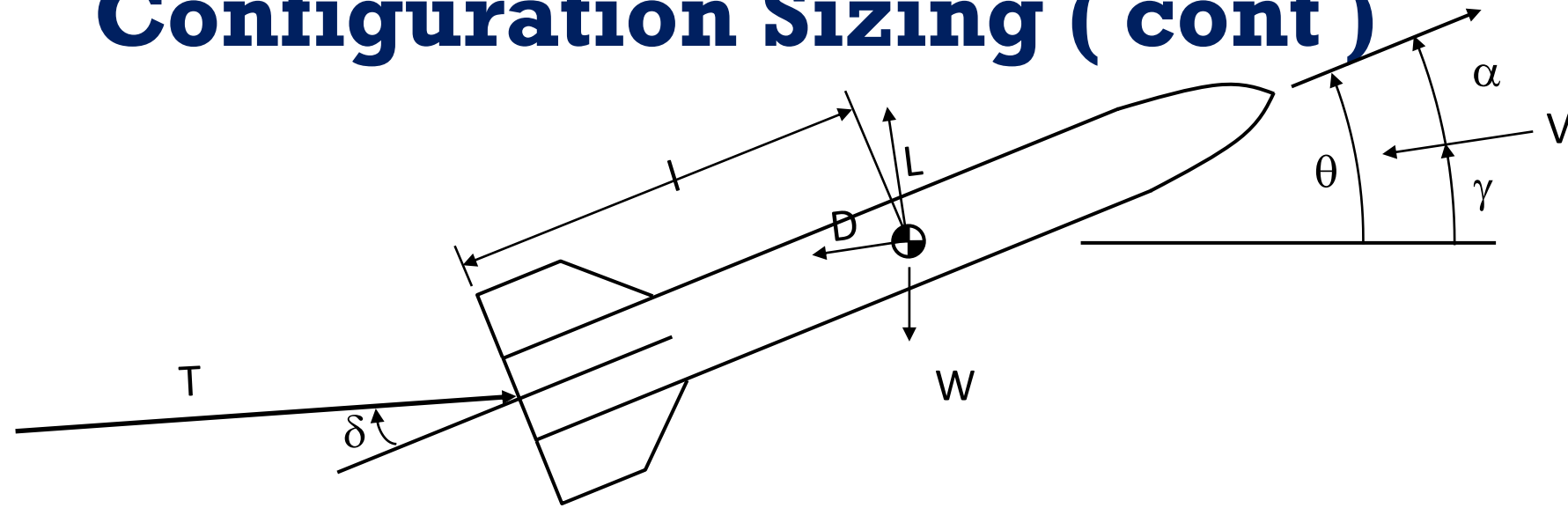
Aero Control Configuration Sizing Implication

High Agility / Fast Rotation $\Rightarrow C_{m\delta} > C_{m\alpha}$, I_y small (W small), q large

Large / Fast Heading Change $\Rightarrow C_N$ large ($C_{N\alpha} \alpha$ or $C_{N\delta} \delta$ large), W small, ρ large (low alt), V large, T / V large

High Speed / Long Range \Rightarrow Total Impulse large, C_A small, q small

3-DOF Simplified Equations of Motion Show Drivers for missile Configuration Sizing (cont)



Thrust Vector Control Sizing Implication*

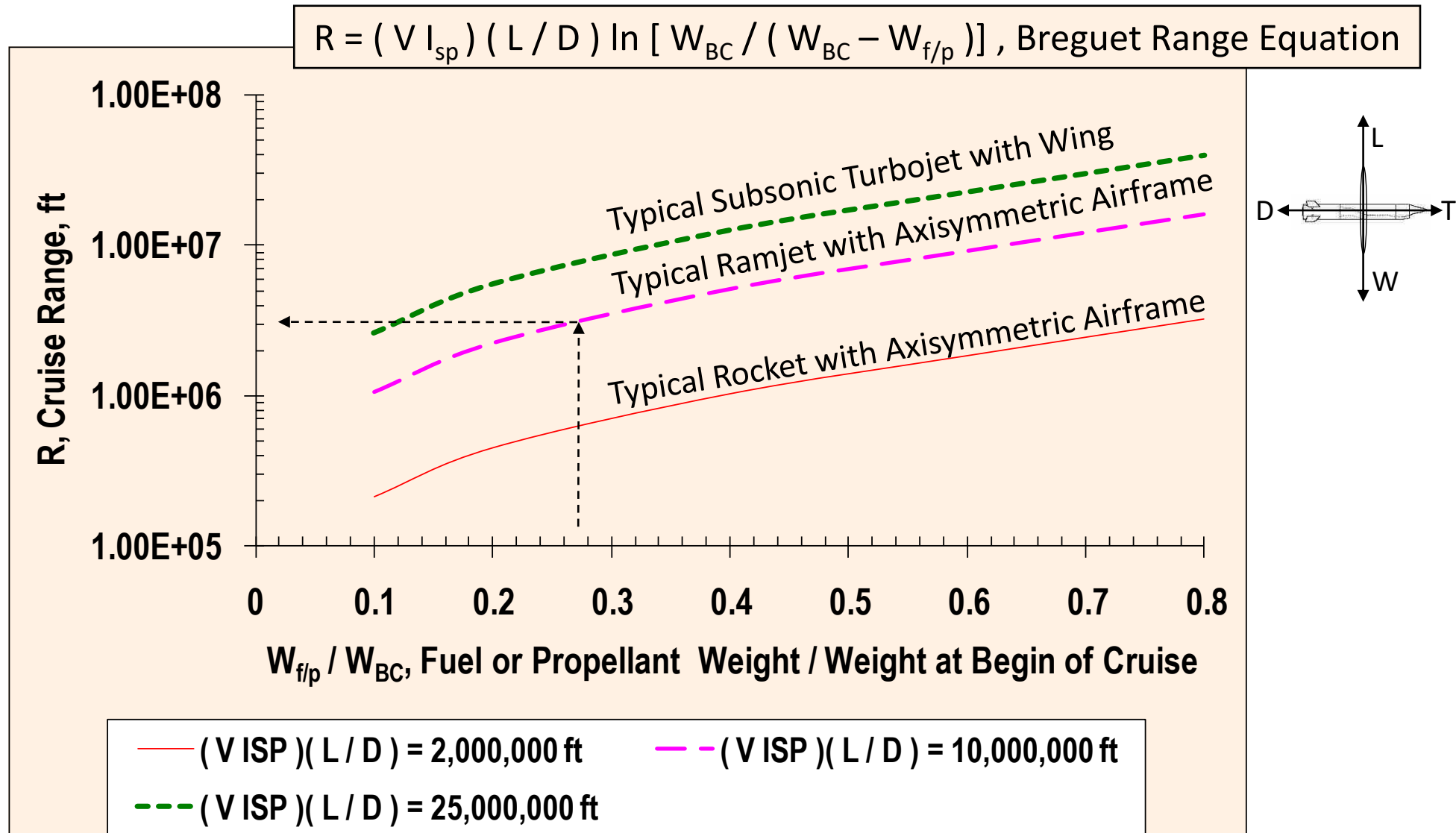
High Agility / Fast Rotation $\Rightarrow T, l, \delta$ large, I_y small (W small)

Large / Fast Heading Change $\Rightarrow T \sin \alpha / V$ large

High Speed / Long Range \Rightarrow Total Impulse large, C_D small, q small

*Assumption: Aero Moment Small Compared to TVC Moment

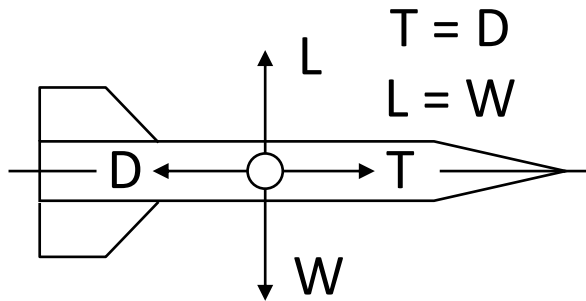
For Long Range Cruise - Maximize $V I_{sp}$, L / D , and Weight Fraction of Fuel / Propellant



Note: R = cruise range, V = cruise velocity, I_{sp} = specific impulse, L = lift, D = drag, W_{BC} = weight at begin of cruise, $W_{f/p}$ = weight of fuel or propellant

Flight Range in Steady Flight Is Enhanced by High L / D and Light Weight

Steady Level Flight (Cruise)

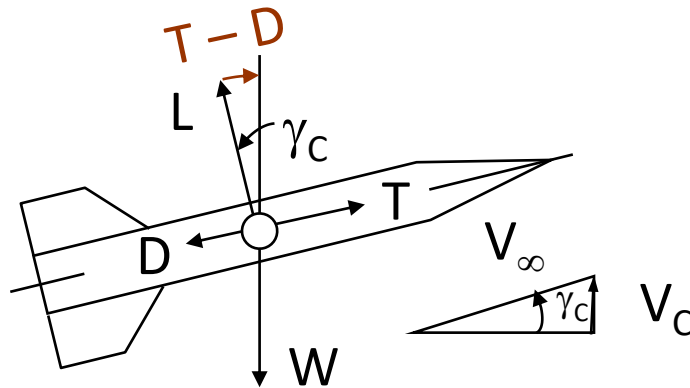


$$T = W / (L / D)$$

Note:

- Small Angle of Attack
- Equilibrium Flight
- V_C = Velocity of Climb
- V_D = Velocity of Descent
- γ_C = Flight Path Angle During Climb
- γ_D = Flight Path Angle During Descent
- V_∞ = Total Velocity
- Δh = Incremental Altitude
- R_C = Horizontal Range in Steady Climb
- R_D = Horizontal Range in Steady Dive (Glide)

Steady Climb

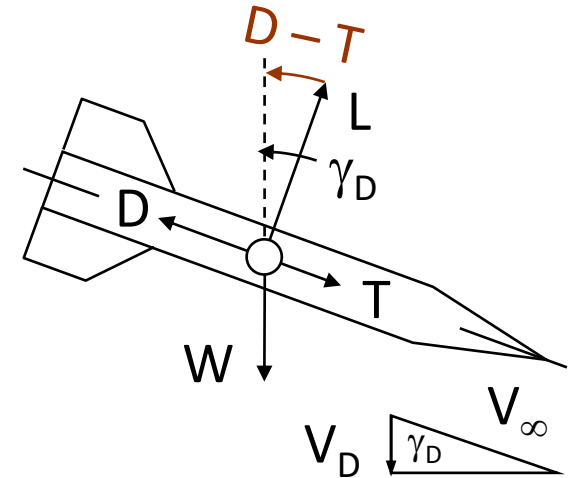


$$\sin \gamma_C = (T - D) / W = V_C / V_\infty$$

$$V_C = (T - D) V_\infty / W$$

$$R_C = \Delta h / \tan \gamma_C = \Delta h (L / D)$$

Steady Descent (Glide)



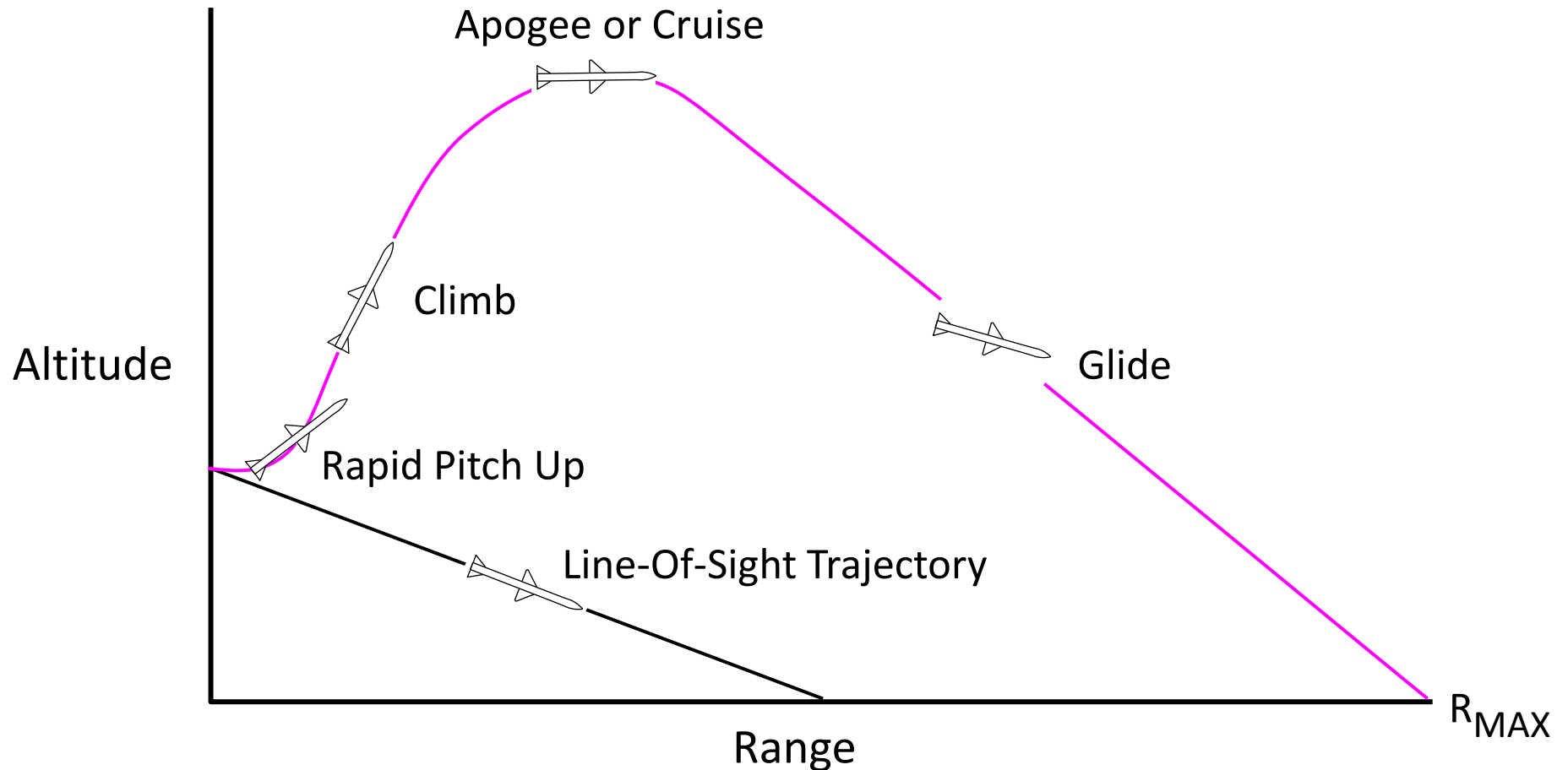
$$\sin \gamma_D = (D - T) / W = V_D / V_\infty$$

$$V_D = (D - T) V_\infty / W$$

$$R_D = \Delta h / \tan \gamma_D = \Delta h (L / D)$$

Reference: Chin, S.S., "Missile Configuration Design," McGraw Hill Book Company, New York, 1961

Flight Trajectory Shaping Provides Extended Range for High Performance Missiles



Boost-Loft-Glide Trajectory Design Guidelines for Horizontal Launch:

- High thrust-to-weight ≈ 10 for safe separation
- Rapid pitch up minimizes time / propellant to reach efficient altitude
- Climb at $\gamma \approx 45$ deg, thrust-to-weight $T / W \approx 2$, and $q \approx 700$ psf to minimize drag / propellant
- Apogee at $q \approx 700$ psf, followed by either $(L / D)_{max}$ cruise or $(L / D)_{max}$ glide