Nose Cone & Fin Optimization

Tripoli Minnesota

Gary Stroick

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Purpose

Focus is on drag optimization to maximize rocket performance!

Agenda

- Definitions
- Mission Parameters
- Nose Cone Design
- Fin Design
- Summary
- Appendices
- References & Web Sites

Definitions[1]

- Drag Coefficient
  - Parasitic Drag
    - Form/Pressure/Profile Drag
      - Dependence upon the profile of the object
      - Base Drag
        - Due to Boundary Layer separation at base of airframe/fins
    - Skin Friction (Viscous) Drag
      - Friction of the fluid against the skin of the object
    - Interference Drag
      - Incremental drag above sum of all other drag components. Created at protrusion intersections.
  - Induced (Lift-Induced) Drag
    - Due to redirection of airflow
  - Wave (Compressibility) Drag
    - Due to shockwaves when moving near or above the speed of sound (typically leading & trailing edges)
  - Rotational Drag
    - Circumferential velocity from roll will thicken boundary layer and result in increased drag

Definitions[1]

- **Wetted Area**
  - **Surface Area exposed to airflow**
- **Fineness (Aspect) Ratio**
  - **Nose Cone Length/Base Diameter**
- **Bluffness Ratio**
  - **Tip Diameter/Base Diameter**
  - **Hemispherical Blunting**
  - **Me'plat Diameter is a Flat Truncation (e.g., bullets and artillery shells)**

Definitions[1]

- **Laminar Boundary Layer**
  - Fluid streams move in parallel (negligible transfer of momentum)
- **Turbulent Boundary Layer**
  - Fluid streams transverse with velocity variations around an average value
- **Boundary Layer Separation**
  - Boundary layer separates from object's surface creating an effective profile
- **Reynolds Number**
  - Dimensionless ratio of inertial / viscous forces
  - http://www.grc.nasa.gov/WWW/BGH/reynolds.html

Definitions[1]

- Aspect Ratio (AR)
  - Fin Span / Average Fin Cord
- Effective Aspect Ratio
  - Working AR due to Airflow Effects
- Taper Ratio
  - Tip Cord / Root Cord

Definitions

- Thrust Profile
  - Thrust vs. Time Curve
- Velocity Definitions
  - Subsonic: < .8 Mach
  - Transonic: .8 to 1.2 Mach
  - Supersonic: 1.2 to 5 Mach
  - Hypersonic: > 5 Mach

Mission Parameters

- Velocity
  - Coefficient of Drag
  - Thrust Profile
  - Total Mass
- Altitude
  - Coefficient of Drag
  - Thrust Profile
  - Total and Coasting Mass
- Mass
  - Material Volume and Strength
  - Payload
- Payload
  - Available Volume
  - Stability Impacts
- Stability (CP&CG - Discussed Last Year)

Nose Cone Design

- Mission Dependent Variables
  - Payload
  - Stability (CP, CG)
- Independent Variables
  - Atmospheric Density
  - Temperature
  - Wind Conditions
  - Surface Finish
  - Angle of Attack

Nose Cone Design

- Assumptions
  - Zero Angle of Attack
  - Constant Surface Finish
  - No Roll
  - No Aerodynamic Heating Effects

Nose Cone Solutions

Best in Class

Subsonic[1]

1. Elliptical

Transonic[4]

1. LD-Haack (Von Karman)
2. $X^{1/2}$ Power Series
3. LV-Haack (< Mach 1)

Supersonic[7]

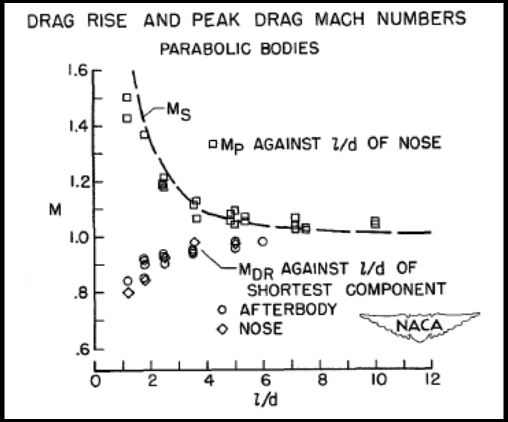
1. Eggers Minimum Drag
2. $X^{3/4}$ Power Series

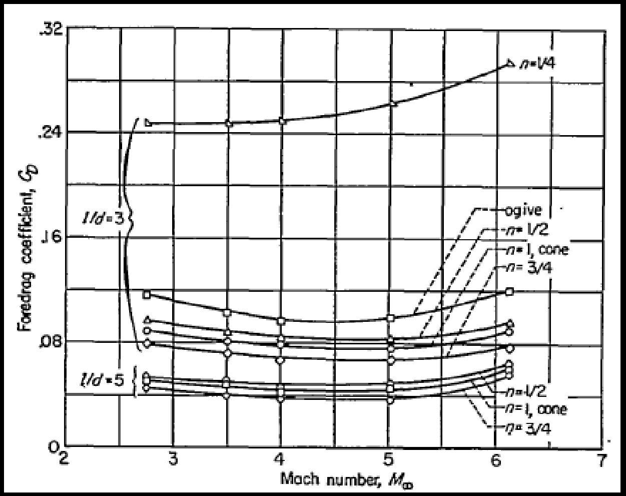
Hypersonic[8,9,10]

1. Love Minimum Drag
2. $X^{.6}$ Power Series

Fineness Ratio[6,7]

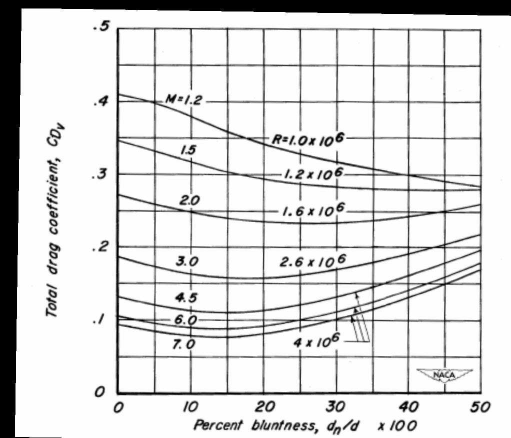
- Increasing Fineness Ratio
  - Decreases Wave Drag
  - Increases Skin Friction Drag
  - Optimum Ratio is approximately 5

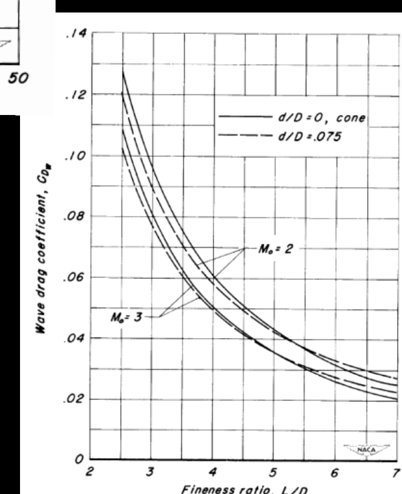




Bluntness Ratio[2,3,5]

- **Optimal ratio is .15**
  - **Provided length remains constant**
- **Applicability dependent upon fineness ratio and velocity**
  - **Fineness ratio ≤ 5**
  - **Below Hypersonic**

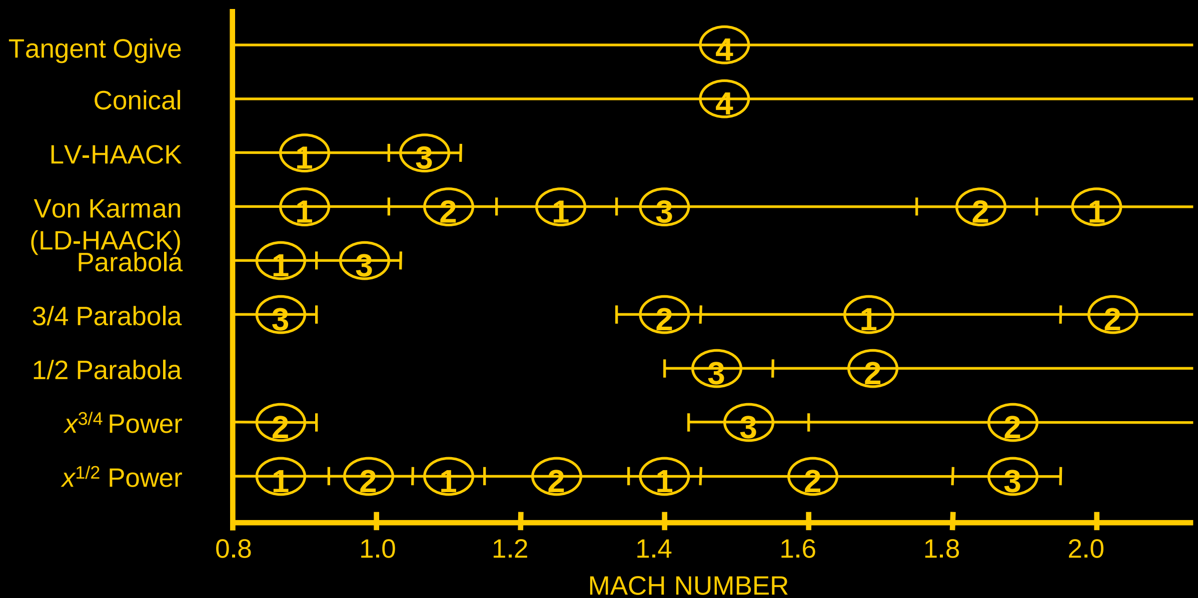


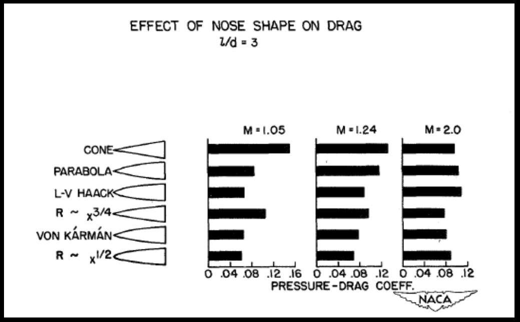


Coefficient of Drag (C_D) Subsonic[1]

- Primarily Skin Friction Drag
- Minimal Pressure Drag
- No Wave Drag
- No Interference Drag
- No Induced Drag
- Elliptical
  - Fineness Ratio of 2

Coefficient of Drag (C_D) Transonic[4]



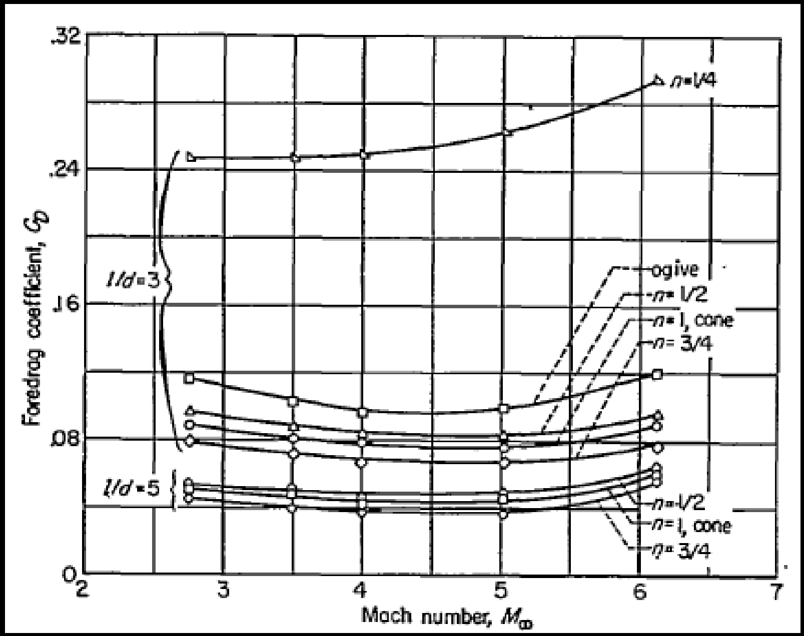


Comparison of drag characteristics of various nose shapes in the transonic-to-low Mach regions. Rankings are: superior (1), good (2), fair (3), inferior (4).

- **Wave Drag Increases Substantially**
- **Pressure Drag becomes Significant**
- **Fineness Ratio of 5 is Critical**

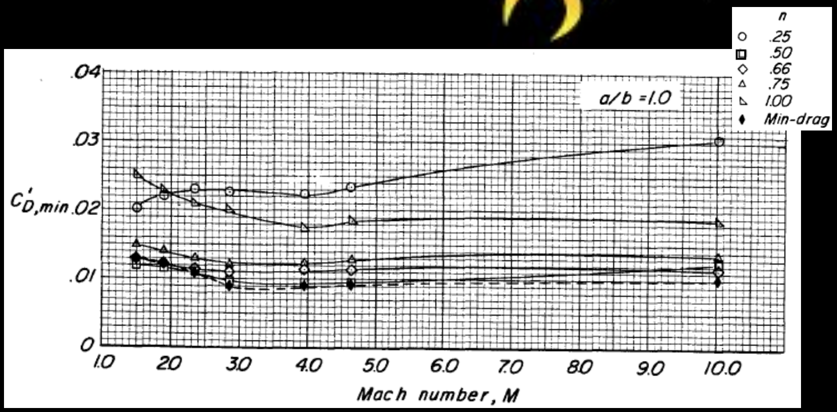
Coefficient of Drag (C_D) Supersonic[7]

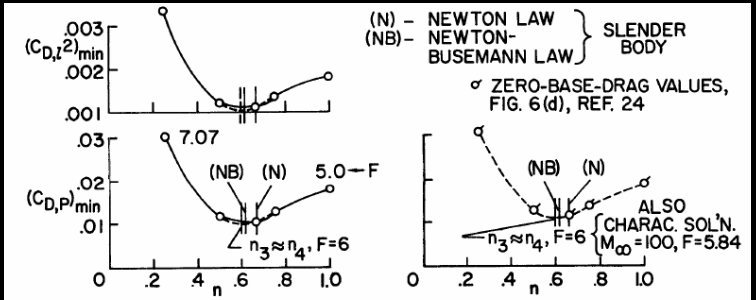
- **Pressure Drag Decreases**
- **Wave Drag Decreases**
- **Fineness Ratio of 5 is Critical**



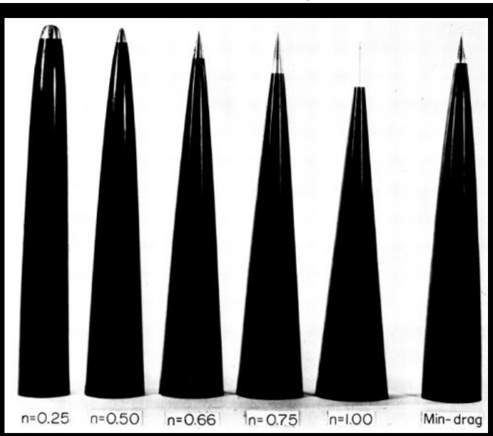
Coefficient of Drag (C_D) Hypersonic[8,9,10]

- $X^{.6}$ Power Series
  - Fineness Ratio of 5 or 6
- Varies with Fineness Ratio
- No Blunting





(a) $M_\infty = 10.03;\ \gamma = 7/5.$



Fin Design

- Mission Dependence
  - Stability (CP, CG, Roll, ...)
- Independent Variables
  - Atmospheric Density
  - Temperature
  - Wind Conditions
  - Surface Finish (Assumed Constant)
  - Angle of Attack (Assumed Zero)

Fin Optimization

- Minimize Drag
- Maintain Structural Integrity
  - Minimize Divergence
  - Minimize Bending-Torsion Flutter
  - Minimize Mass
- Maximize Fin Joint Strength
- Maintain Passive Stability

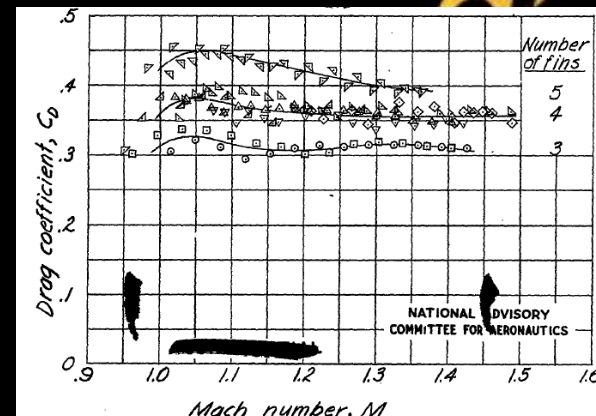
Fin Drag Optimization

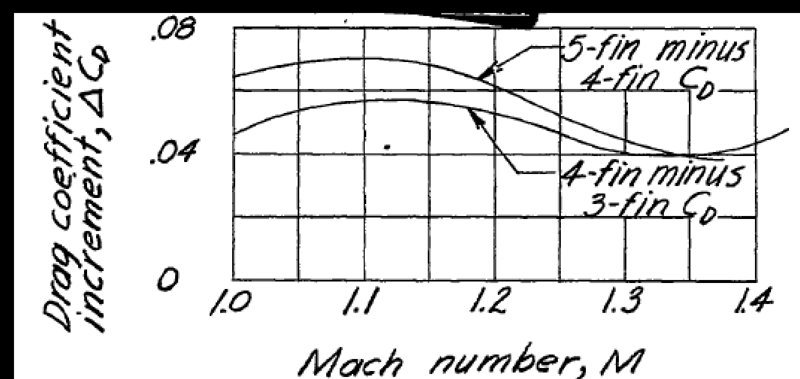
- No General Solution Unearthed
  - Computational Models Exist at Subsonic, Transonic, and Supersonic Speeds
- Solution Factors
  - Velocity
  - Density
  - Lift Requirements (Corrective Moment) at Angles of Attack
  - …
- Structural Strength

Fin Count[11]

- **Fin Count > 3**
  - **Skin Friction Drag Increases**
  - **Interference Drag Increases up to Mach 1.35**

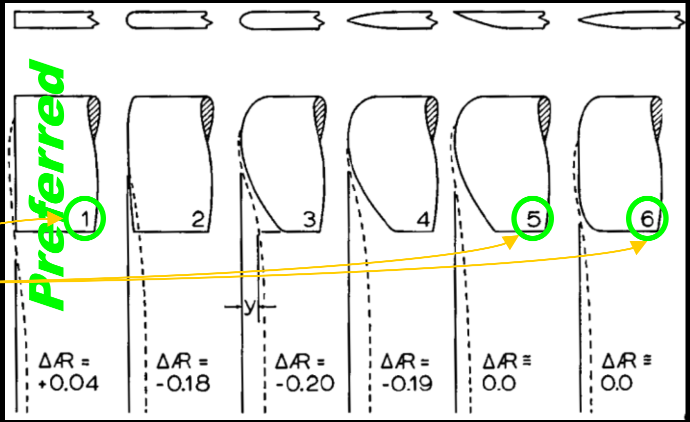
Fin Count → 3 but not always …





Fin Tip Vortices[1]

Desired

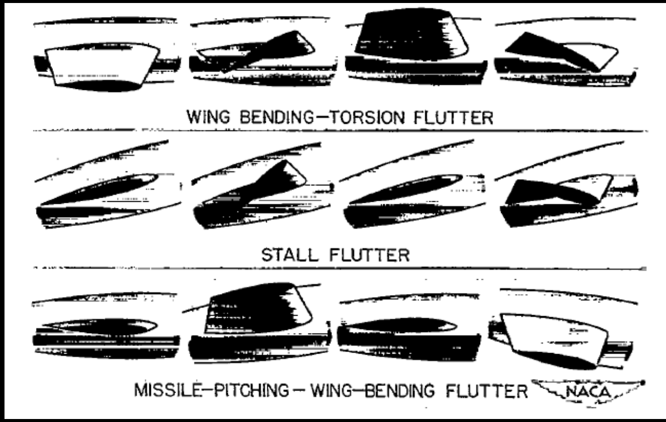


- **Vortices alter Fin Effective Aspect Ratio**
- **Positive or Neutral Ratio Desired**
  - **Lower Angles of Attack for Given Lift (Increases Corrective and Damping Moments)**
  - **Lower Induced Drag for Given Lift**
- **Desire Zero or Positive Effective Aspect Ratio**
- **Ease of Manufacture**
  - **Implies Fins with a Tip Cord > 0**
  - **Square Edge Tips**

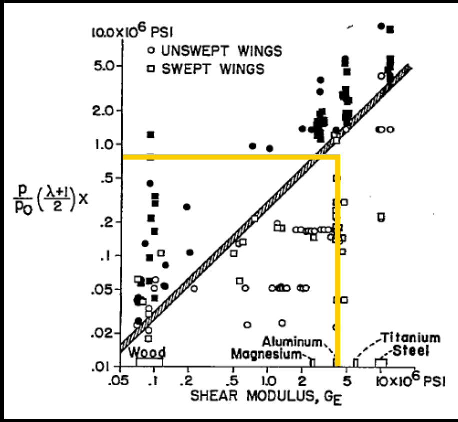
Fin Flutter[20]

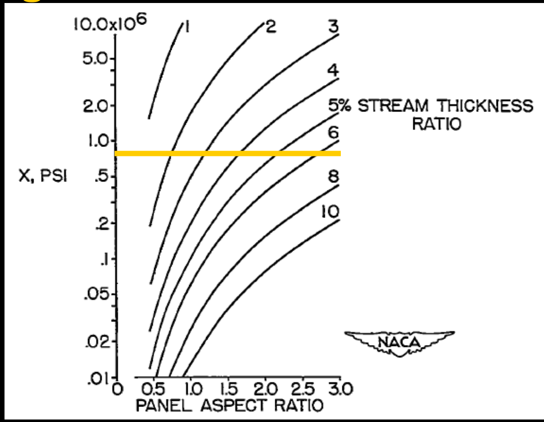
- **NASA Safety Factors**
  - **15% between vehicle & flutter velocity**
  - **32% between vehicle and flutter dynamic pressure**

Fin Flutter[16]



- Stall Flutter not applicable
- Choose Shear Modulus for Material
- Apply Contingency when selecting Flutter criterion
- Criterion then used with Aspect Ratio to find Thickness Ratio
- Multiple Thickness Ratio & Cord to get Thickness

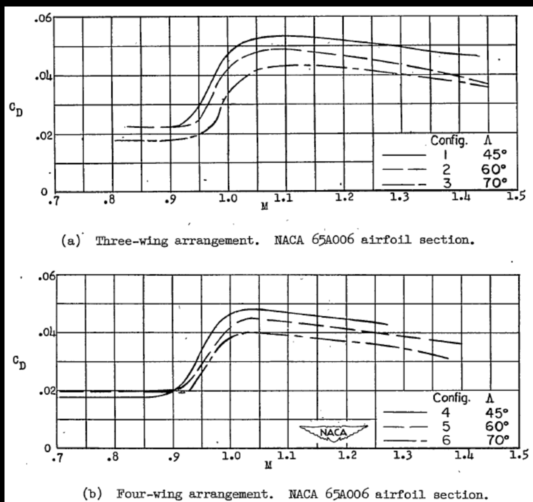


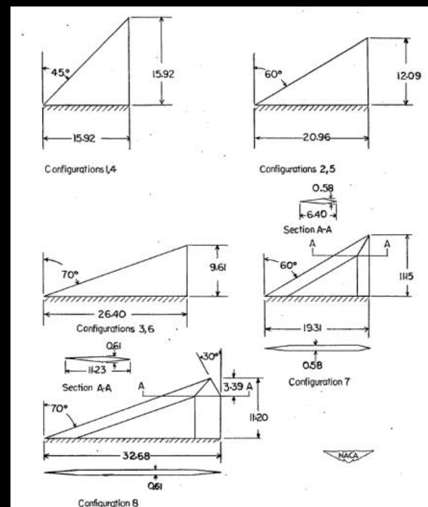


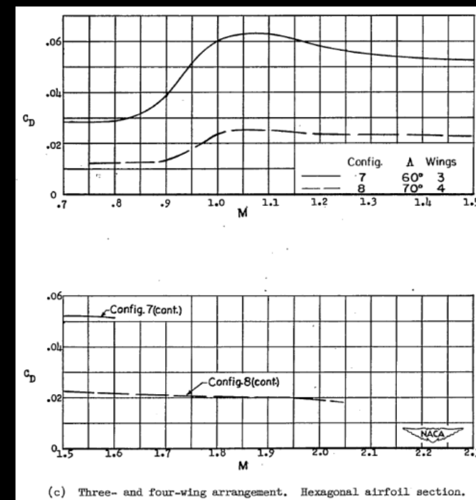
Fin Joint Drag[1,12]

- **Interference Drag**
  - Minimized when fillet radius is between 4% and 8% of fin root cord
  - 10” Root Cord → $^{1}/_{2}$” Radius
  - Consider Structural Strength
- **Wing (Leading Edge) Fillets Increase Drag in the Transonic Region**

Sweep Angle[13]

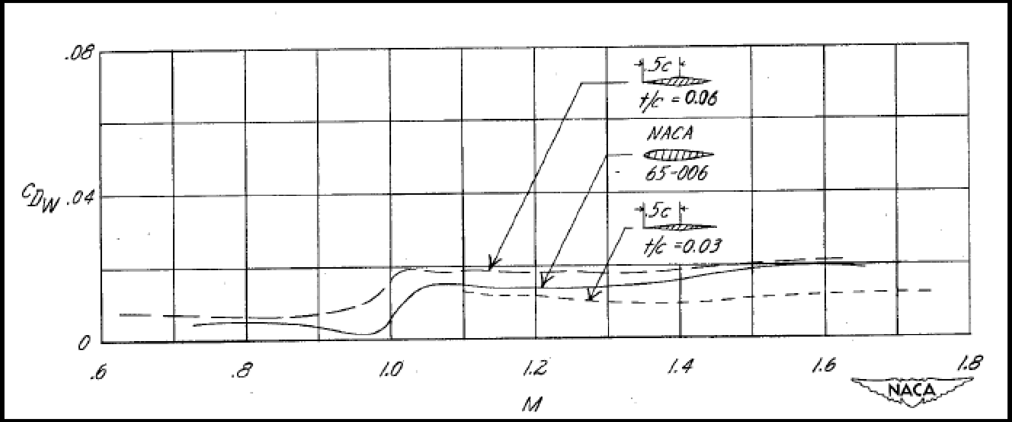






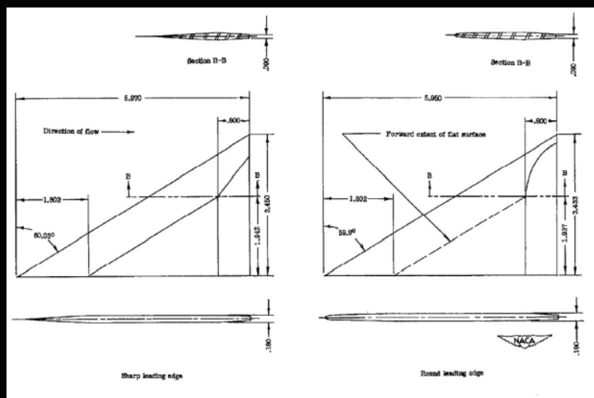
- **70° Sweep Angle Superior to Smaller Angles in Sub, Trans, & Supersonic Ranges**
  - **4 Fin Configuration Exception in Subsonic Region**

Fin Thickness[15,17,18]

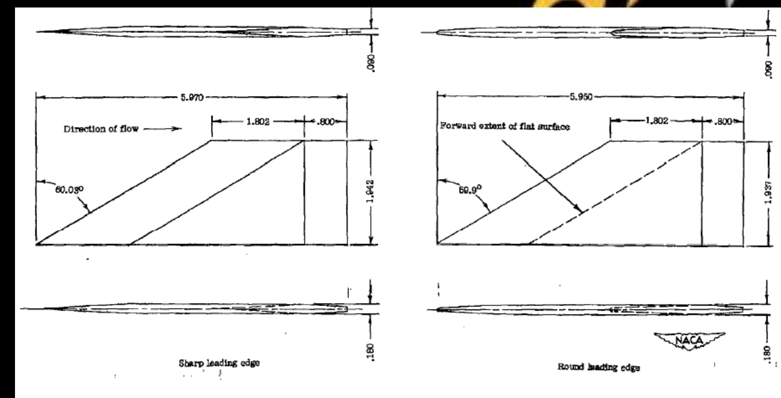


- **Thinner Symmetrical Fins Result in Lower C_D in Sub, Trans, and Supersonic Regions**

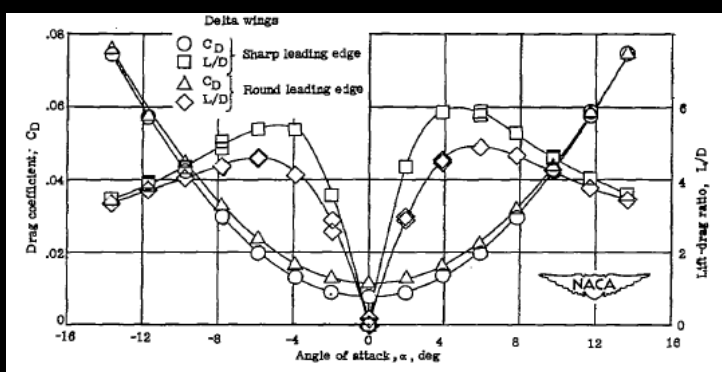
Leading Edge[14]



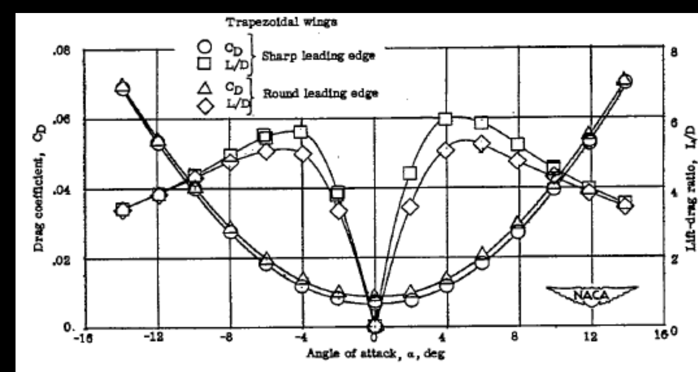
(a) Delta wings.



(b) Trapezoidal wings.

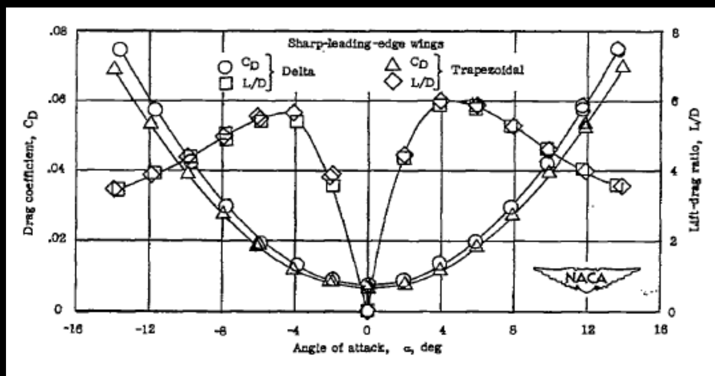


(b) Drag coefficients and lift-drag ratios.

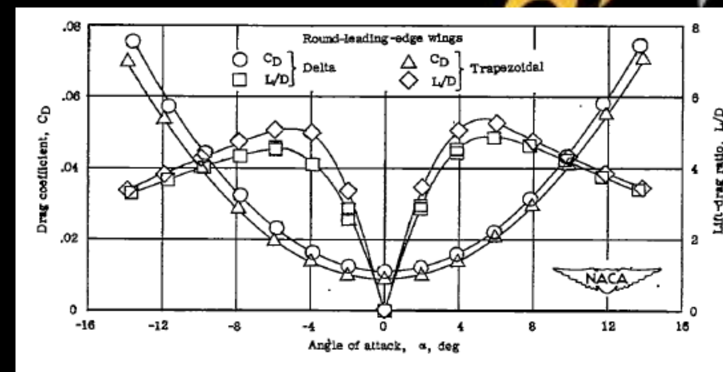


(b) Drag coefficients and lift-drag ratios.

Leading Edge[14]



(b) Drag coefficients and lift-drag ratios.



(b) Drag coefficients and lift-drag ratios.

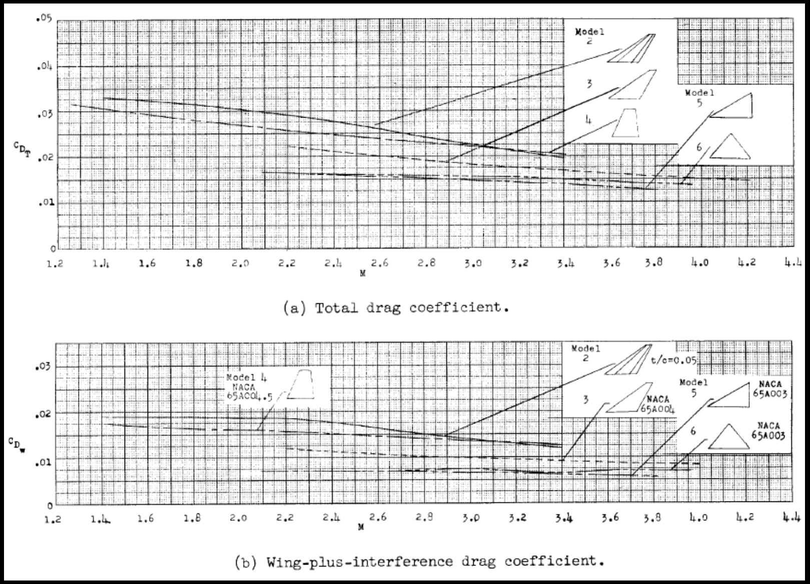
- **At Mach 4**
  - **Sharp Leading Edge has Lower C_D at all Angles of Attack**
  - **Trapezoidal (Clipped Delta) has Lower C_D than Delta**

Trailing Edge[21]

- Trailing-edge Thickness up to 0.7% Root Cord Reduces Transonic Drag
  - Does not Impact Subsonic Drag
- Trailing Edge Thickness > 0.7% Results in Increased Drag
- Varies with Airfoil Thickness and Optimum is < 0.7%
  - 10” Root Cord → $^{1}/_{16}$” Thick Trailing Edge

Fin Cross Section[13,19]

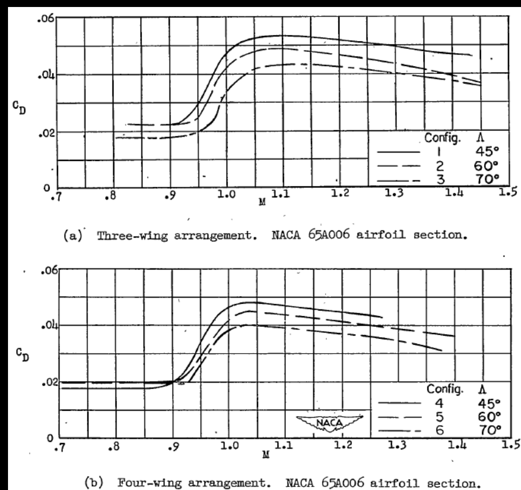
- **Sub, Trans, and Supersonic**
  - **Hexagonal Lower C_D than Double Wedge**
- **Supersonic**
  - **C_D NACA 65A003 < 65A004 < Hexagonal**



Shape[14,19]

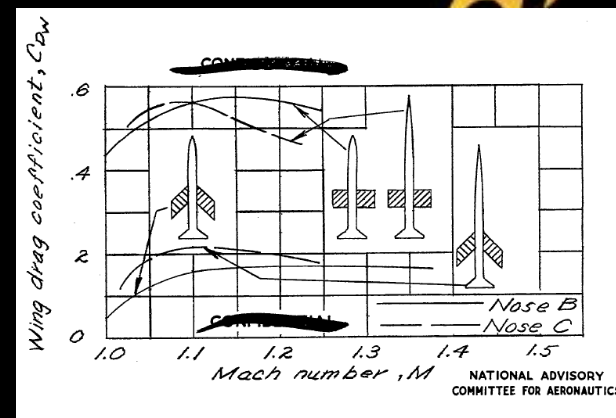
- **Supersonic Data**
  - **Trapezoidal (Clipped Delta) Lower C_D than Delta**
  - **Delta and Diamond have Similar C_D**

Multi-Disciplinary Design Optimization (MDO)[x]



(a) Three-wing arrangement. NACA 65A006 airfoil section.

(b) Four-wing arrangement. NACA 65A006 airfoil section.



- **Optimizing Individual Components may not Result in an Optimum Design**
  - **Increasing Fin count from 3 to 4**
  - **Improving Nose Cone Fineness Ratio (3.5 vs. 7) may Result in Increased Fin Drag at Some Velocities**

Summary

- **Optimal Nose Cones**
  - **Subsonic – Elliptical**
  - **Transonic – Von Karman (Blunted 15% of Base Diameter)**
  - **Supersonic - $X^{3/4}$ Power Series**
  - **Hypersonic – $X^{.6}$ Power Series**
  - **Fineness Ratio of 5**
- **Fin Optimization**
  - **Fin Count of 3**
  - **Fin Joints 4% to 8% of Root Cord**
  - **Thickness < 10% of Root Cord often between 3% & 6%**
  - **Trailing Edge Flat but < 0.7% of Root Cord in Thickness**
  - **Leading Edge may be Sharp**
  - **Sweep Angle between 45° and 70°**
  - **Flat Fin Tips**
  - **Hexagonal Cross Section**
  - **Clipped Delta Shape**

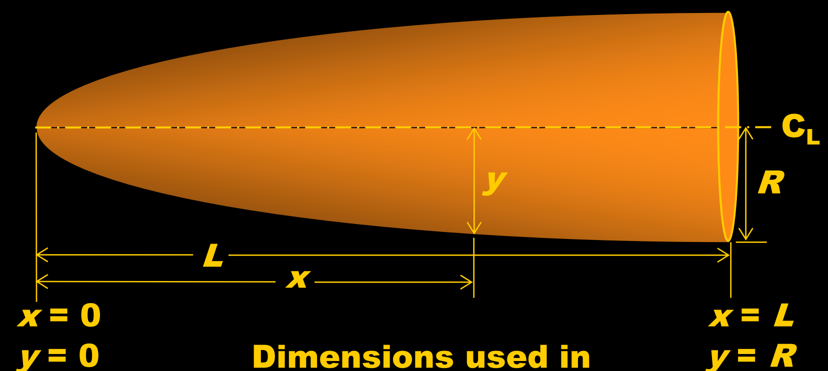
Appendices

Nose Cones

Nose Cone Geometries

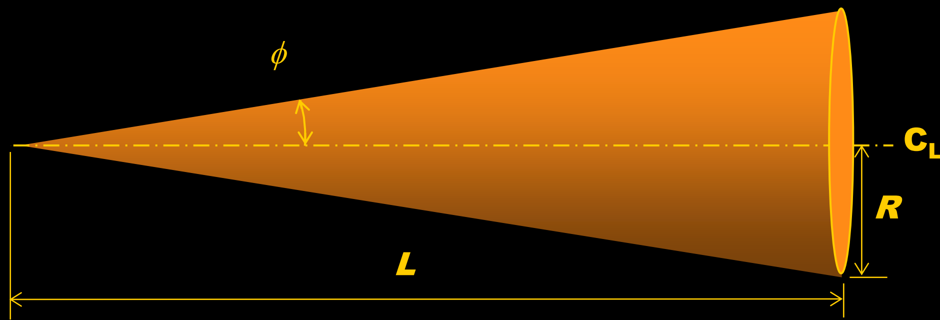
- Conical
- Elliptical
- Ogive (Tangent)
- Parabolic
- Power Series
- Sears-Haack (Von Karman)

Nose Cone Parameters



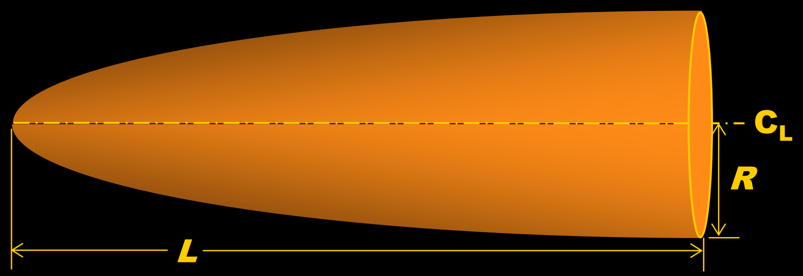
- ***L*** **is the overall length of the nosecone**
- ***R*** **is the radius of the base of the nosecone**
- ***y*** **is the radius at any point *x*, as *x* varies from 0 at the tip of the nosecone to *L***
- **The full body of revolution of the nosecone is formed by rotating the profile around the centerline (C_L)**

Conical Nose Cones



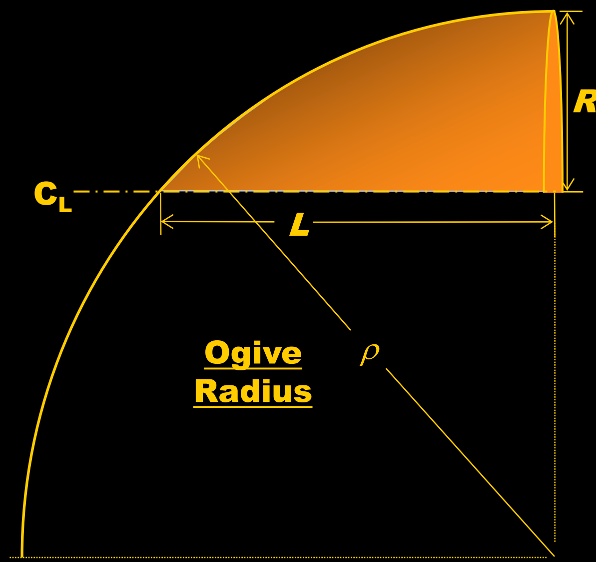
- The sides of a cone are straight lines, so the diameter equation is simply, $y = {}^{Rx}/_{L}$
- Cones are sometimes defined by their 'half angle', $\phi = \tan^{-1}({}^{R}/_{L})$ and $y = x \tan \phi$
- $C_p = {}^{L}/_{3}$
- $V = \pi R^2 L/3$
- $S = \pi R(R^2 + L^2)^{.5}$

Elliptical Nose Cones



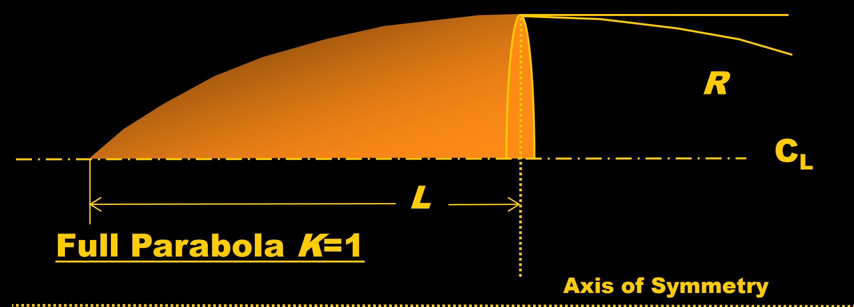
- The profile of this shape is one-half of an ellipse, with the major axis being the centerline and the minor axis being the base of the nosecone
- This shape is advantageous for subsonic flight due to its blunt nose and tangent base
- It is defined by: $y = R(1 - {}^{x^2}/_{L^2})^{½}$
- $C_p = {}^{3L}/_{2}$
- $V = 2\pi R^2 L/3$
- $S = \pi L^2 + [\pi R^2/\sigma[\ln\{(1+\sigma)/(1-\sigma)\}]]/2$ where $\sigma = (L^2 + R^2)/L$

Tangent Ogive Nose Cones



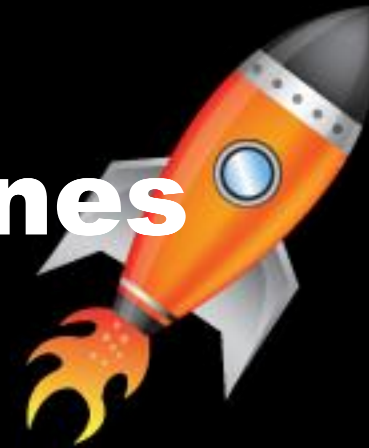
- **This shape is formed by a circle segment where the base is on the circle radius and the airframe is tangent to the curve of the nosecone at its base**
- **The radius of the circle that forms the ogive is: $\rho = (R^2 + L^2)/2R$**
- **The radius *y* at any point *x*, as *x* varies from 0 to *L* is: $y = (\rho^2-(x-L)^2)^{1/2}+R-\rho$ where $L \leq \rho$**
- **$C_p=V/\pi R^2$**
- **$V=\pi[L\sigma^2 - L^3/\sigma - (\sigma^3 - R\sigma^2)\sin^{-1}(L/\sigma)]$ where $\sigma=(R^2 + L^2)/2R$**
- **S=?**

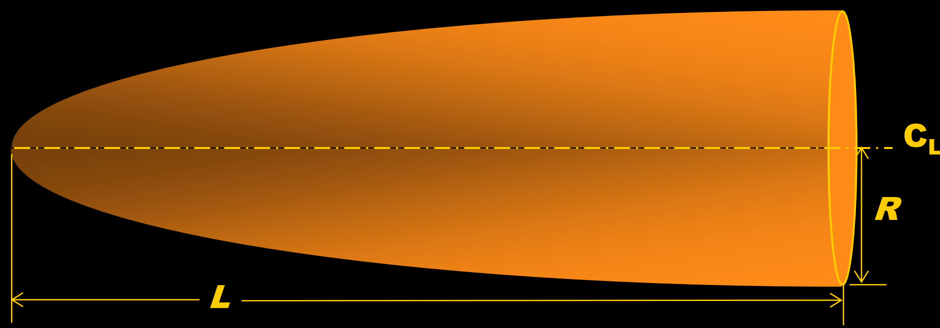
Parabolic Nose Cones



- The Parabolic Series nose shape is generated by rotating a segment of a parabola around a line parallel to its axis of symmetry.
- $y=R\{(2[{}^{x}/_{L}]-K[{}^{x}/_{L}]^2)/(2-K)\}$ for $0 \le K \le 1$
  - $K = 0$ for a CONE
  - $K = .5$ for a 1/2 PARABOLA
  - $K = .75$ for a 3/4 PARABOLA
  - $K = 1$ for a PARABOLA (base tangent to airframe)
- $C_p = {}^{L}/_{2}$
- $V = \pi R^2 L/2$
- $S = R^2/4L$

Power Series Nose Cones

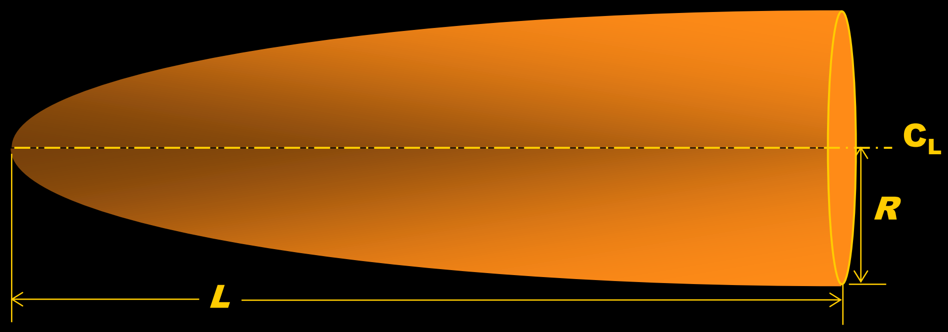




Power Series

- **The Power Series shape is characterized by its (usually) blunt tip, and by the fact that its base is not tangent to the body tube.**
- **The Power series nose shape is generated by rotating a parabola about its major axis. The base of the nosecone is parallel to the latus rectum of the parabola, and the factor *n* controls the 'bluntness' of the shape. As *n* decreases towards zero, the Power Series nose shape becomes increasingly blunt; at values of *n* above about .7, the tip becomes sharp.**
- $y=R(^{x}/_{L})^{n}$ **for** $0 \le n \le 1$
  - ***n* = 1** **for a CONE**
  - ***n* = .75** **for a ¾ POWER**
  - ***n* = .5** **for a ½ POWER (PARABOLA)**
  - ***n* = 0** **for a CYLINDER**
- C_p**=?**
- **V=?**
- **S=?**

Sears-Haack Nose Cones



Sears-Haack

- Not constructed from geometric figures
- Mathematically derived for drag minimization
- Not tangent to body at base
- Rounded not sharp nose tips
- $y = R\{\theta-[\sin(2\theta)/2]+C\sin^3(\theta)\}^{1/2}/(\pi)^{1/2}$ where $0 \leq C$ and $\theta = \cos^{-1}(1-2x/L)$
  - C = 0 minimum drag for given Length and Volume (LV)
  - C = 1/3 minimum drag for given Length and Diameter (LD - Von Karman)
- $C_p={}^{L}/_{2}$ Von Karman; $C_p= .437L$ LV-Haack
- V=?
- S=?

Nose Cone References

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