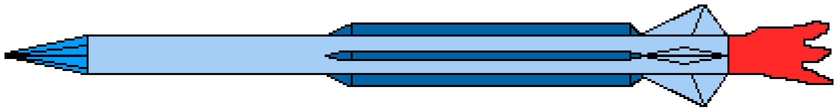
Maximizing Missile Flight Performance



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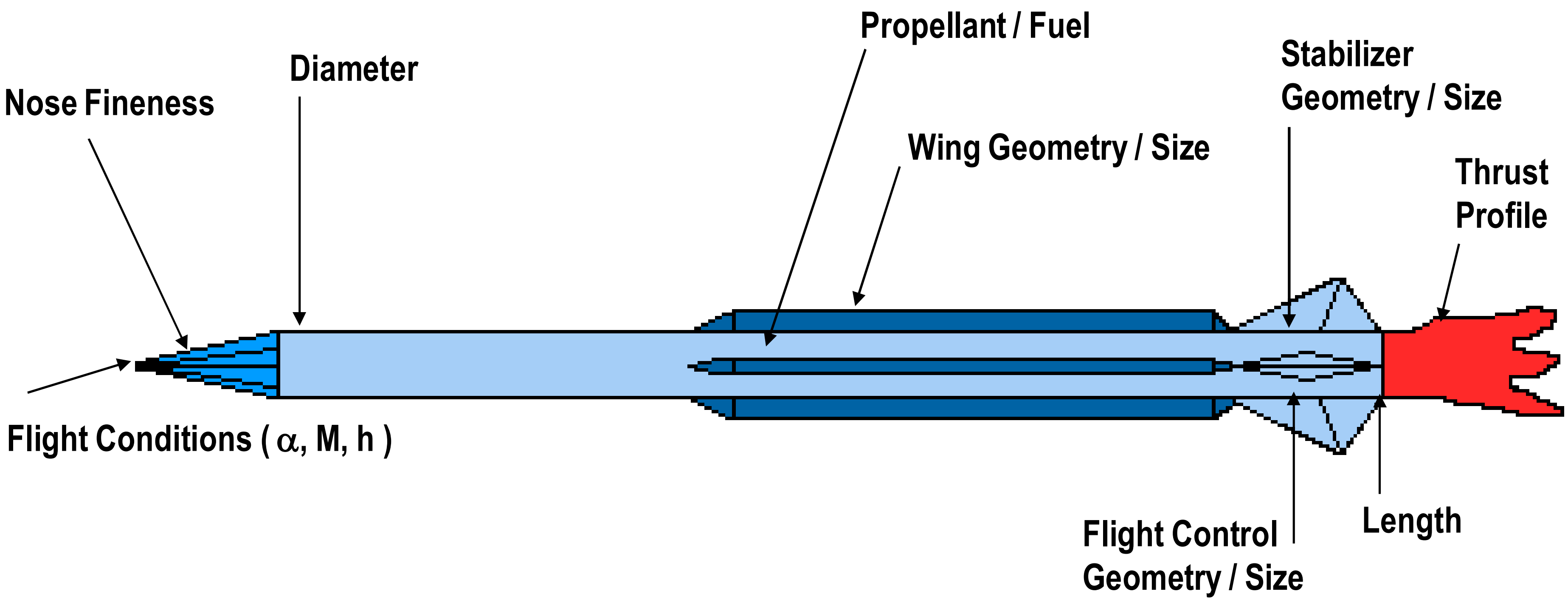
Outline

- Parameters and Technologies That Drive Missile Flight Performance
- Missile Flight Performance Prediction
- Examples of Maximizing Missile Flight Performance (Workshop)
- Summary

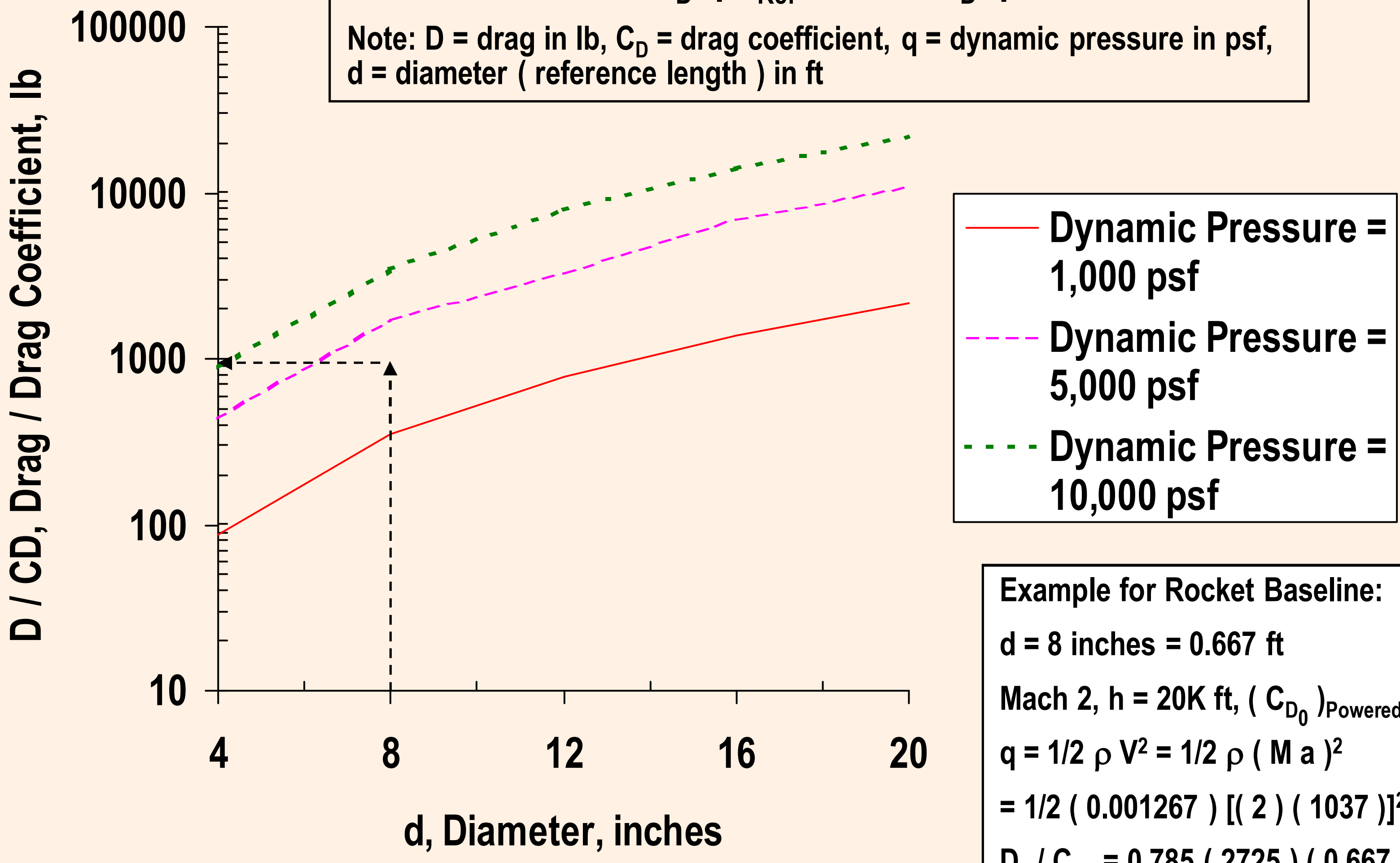
Parameters That Drive Missile Flight Performance

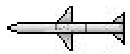


Small Diameter Missiles Have Low Drag

$$D = C_D\, q\, S_{Ref} = 0.785\, C_D\, q\, d^2$$

Note: D = drag in lb, C_D = drag coefficient, q = dynamic pressure in psf, d = diameter (reference length) in ft



Example for Rocket Baseline: 

d = 8 inches = 0.667 ft

Mach 2, h = 20K ft, $(C_{D_0})_{Powered} = 0.95$

$q = 1/2\, \rho\, V^2 = 1/2\, \rho\, (M\, a)^2$

$= 1/2 (0.001267) [(2) (1037)]^2 = 2{,}725$ psf

$D_0 / C_{D_0} = 0.785 (2725) (0.667)^2 = 952$

$D_0 = 0.95 (952) = 900$ lb

Supersonic Drag Is Driven by Nose Fineness While Subsonic Drag is Driven by Skin Friction

$(C_{D_0})_{Body,\,Wave} = (1.59 + 1.83 / M^2) \{ \tan^{-1} [0.5 / (l_N / d)] \}^{1.69}$, for $M > 1$. Based on Bonney reference, $\tan^{-1}$ in rad.

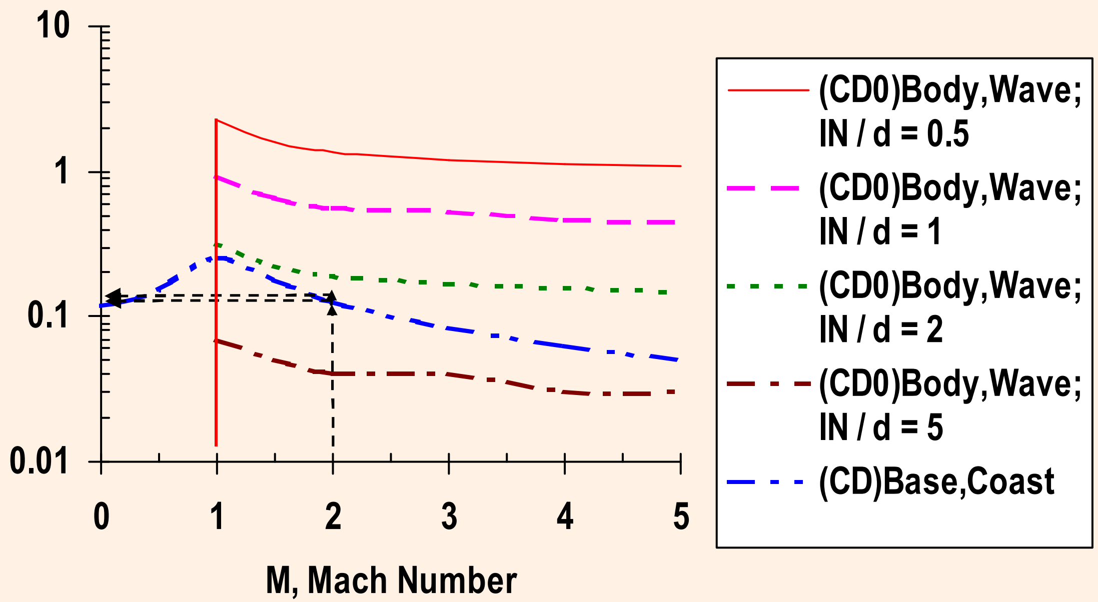
$(C_{D_0})_{Base,Coast} = 0.25 / M$, if $M > 1$ and $(C_{D_0})_{Base,Coast} = (0.12 + 0.13 M^2)$, if $M < 1$

$(C_{D_0})_{Base,Powered} = (1 – A_e / S_{Ref}) (0.25 / M)$, if $M > 1$ and $(C_{D_0})_{Base,Powered} = (1 – A_e / S_{Ref}) (0.12 + 0.13 M^2)$, if $M < 1$

$(C_{D_0})_{Body,Friction} = 0.053 (l / d) [M / (q\, l)]^{0.2}$. Based on Jerger reference, turbulent boundary layer, q in psf, l in ft.

$(C_{D_0})_{Body} = (C_{D_0})_{Body,\,Wave} + (C_{D_0})_{Base} + (C_{D_0})_{Body,Friction}$

Note: $(C_{D_0})_{Body,Wave}$ = body zero-lift wave drag coefficient, $(C_{D_0})_{Base}$ = body base drag coefficient, $(C_{D_0})_{Body,\,Friction}$ = body skin friction drag coefficient, $(C_{D_0})_{Body}$ = body zero-lift drag coefficient, l_N = nose length, d = missile diameter, l = missile body length, A_e = nozzle exit area, S_{Ref} = reference area, q = dynamic pressure, $\tan^{-1} [0.5 / (l_N / d)]$ in rad



Example for Rocket Baseline:

$(C_{D_0})_{Body,\,Wave}$ $(C_{D_0})_{Body,\,Friction}$ $(C_D)_{Base}$

$l_N / d = 2.4$, $A_e = 11.22\ in^2$, $S_{Ref} = 50.26\ in^2$, M = 2, h = 20K ft, q = 2725 psf, l / d = 18, l = 12 ft

$(C_{D_0})_{Body,\,Wave} = 0.14$

$(C_D)_{Base\ Coast} = 0.25 / 2 = 0.13$

$(C_D)_{Base\ Powered} = (1 - 0.223) (0.25 / 2) = 0.10$

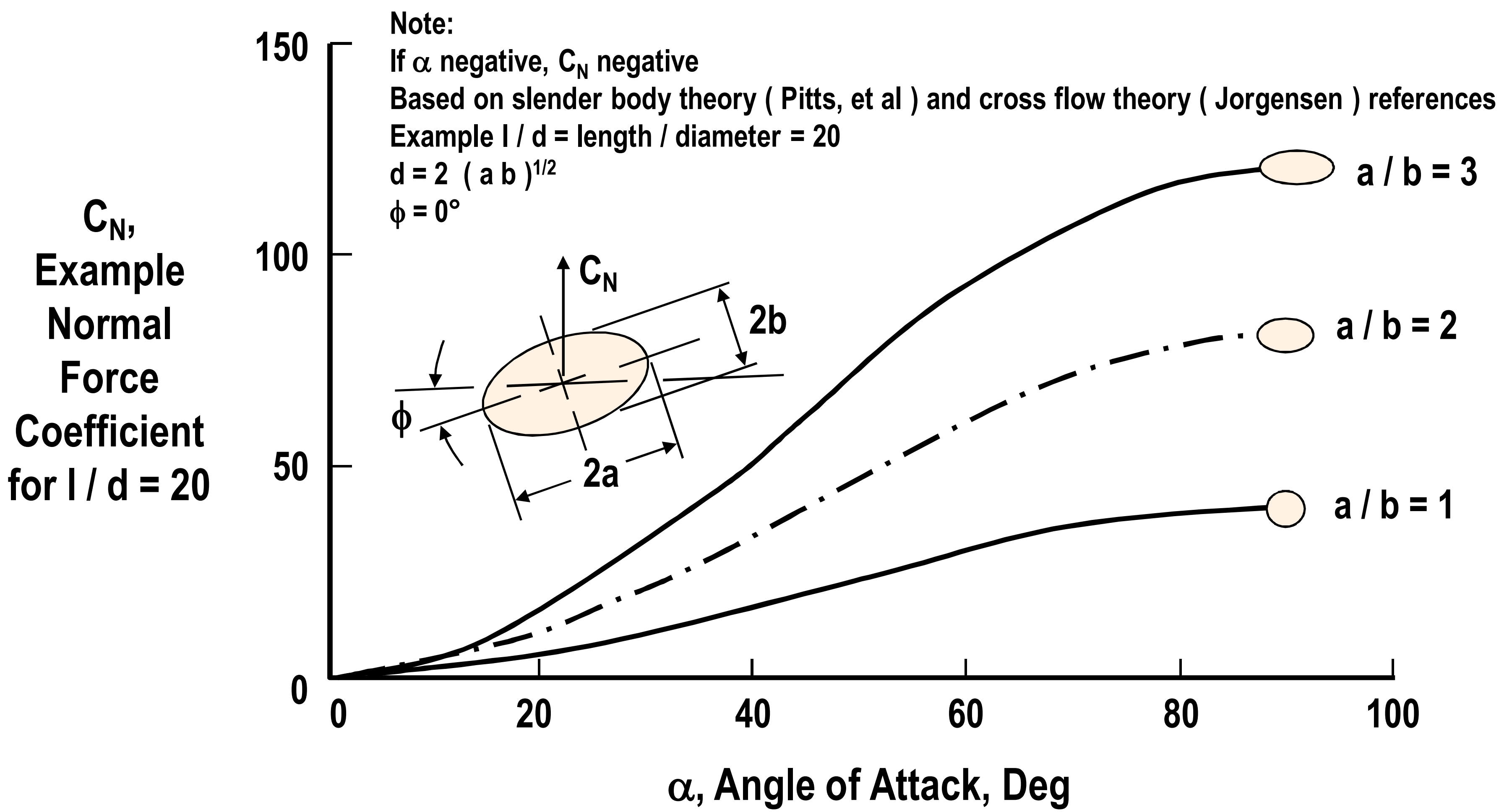
$(C_{D_0})_{Body,\,Friction} = 0.053 (18) \{ (2) / [(2725) (12)]\}^{0.2} = 0.14$

$(C_{D_0})_{Body,\,Coast} = 0.14 + 0.13 + 0.14 = 0.41$

$(C_{D_0})_{Body,\,Powered} = 0.14 + 0.10 + 0.14 = 0.38$

Lifting Body Has Higher Normal Force

$$\left| C_N \right| = \left[\left| (a/b)\cos\phi + (b/a)\sin\phi \right| \right] \left[\left| \sin(2\alpha)\cos(\alpha/2) \right| + 2\,(l/d)\sin^2\alpha \right]$$

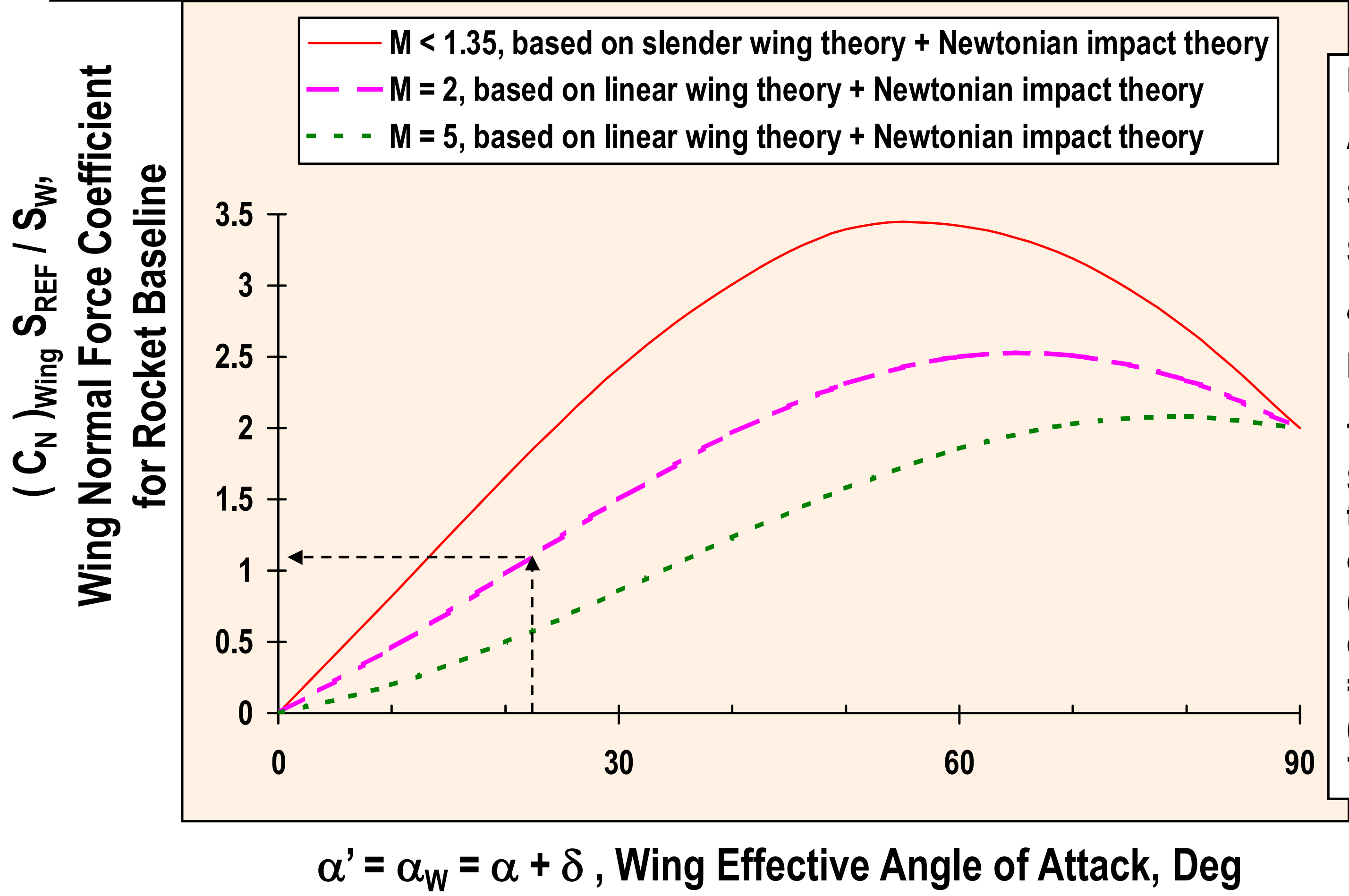


Large Surface Area Increases Normal Force and Maneuverability

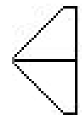
$$\left| (C_N)_{Wing} \right| = \left[4 \left| \sin\alpha' \cos\alpha' \right| / (M^2 - 1)^{1/2} + 2 \sin^2\alpha' \right] (S_W / S_{Ref}), \text{ if } M > \{ 1 + [8 / (\pi A)]^2 \}^{1/2}$$

$$\left| (C_N)_{Wing} \right| = \left[(\pi A / 2) \left| \sin\alpha' \cos\alpha' \right| + 2 \sin^2\alpha' \right] (S_W / S_{Ref}), \text{ if } M < \{ 1 + [8 / (\pi A)]^2 \}^{1/2}$$

Note: Linear wing theory applicable if $M > \{ 1 + [8 / (\pi A)]^2 \}^{1/2}$, slender wing theory applicable if $M < \{ 1 + [8 / (\pi A)]^2 \}^{1/2}$,
A = Aspect Ratio, S_W = Wing Planform Area, S_{Ref} = Reference Area



Example for Rocket Baseline



$A_W = 2.82$

$S_W = 2.55\ ft^2$

$S_{Ref} = 0.349\ ft^2$

$\delta = 13$ deg, $\alpha = 9$ deg

$M = 2$

$\{ 1 + [8 / (\pi A)]^2 \}^{1/2} = 1.35$

Since $M > 1.35$, use linear wing theory + Newtonian theory

$\alpha' = \alpha_W = \alpha + \delta = 22°$

$(C_N)_{Wing} S_{Ref} / S_W = [4 \sin 22° \cos 22° / (2^2 - 1)^{1/2} + 2 \sin^2 22°] = 1.083$

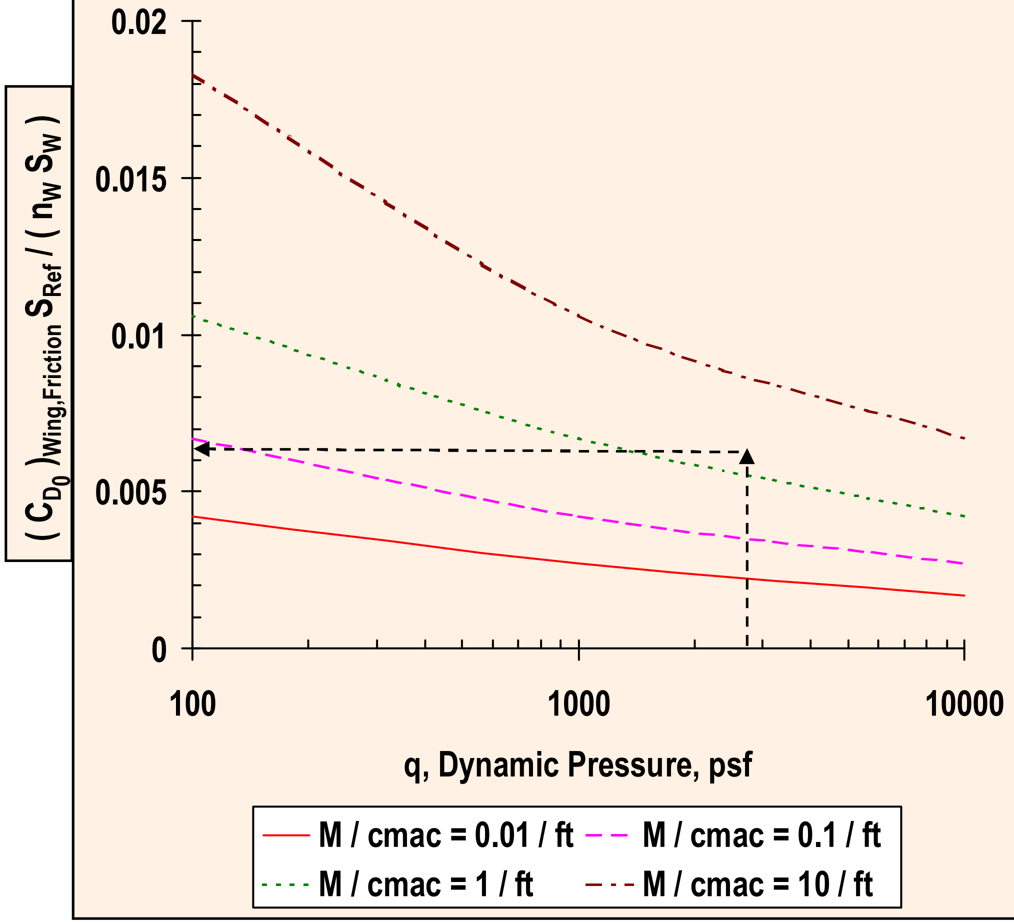
$(C_N)_{Wing} = 1.08 (2.55) / 0.349 = 7.91$

Wing Skin Friction Drag Is Larger Than Shock Wave Drag for a Thin Wing

$(C_{D_0})_{Wing,Friction} = n_W \{ 0.0133 [M / (q\, c_{mac})]^{0.2} \} (2 S_W / S_{Ref})$, based on Jerger, turbulent, q in psf, c_{mac} in ft

$(C_{D_0})_{Wing,Wave} = n_W [2 / (\gamma M_{\Lambda_{LE}}^2)]\{\{[(\gamma + 1) M_{\Lambda_{LE}}^2] / 2 \}^{\gamma / (\gamma - 1)} \{(\gamma + 1) / [2 \gamma M_{\Lambda_{LE}}^2 - (\gamma - 1)]\}^{1 / (\gamma - 1)} - 1 \} \sin^2 \delta_{LE} \cos \Lambda_{LE}\ t_{mac}\ b / S_{Ref}$, based on Newtonian impact theory

$(C_{D_0})_{Wing} = (C_{D_0})_{Wing,Wave} + (C_{D_0})_{Wing,Friction}$



- n_W = number of wings (cruciform = 2)
- q = dynamic pressure in psf
- c_{mac} = length of mean aero chord in ft
- γ = Specific heat ratio = 1.4
- $M_{\Lambda_{LE}} = M \cos \Lambda_{LE}$ = Mach number ⊥ leading edge
- δ_{LE} = leading edge section total angle
- Λ_{LE} = leading edge sweep angle
- t_{mac} = max thickness of mac
- b = span

Example for Rocket Baseline Wing:

$n_W = 2$, h = 20K ft (q = 2,725 psf), c_{mac} = 1.108 ft, S_{Ref} = 50.26 in^2, S_W = 367 in^2, δ_{LE} = 10.01 deg, Λ_{LE} = 45 deg, t_{mac} = 0.585 in, b = 32.2 in, M = 2 ($M_{\Lambda_{LE}}$ = 1.41)

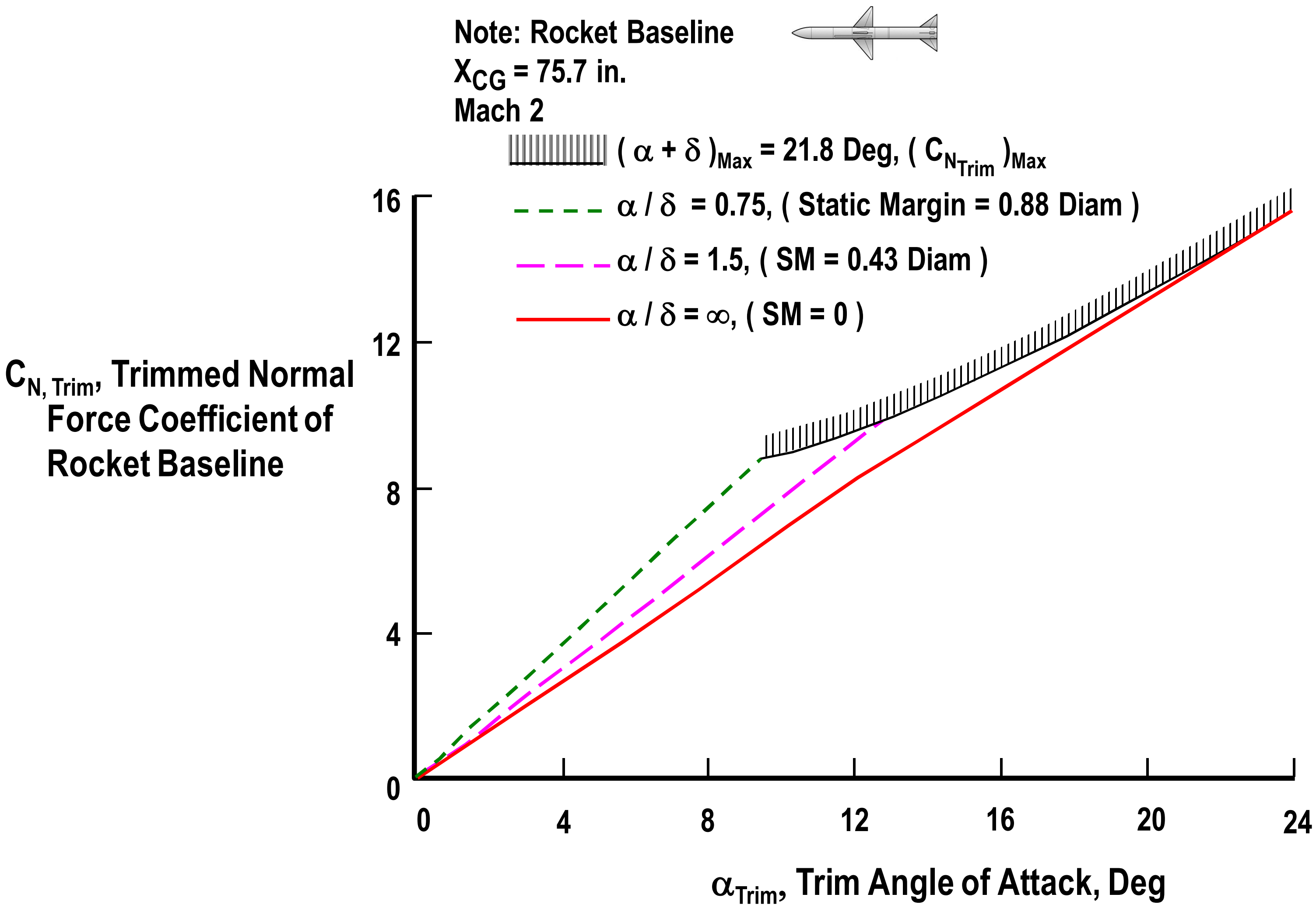
$(C_{D_0})_{Wing,Friction} S_{Ref} / [n_W S_W] = 2 \{(0.0133) \{ 2 / [(2725) (1.108)]\}^{0.2} \} = 0.00615$

$(C_{D_0})_{Wing,Friction} = 0.00615 (2) (367) / 50.26 = 0.090$

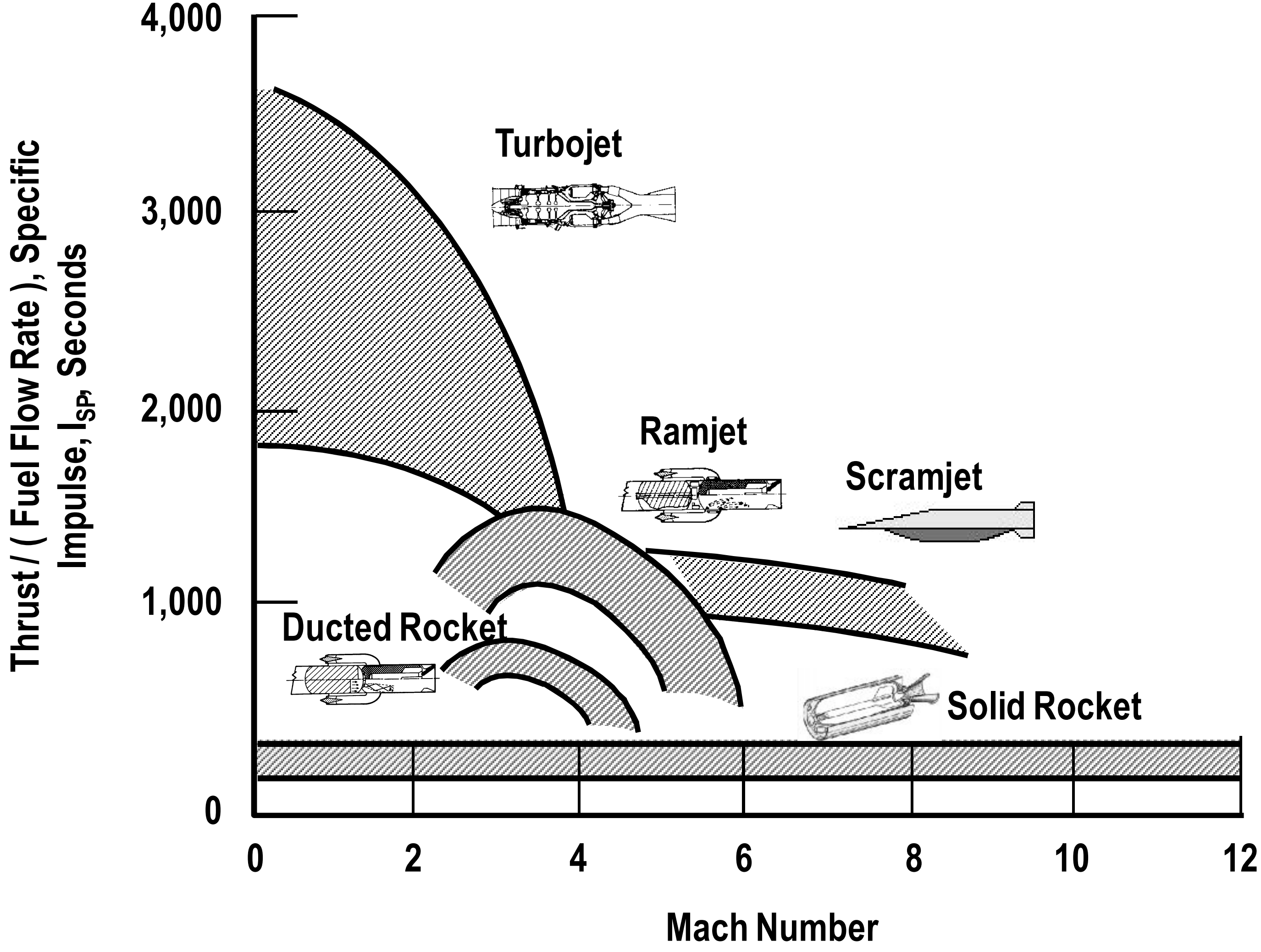
$(C_{D_0})_{Wing,Wave} = 0.024$

$(C_{D_0})_{Wing} = 0.024 + 0.090 = 0.11$

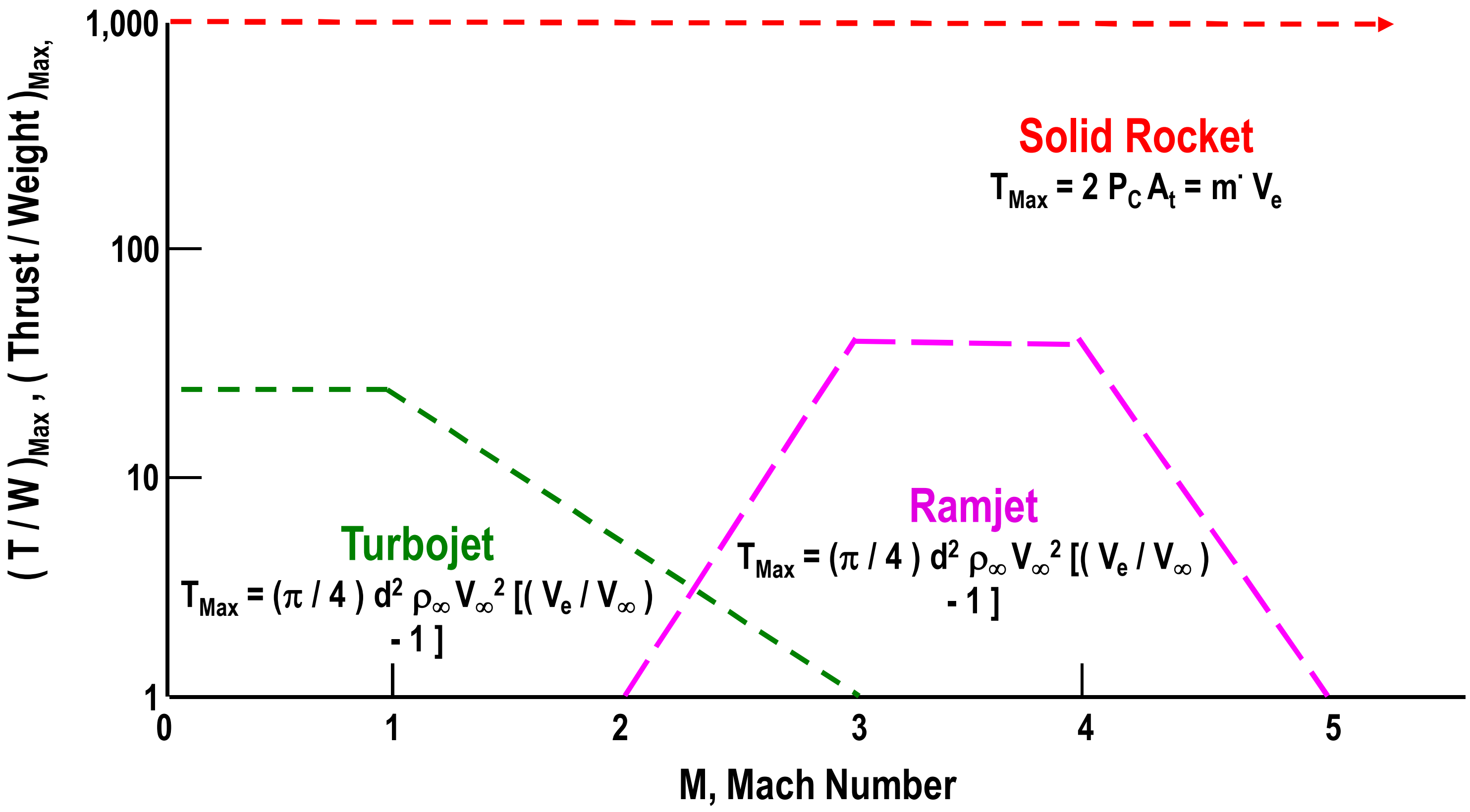
Relaxed Static Margin Allows Higher Trim Angle of Attack and Higher Normal Force



High Specific Impulse Provides Higher Thrust and Reduces Fuel Consumption



Solid Rockets Have High Acceleration Capability



Note:

P_C = Chamber pressure, A_t = Nozzle throat area, $\dot{m}$ = Mass flow rate

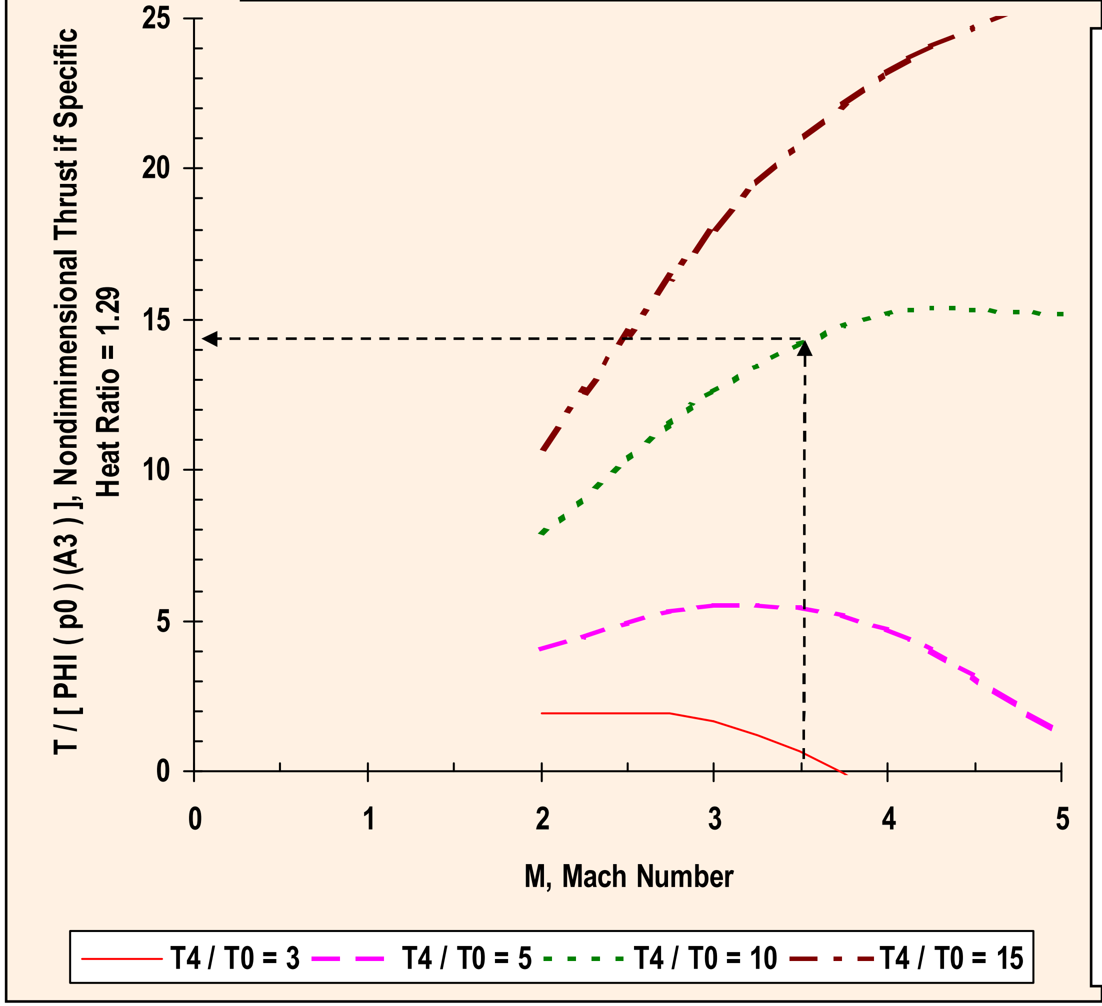
d = Diameter, ρ_∞ = Free stream density, V_∞ = Free stream velocity,

V_e = Nozzle exit velocity (Turbojet: V_e ~ 2,000 ft / sec, Ramjet: V_e ~ 4,500 ft / sec, Rocket: V_e ~ 6,000 ft / sec)

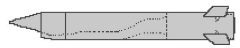
High Thrust for a Ramjet Occurs from Mach 3 to 5 with High Combustion Temperature

$$T / (\phi p_0 A_3) = \gamma M_0^2 \{\{[T_4 / T_0] / \{ 1 + [(\gamma - 1) / 2] M_0^2 \}\}^{1/2} - 1 \}$$

Note: Ideal ramjet, isentropic flow, exit pressure = free stream pressure, $\phi \leq 1$, T in °R



Example for Ramjet Baseline:



M = 3.5, h = 60 Kft, T_4 = 4,000 deg R, (f / a) = 0.06, ϕ = 0.900, T_0 = 392 Rankine, p_0 = 1.047 psi, A_3 = 287.1 in^2, γ = 1.29

$T / (\phi p_0 A_3) = 1.29 (3.5)^2 \{\{[4000 / 392] / \{ 1 + [(1.29 – 1) / 2] (3.5)^2 \}\}^{1/2} – 1 \} = 14.49$

T = 14.49 (0.900) (1.047) (287.1) = 3920 lb

Note:

T = Thrust

p_0 = Free stream static pressure

A_3 = Combustor flameholder entrance area

γ = Specific heat ratio

M_0 = Free stream Mach number

T_4 = Combustor exit temperature

T_0 = Free stream temperature

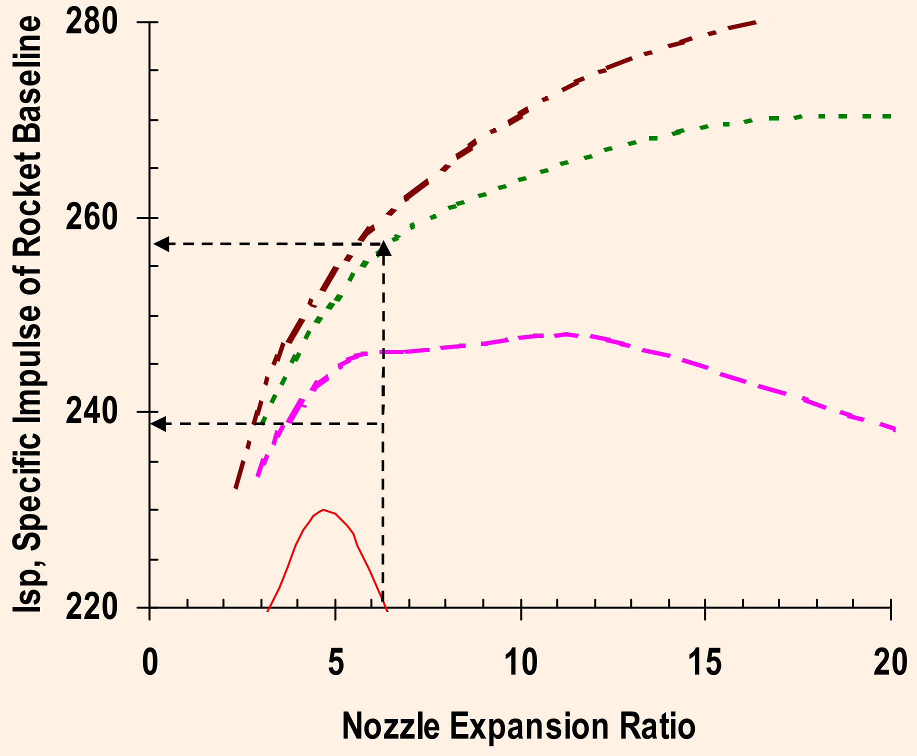
ϕ = Equivalence ratio

Maximum Specific Impulse And Thrust of Rocket Occur at High Chamber Pressure and Altitude

$I_{SP} = c_d \{\{[\, 2\,\gamma^2 / (\gamma - 1)]\,[\, 2 / (\gamma + 1)]^{(\gamma-1)/(\gamma+1)}[\, 1 - (p_e / p_c)^{(\gamma-1)/\gamma}]\}^{1/2} + (p_e / p_c)\,\varepsilon - (p_0 / p_c)\,\varepsilon\,\}\, c^* / g_c$

$T = (g_c / c^*)\, p_c\, A_t\, I_{SP}$

$\varepsilon = \{[\, 2 / (\gamma + 1)^{1/(\gamma-1)}\,][(\gamma - 1) / (\gamma + 1\,)]^{1/2}\,]\} / \{(p_e / p_c)^{1/\gamma}[\, 1 - (p_e / p_c)^{(\gamma-1)/\gamma}]^{1/2}\}$



Note:
- ε = nozzle expansion ratio
- p_e = exit pressure
- p_c = chamber pressure
- p_0 = atmospheric pressure
- A_t = nozzle throat area
- γ = specific heat ratio = 1.18 in figure
- c_d = discharge coefficient = 0.96 in figure
- c^* = characteristic velocity = 5,200 ft / sec in figure

Example for Rocket Baseline:

$\varepsilon = A_e / A_t = 6.2$, $A_t = 1.81\ in^2$

h = 20 Kft, $p_0 = 6.48$ psi

$(p_c)_{boost} = 1769$ psi, $(I_{SP})_{boost} = 257$ sec

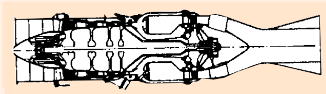
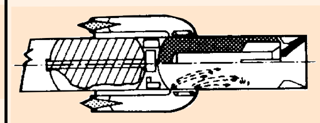
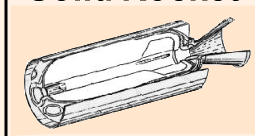
$(T)_{boost} = (32.2 / 5200)(1769)(1.81)(257) = 5096$ lb

$(p_c)_{sustain} = 301$ psi, $(I_{SP})_{sustain} = 239$ sec

$(T)_{boost} = (32.2 / 5200)(301)(1.81)(239) = 807$ lb

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

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

Parameter	Typical Value for 2,000 lb Precision Strike Missile			
	Subsonic Turbojet Missile 	Liquid Fuel Ramjet Missile 	Hydrocarbon Fuel Scramjet Missile 	Solid Rocket 
L / D, Lift / Drag	10	5	3	5
I_{sp}, Specific Impulse	3,000 sec	1,300 sec	1,000 sec	250 sec
V_{AVG} , Average Velocity	1,000 ft / sec	3,500 ft / sec	6,000 ft / sec	3,000 ft / sec
W_P / W_L, Cruise Propellant or Fuel Weight / Launch Weight	0.3	0.2	0.1	0.4
R, Cruise Range	1,800 nm	830 nm	310 nm	250 nm

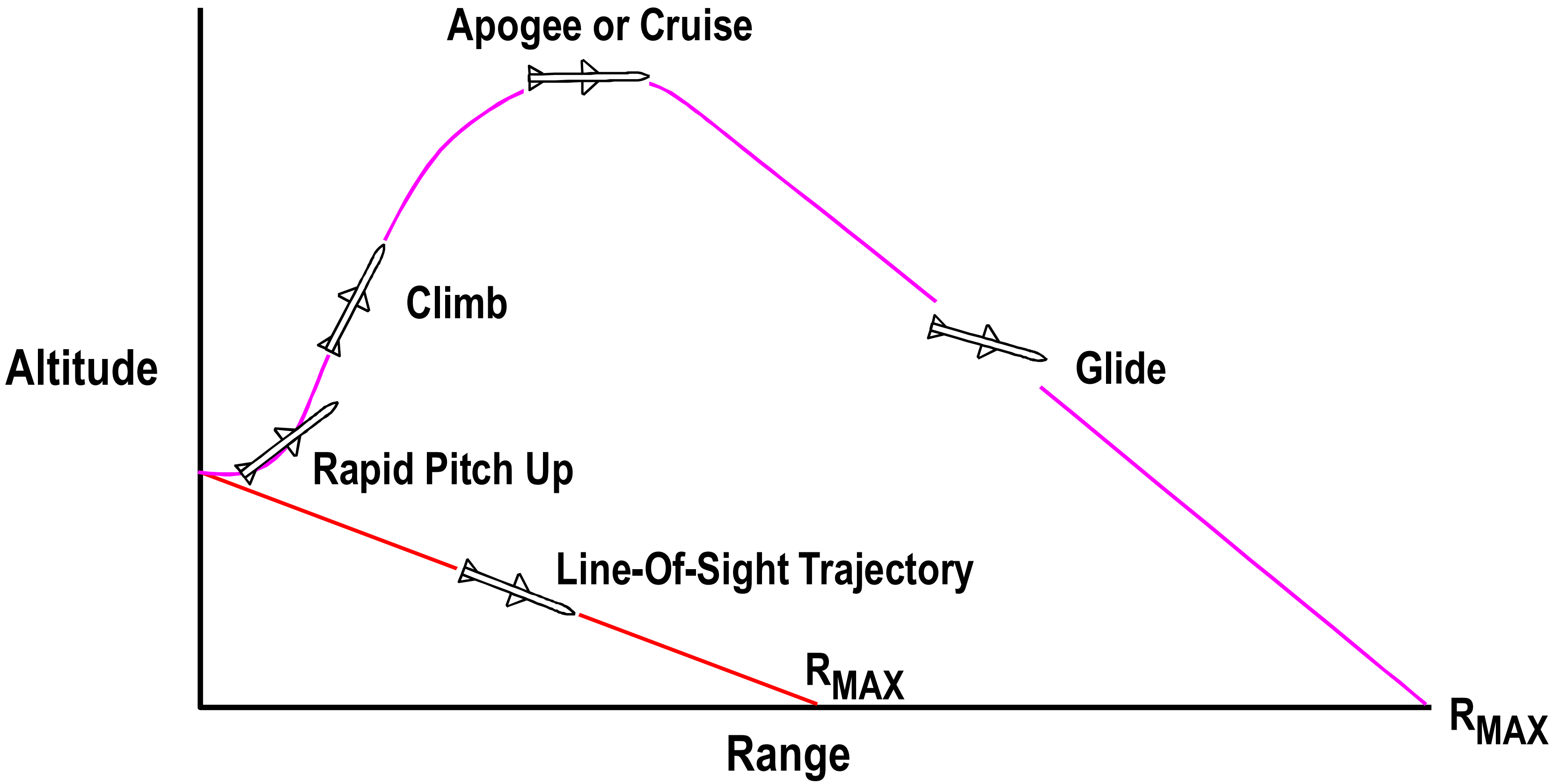
Note: Ramjet and Scramjet missiles booster propellant for Mach 2.5 to 4 take-over speed not included in W_P for cruise. Rockets require thrust magnitude control (e.g., pintle, pulse, or gel motor) for effective cruise. Max range for a rocket is usually a semi-ballistic flight profile, instead of cruise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

Slurry Fuel and Efficient Packaging Provide Extended Range Ramjet

Propulsion / Configuration	Fuel Type / Volumetric Performance (BTU / in3) / Density (lb / in3)	Fuel Volume (in3) / Fuel Weight (lb)	ISP (sec) / Cruise Range at Mach 3.5, 60K ft (nm)
Liquid Fuel Ramjet 	RJ-5 / 581 / 0.040	11900 / 476	1120 / 390
Ducted Rocket (Low Smoke) 	Solid Hydrocarbon / 1132 / 0.075	7922 / 594	677 / 294
Ducted Rocket (High Performance) 	Boron / 2040 / 0.082	7922 / 649	769 / 366
Solid Fuel Ramjet 	Boron / 2040 / 0.082	7056 / 579	1170 / 496
Slurry Fuel Ramjet 	40% JP-10, 60% boron carbide / 1191 / 0.050	11900 / 595	1835 / 770

Note: Flow Path (black) Available Fuel (blue) $R_{cruise} = V I_{SP} (L / D) \ln [W_{BC} / (W_{BC} - W_f)]$

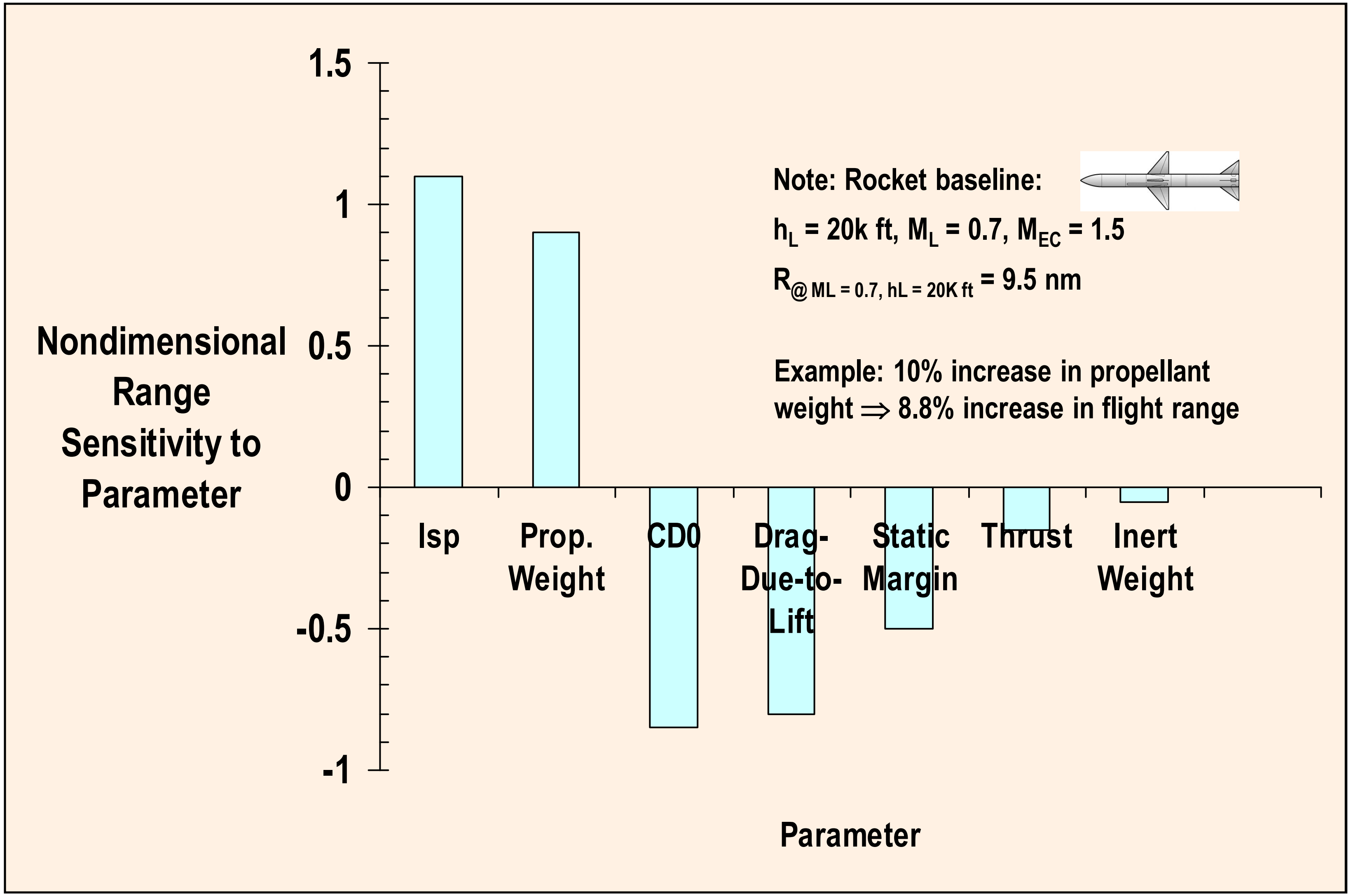
Flight Trajectory Shaping Provides Extended Range



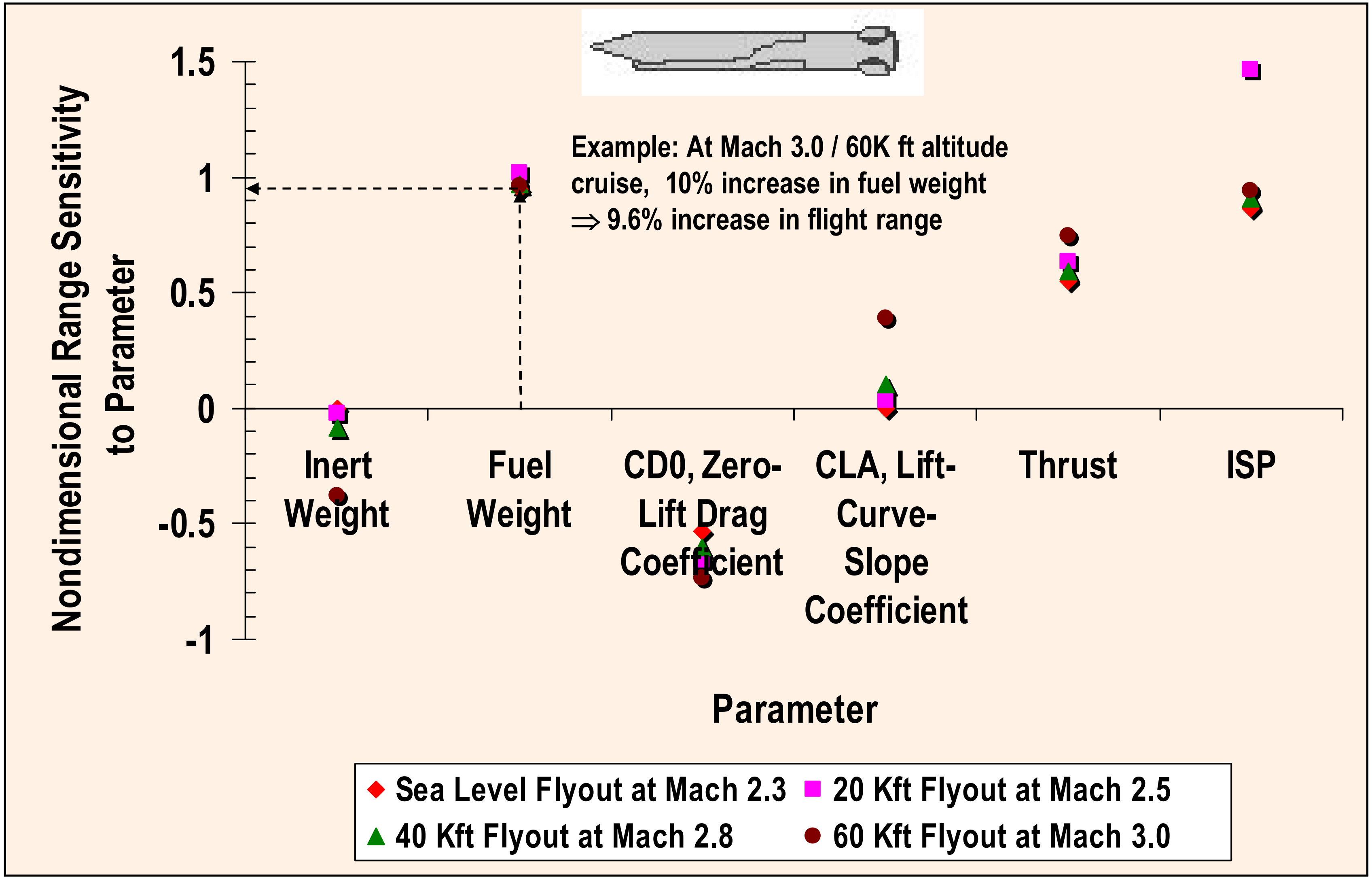
Design Guidelines for Horizontal Launch:

- High thrust-to-weight ≈ 10 for safe separation
- Rapid pitch up minimizes time / propellant to reach efficient altitude
- Climb at a ≈ 0 deg with thrust-to-weight ≈ 2 and q ≈ 700 psf minimizes drag / propellant to reach efficient cruise altitude for $(L / D)_{MAX}$
- High altitude cruise at $(L / D)_{MAX}$ and q ≈ 700 psf maximizes range
- Glide from high altitude at $(L / D)_{Max}$ and q ≈ 700 psf provides extended range

Rocket Baseline Missile Range Driven by I_{SP}, Propellant Weight, Drag, and Static Margin



Ramjet Baseline Range Is Driven by I_{SP}, Fuel Weight, Thrust, and Zero-Lift Drag Coefficient

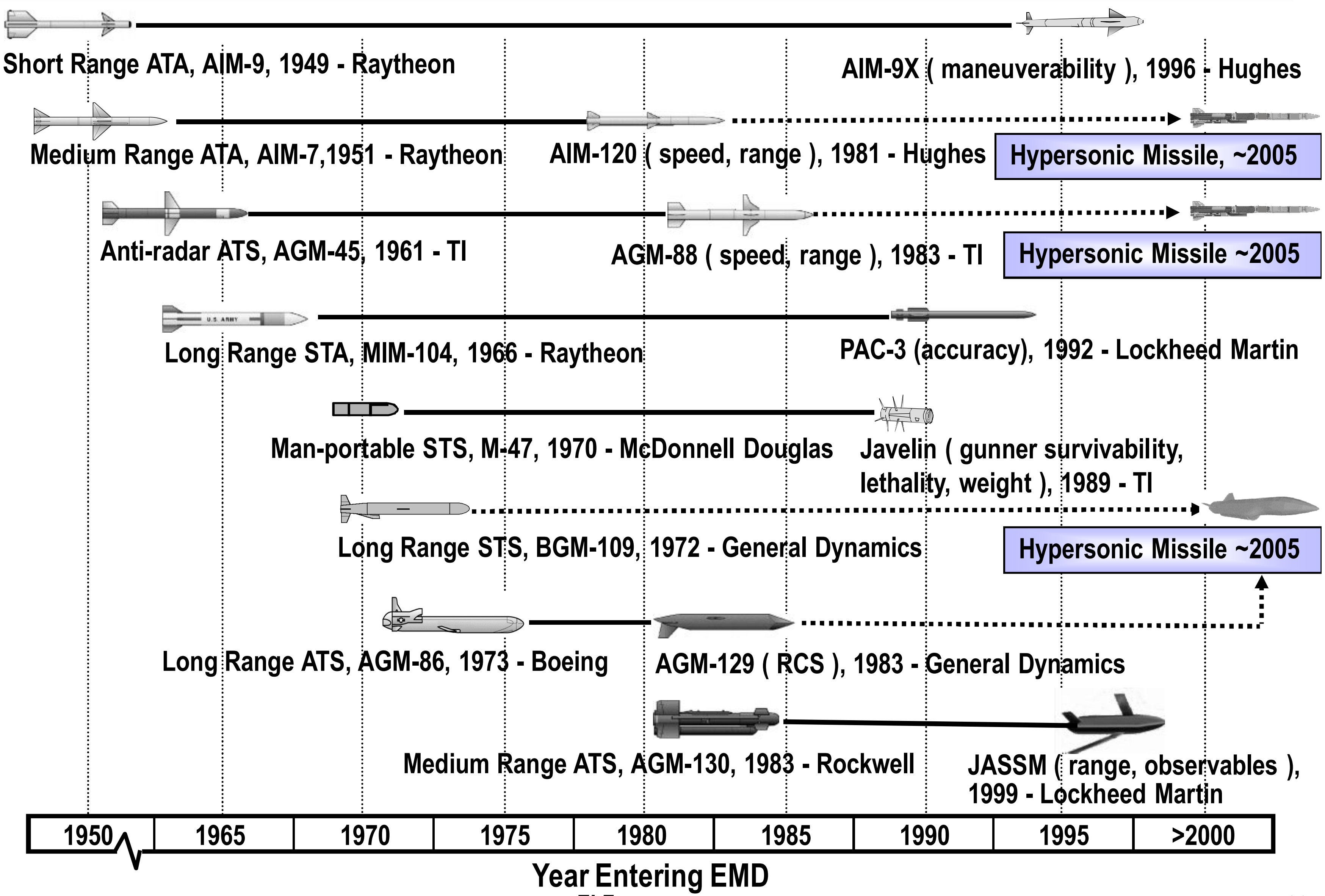


Ramjet Baseline Flight Range Uncertainty Is +/- 7%, 1 σ

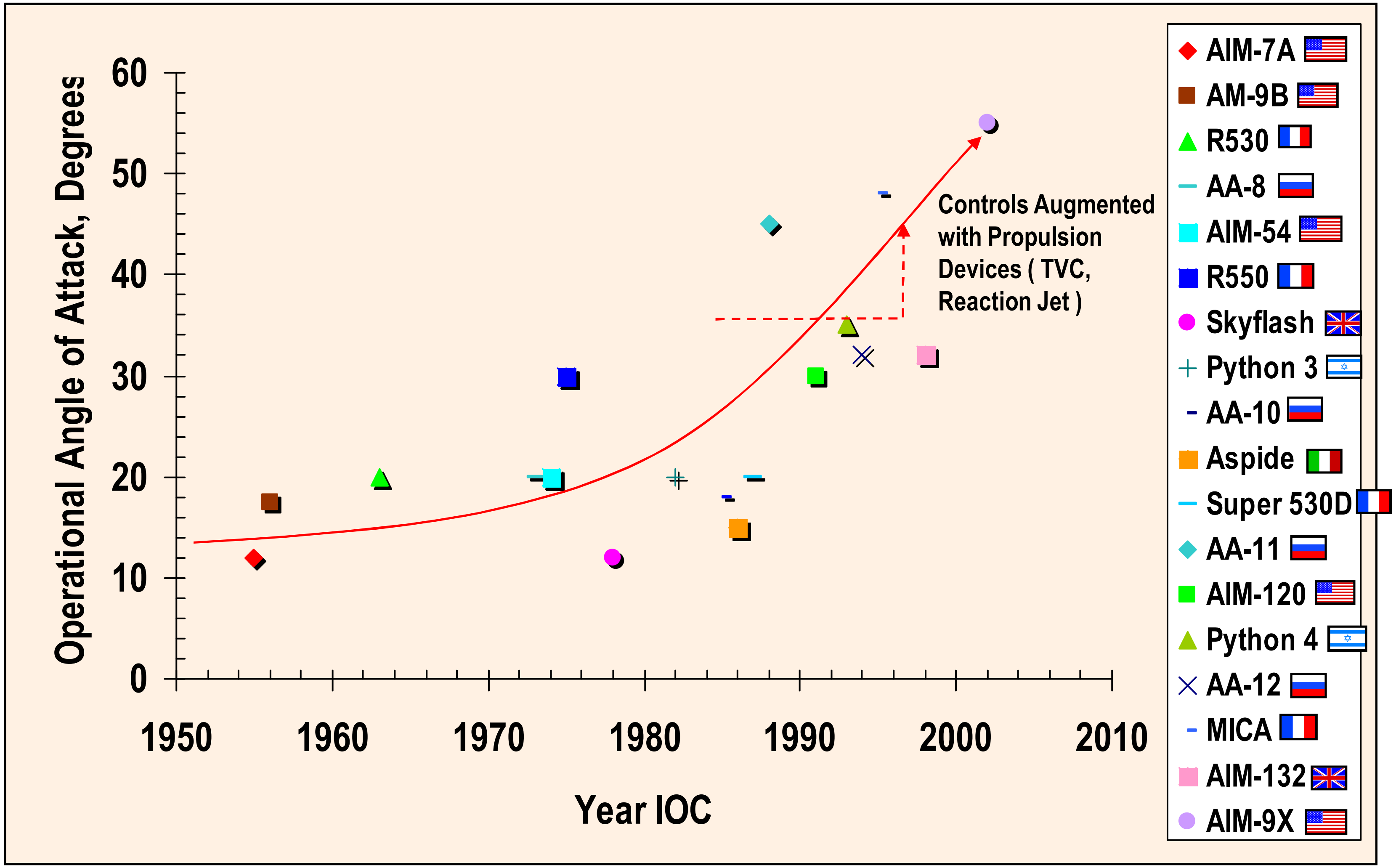
Parameter	Baseline Value at Mach 3.0 / 60k ft	Uncertainty in Parameter	ΔR / R due to Uncertainty
1. Inert Weight	1205 lb	+/- 2%, 1σ	+/- 0.8%, 1σ
2. Ramjet Fuel Weight	476 lb	+/- 1%, 1σ	+/- 0.9%, 1σ
3. Zero-Lift Drag Coefficient	0.17	+/- 5%, 1σ	+/- 4%, 1σ
4. Lift Curve Slope Coefficient	0.13 / deg	+/- 3%, 1σ	+/- 1%, 1σ
5. Cruise Thrust (ϕ = 0.39)	458 lb	+/- 5%, 1σ	+/- 2%, 1σ
6. Specific Impulse	1040 sec	+/- 5%, 1σ	+/- 5%, 1σ

- Level of Maturity of Ramjet Baseline Based on Flight Demo of Prototype and Subsystem Tests
  - Wind tunnel tests
  - Direct connect, freejet, and booster firing propulsion tests
  - Structure test
  - Hardware-in-loop simulation
- Total Flight Range Uncertainty at Mach 3.0 / 60K ft Flyout
  - $\Delta R / R = [(\Delta R / R)_1^2 + (\Delta R / R)_2^2 + (\Delta R / R)_3^2 + (\Delta R / R)_4^2 + (\Delta R / R)_5^2 + (\Delta R / R)_6^2]^{1/2}$ = +/- 6.9%, 1σ
  - R = 445 nm +/- 31 nm, 1σ

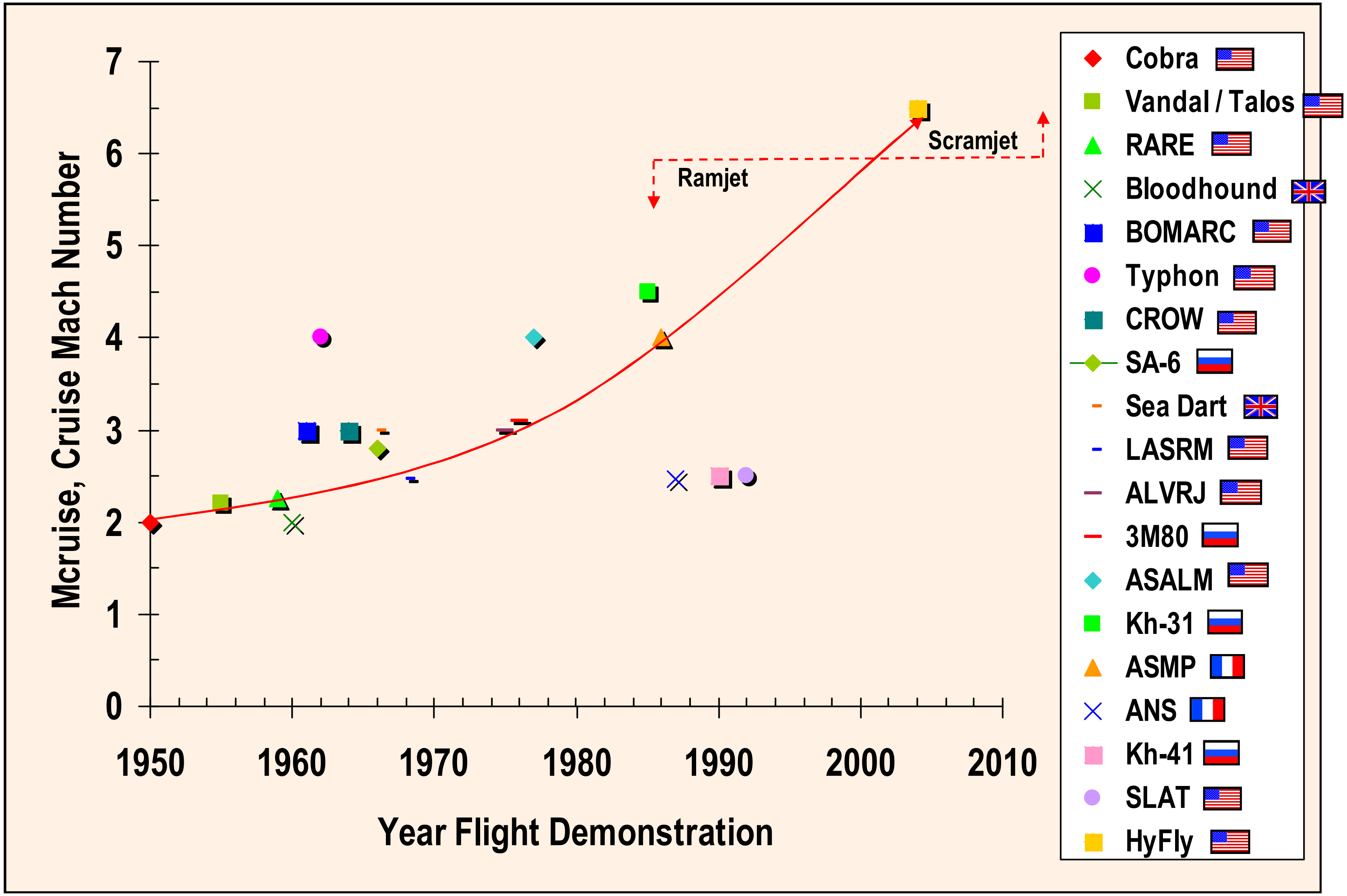
US Tactical Missile Follow-On Programs Provide Enhanced Performance



Example of Missile Technology State-of-the-Art Advancement: Missile Maneuverability



Example of Missile Technology State-of-the-Art Advancement: Supersonic Air Breathing Missiles



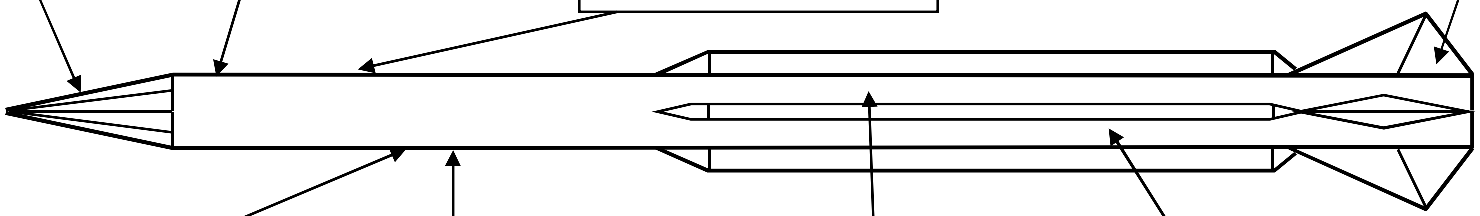
New Technologies That Enhance Tactical Missile Performance

Dome
- ♦Faceted / Window
- ♦Multi-lens

Seeker
- ♦Strapdown
- ♦High Gimbal

G & C
- ♦GPS / INS
- ♦In-flight Optimize
- ♦α, β Feedback

Flight Control
- ♦TVC / Reaction Jet



Power
- ♦MEMS

Airframe
- ♦Lifting Body
- ♦Neutral Static Margin
- ♦Lattice Fins
- ♦Low Drag Inlet
- ♦Mixed Comp. Inlet
- ♦Composite
- ♦Titanium Alloy
- ♦MEMS Data Collection
- ♦Split Canard
- ♦Free-to-roll Tails

Insulation
- ♦Hypersonic
- ♦High Density

Propulsion
- ♦Liquid / Solid Fuel Ramjet
- ♦Variable Flow Ducted Rocket
- ♦Scramjet
- ♦High Temperature Combustor
- ♦High Density Fuel / Propellant
- ♦High Throttle Fuel Control
- ♦Endothermic Fuel
- ♦Composite Case
- ♦Pintle / Pulsed / Gel Motor

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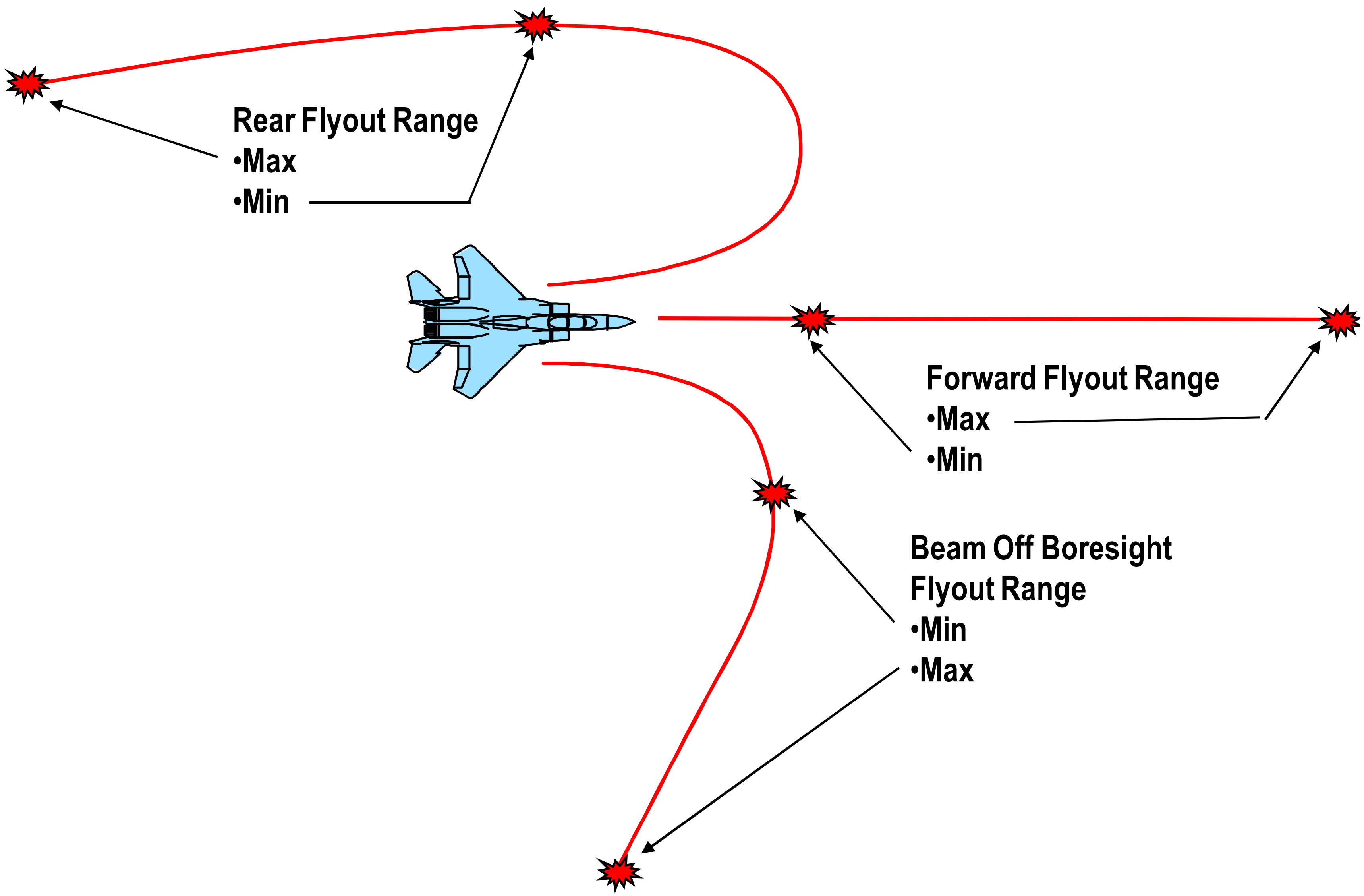
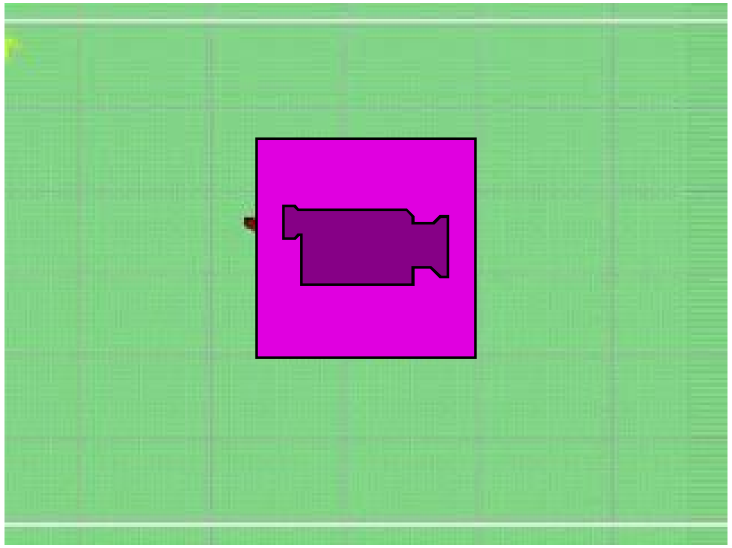
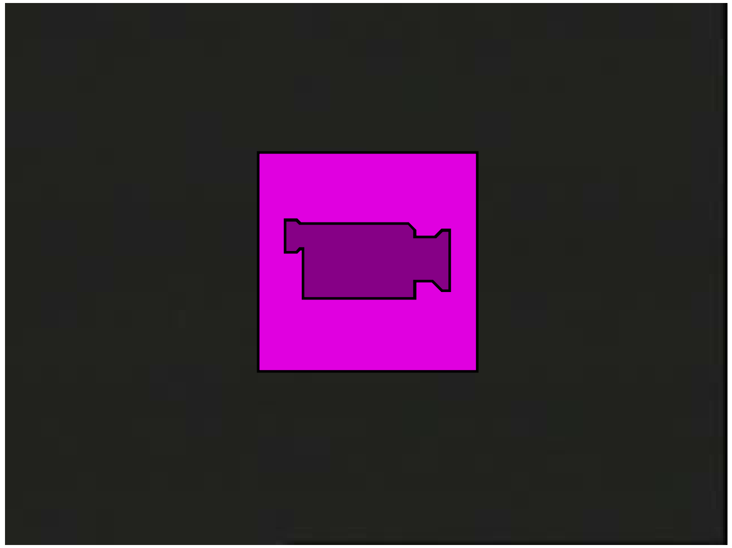
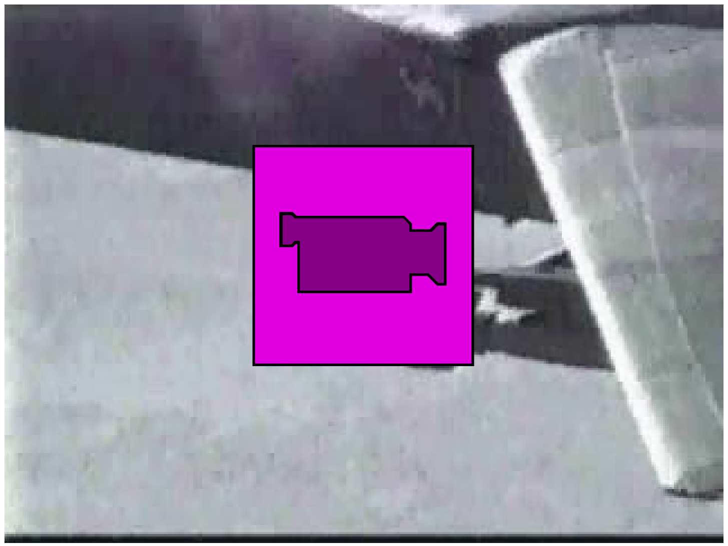
Flight Envelope Should Has Large Max Range, Small Min Range, and Large Off Boresight

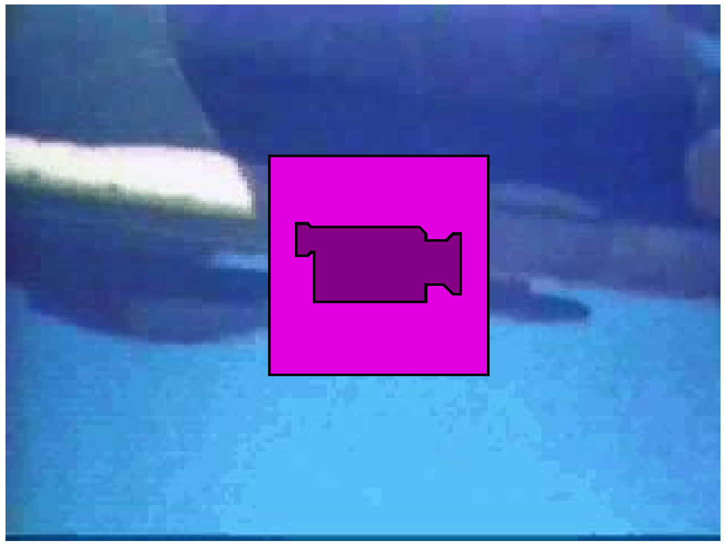


Examples of Air Launched Missile Flight Performance

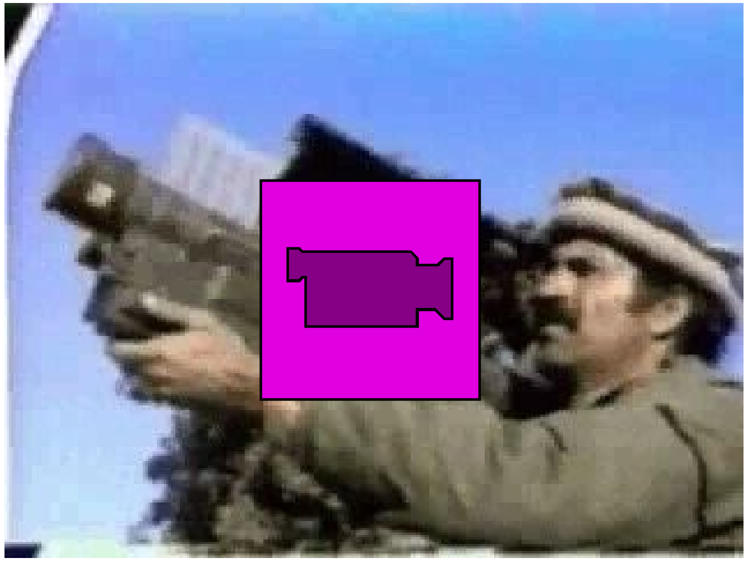
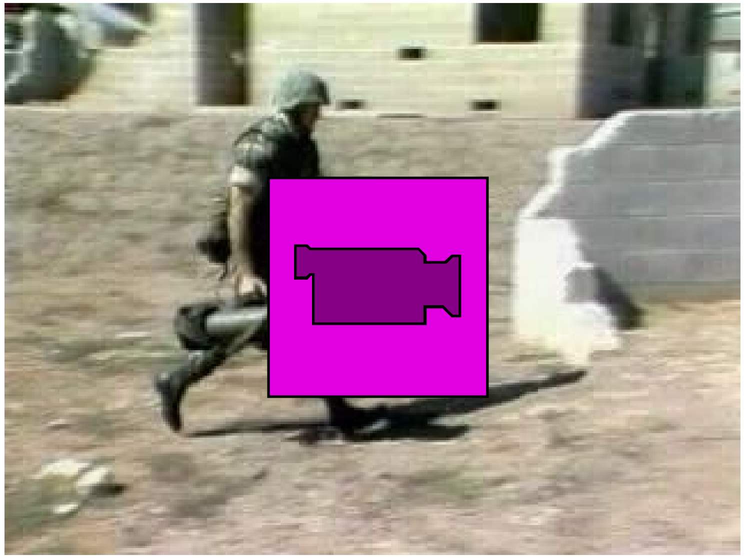
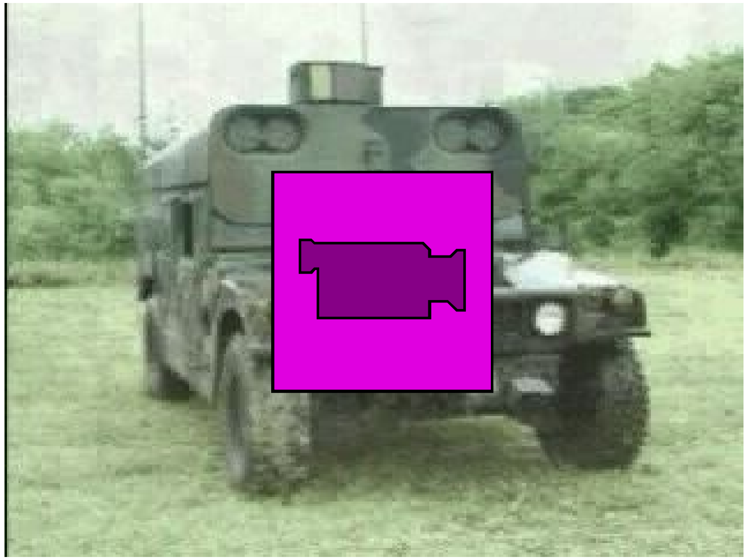
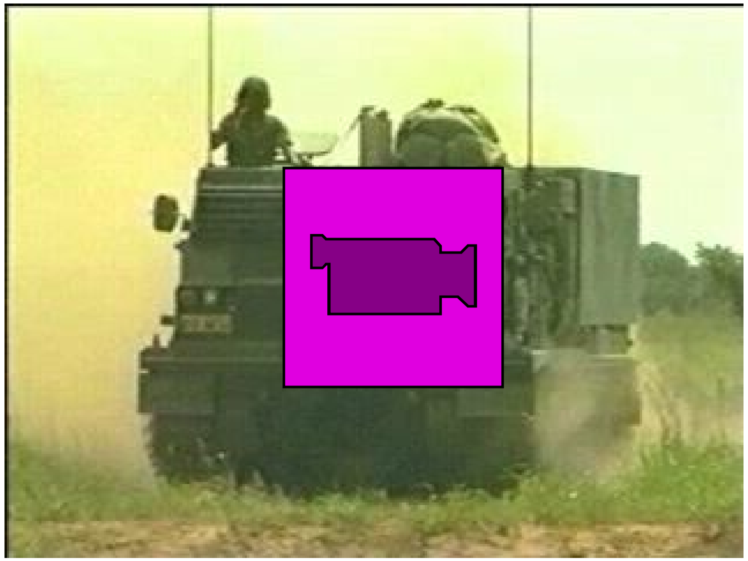






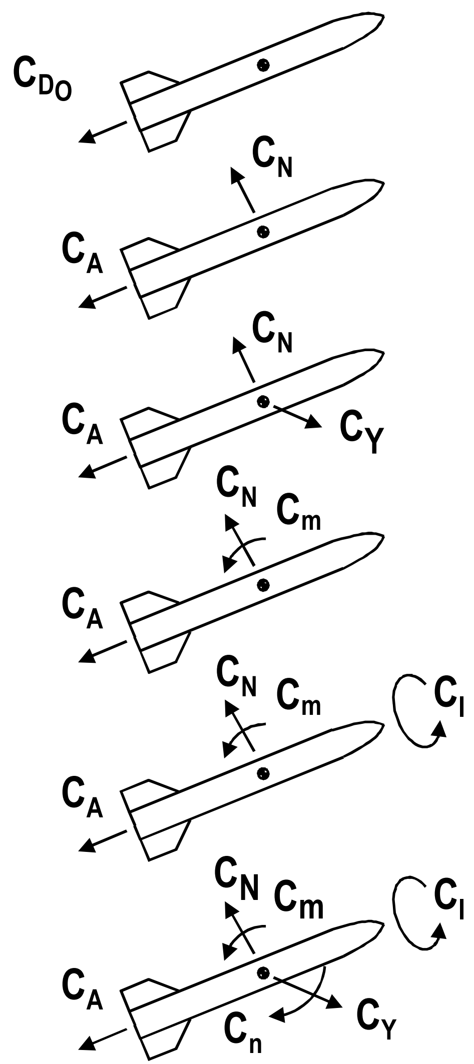


Examples of Surface Launched Missile Flight Performance

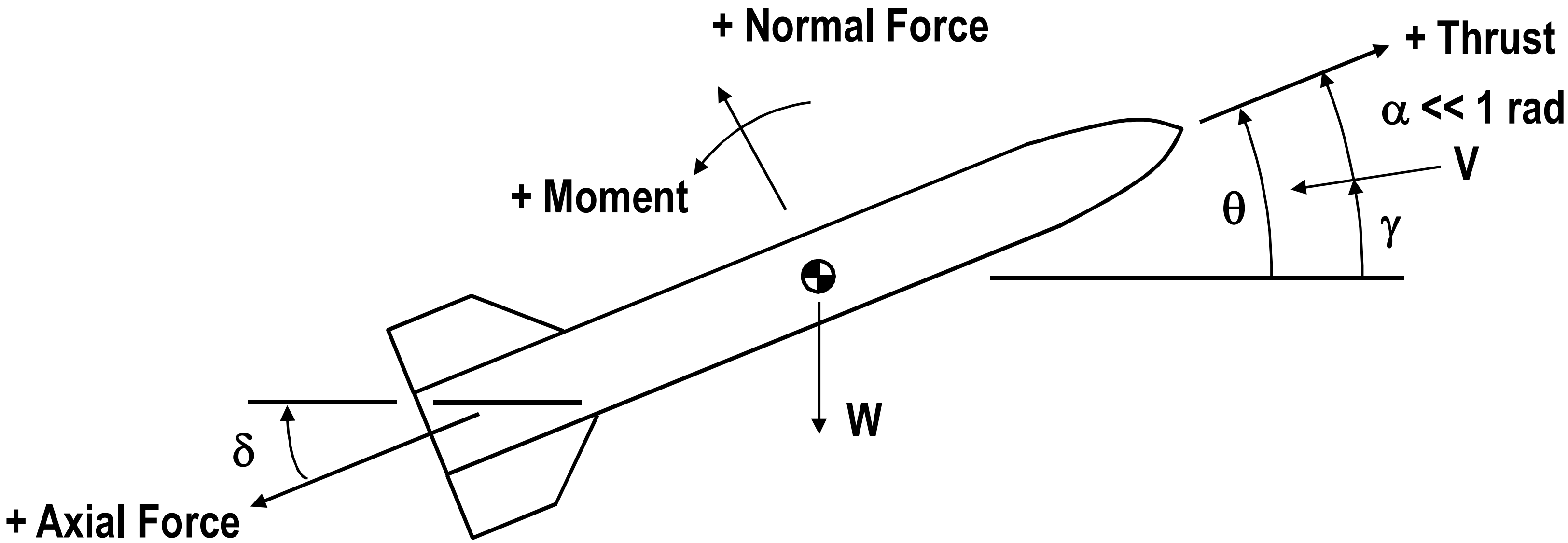





Conceptual Design Modeling Versus Preliminary Design Modeling

- ♦Conceptual Design Modeling
  - ♦1 DOF [Axial force (C_{DO}), thrust, weight]
  - ♦2 DOF [Normal force (C_N), axial force, thrust, weight]
  - ♦3 DOF point mass [3 forces (normal, axial, side), thrust, weight]
  - ♦3 DOF pitch [2 forces (normal, axial), 1 moment (pitch), thrust, weight]
  - ♦4 DOF [2 forces (normal, axial), 2 moments (pitch, roll), thrust, weight]
- ♦Preliminary Design Modeling
  - ♦6 DOF [3 forces (normal, axial, side), 3 moments (pitch, roll, yaw), thrust, weight]



3 DOF Simplified Equations of Motion Show Drivers for Configuration Sizing



$$I_y \ddot{\theta} \approx q\, S_{Ref}\, d\, C_{m_\alpha}\, \alpha + q\, S_{Ref}\, d\, C_{m_\delta}\, \delta$$

$$(W / g_c)\, V \dot{\gamma} \approx q\, S_{Ref}\, C_{N_\alpha}\, \alpha + q\, S_{Ref}\, C_{N_\delta}\, \delta - W \cos \gamma$$

$$(W / g_c)\, \dot{V} \approx T - C_A\, S_{Ref}\, q - C_{N_\alpha}\, \alpha^2\, S_{Ref}\, q - W \sin \gamma$$

Configuration Sizing Implication

High Control Effectiveness ⇒ C_{m_δ} > C_{m_α}, I_y small (W small), q large

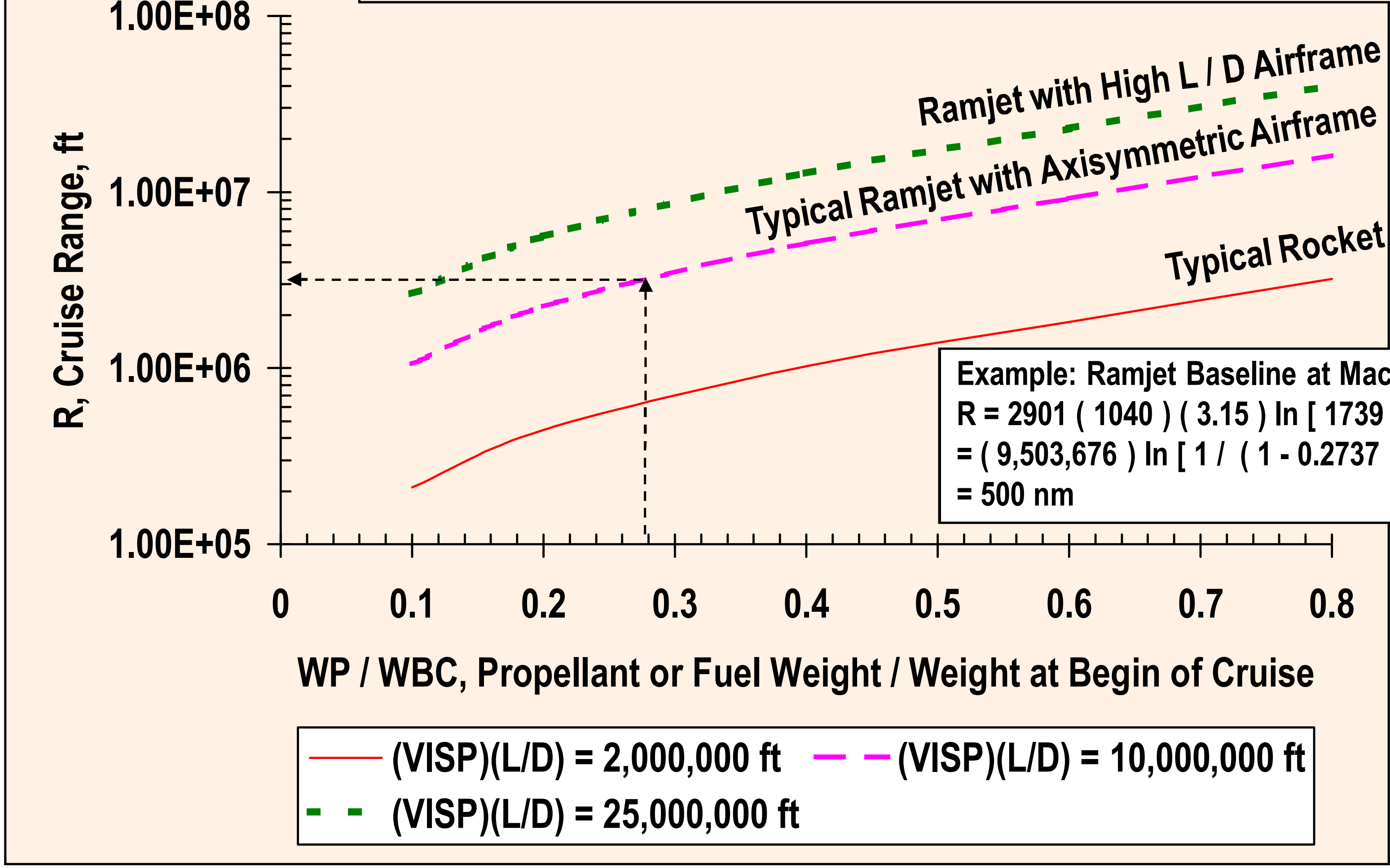
Large / Fast Heading Change ⇒ C_N large, W small, q large

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

Note: Based on aerodynamic control

For Long Range Cruise, Maximize $V\ I_{sp}$, L / D, And Fuel or Propellant Weight Fraction

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

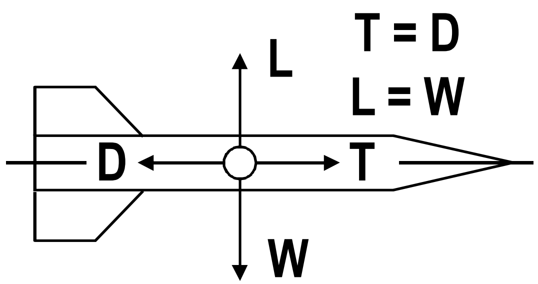


Example: Ramjet Baseline at Mach 3 / 60 Kft alt
R = 2901 (1040) (3.15) ln [1739 / (1739 - 476)]
= (9,503,676) ln [1 / (1 - 0.2737)] = 3,039,469 ft
= 500 nm

Note: R = cruise range, V = cruise velocity, I_{SP} = specific impulse, L = lift, D = drag, W_{BC} = weight at begin of cruise, W_P = weight of propellant or fuel

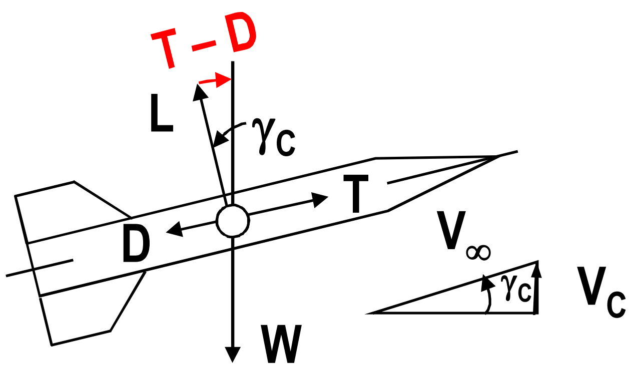
Efficient Steady Flight Is Enhanced by High L / D and Light Weight

Steady Level Flight



$T = W / (L / D)$

Steady Climb

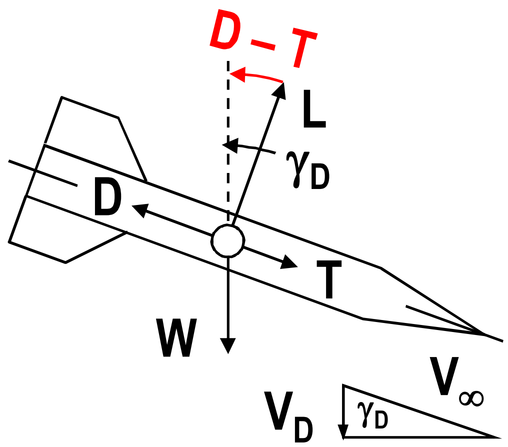


$\text{SIN}\ \gamma_c = (T - D) / W = V_C / V_\infty$

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

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

Steady Descent



$\text{SIN}\ \gamma_D = (D - T) / W = V_D / V_\infty$

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

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

Note:

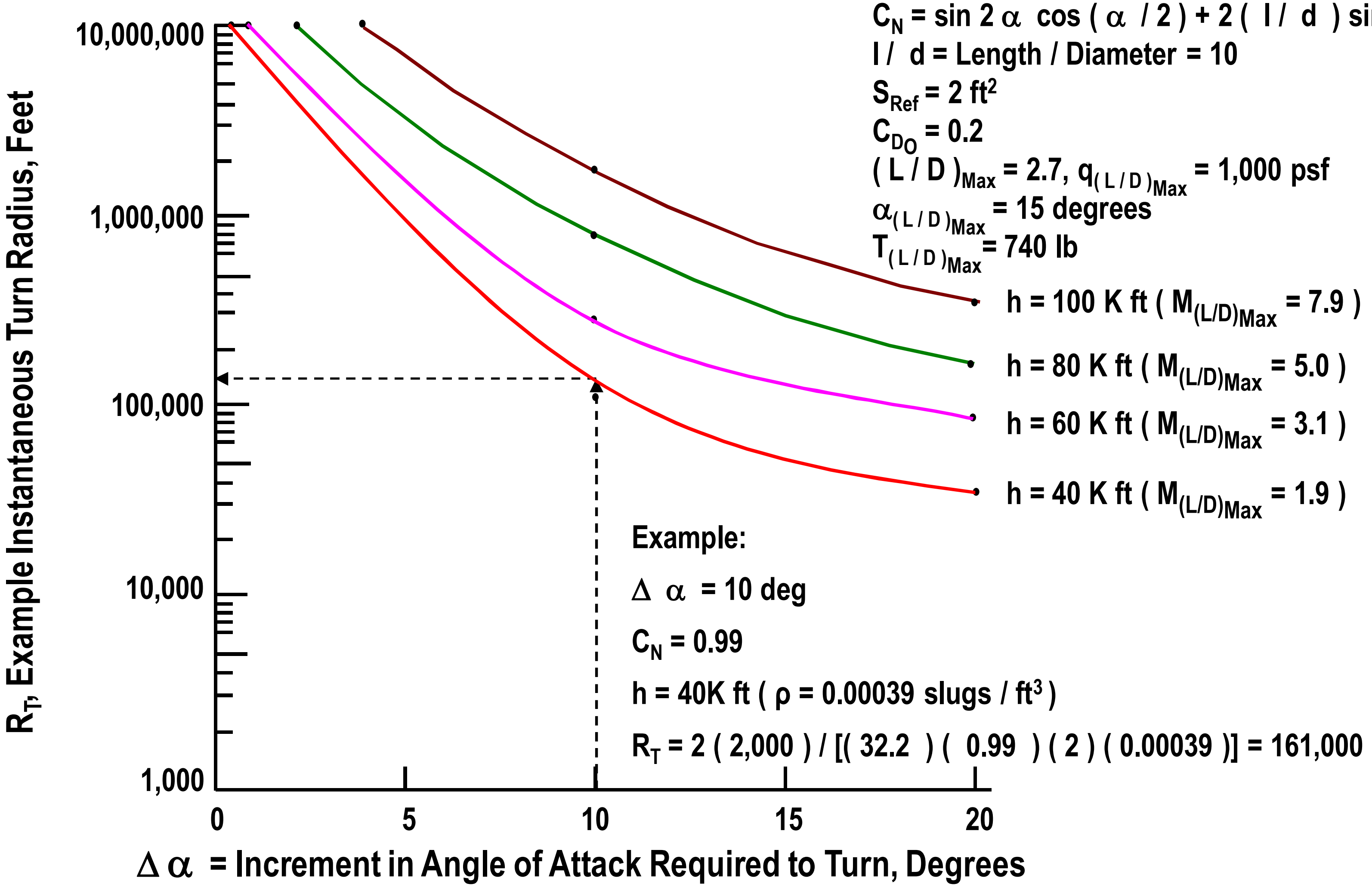
- Small Angle of Attack
- Equilibrium Flight
- V_C = Velocity of Climb
- V_D = Velocity of Descent
- γ_C = Flight Path Angle During Climb
- γ_D = Flight Path Angle During Descent
- V_∞ = Total Velocity
- Δh = Incremental Altitude
- R_C = Horizontal Range in Steady Climb
- R_D = Horizontal Range in Steady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

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

Small Turn Radius Requires High Angle of Attack and Low Altitude Flight

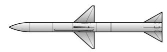
$R_T = V / \dot{\gamma} \approx 2 W / (g_c C_N S_{Ref} \rho)$

Note for Example:
W = Weight = 2,000 lb
a / b = 1 (circular cross section), No wings
$C_N = \sin 2\alpha \cos(\alpha / 2) + 2 (l / d) \sin^2 \alpha$
l / d = Length / Diameter = 10
$S_{Ref} = 2\ ft^2$
$C_{D_O} = 0.2$
$(L / D)_{Max} = 2.7$, $q_{(L / D)_{Max}} = 1{,}000$ psf
$\alpha_{(L / D)_{Max}} = 15$ degrees
$T_{(L / D)_{Max}} = 740$ lb



Example:
$\Delta\alpha$ = 10 deg
$C_N = 0.99$
h = 40K ft ($\rho = 0.00039\ slugs / ft^3$)
$R_T = 2 (2{,}000) / [(32.2) (0.99) (2) (0.00039)] = 161{,}000$ ft

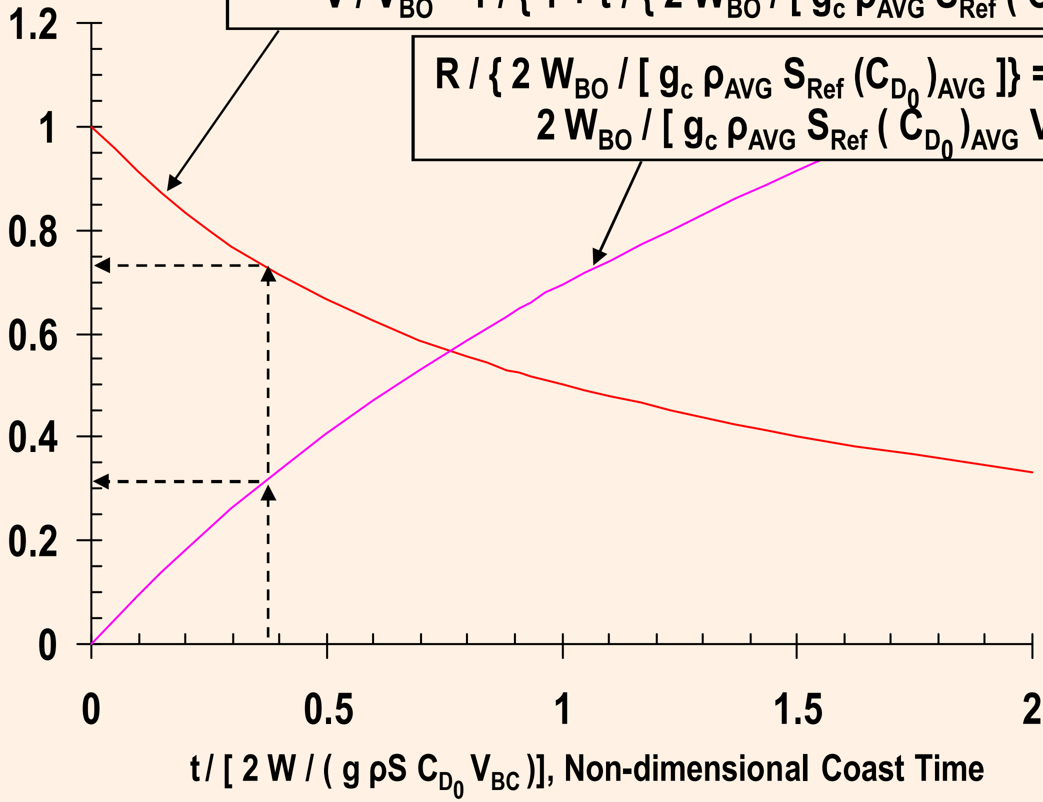
Turn Rate Performance Requires High Control Effectiveness

- $\dot{\gamma} = g_c n / V = [q S_{Ref} C_{N_\alpha} \alpha + q S_{Ref} C_{N_\delta} \delta - W \cos (\gamma)] / [(W / g_c) V]$
- Assume Rocket Baseline @ Mach 0.8 Launch, 20K ft Altitude 
  - $(C_{m_\alpha})_{xcg=84.6} = (C_{m_\alpha})_{xcg=75.7} + C_{N_\alpha} (84.6 – 75.7) / d = - 0.40 + 0.68 (8.9) / 8 = 0.36$ per deg
  - $(C_{m_\delta})_{xcg=84.6} = (C_{m_\delta})_{xcg=75.7} + C_{N_\delta} (84.6 – 75.7) / d = 0.60 + 0.27(8.9) / 8 = 0.90$ per deg
  - $\alpha / \delta = - C_{m_\delta} / C_{m_\alpha} = - 0.90 / 0.36 = - 2.5$
  - $\alpha' = \alpha + \delta < 22$ degrees, $\alpha_{max} = 30$ deg $\Rightarrow \alpha = 30$ deg, $\delta = - 12$ deg
  - $\dot{\gamma} = [436 (0.349)(0.68)(30) + 436 (0.349)(0.27)(- 12) – 500 (1)] / [(500 / 32.2)(830)] =$ 0.164 rad / sec or 9.4 deg / sec
- Assume Rocket Baseline @ Mach 2 Coast, 20K ft Altitude
  - $\alpha / \delta = 0.75$
  - $\alpha' = \alpha + \delta = 22$ degrees $\Rightarrow \delta = 12.6$ deg, $\alpha = 9.4$ deg
  - $\dot{\gamma} = [2725 (0.349)(0.60)(9.4) +2725 (0.349)(0.19)(12.6) – 367 (1)] / (367 / 32.2)(2074) =$ 0.31 rad / sec or 18 deg / sec
  - Note: High q, statically stable, forward wing control, lighter weight $\Rightarrow$ higher climb capability
  - Note: Forward wing deflection to trim increases normal force

For Long Range Coast, Maximize Initial Velocity

$V / V_{BO} = 1 / \{ 1 + t / \{ 2 W_{BO} / [g_c \rho_{AVG} S_{Ref} (C_{D_0})_{AVG} V_{BO}]\}\}$

$R / \{ 2 W_{BO} / [g_c \rho_{AVG} S_{Ref} (C_{D_0})_{AVG}]\} = \ln \{1 + t / \{ 2 W_{BO} / [g_c \rho_{AVG} S_{Ref} (C_{D_0})_{AVG} V_{BO}]\}\}$



Note: Based on 1DoF

$dV / dt = - g_c C_{D_0} S_{Ref}\, q / W$

Assumptions:

- γ = constant
- $\alpha \approx 0$ deg
- $D > W \sin \gamma$

V = velocity during coast

V_{BO} = velocity @ burnout (begin coast)

R = coast range

$V_x = V \cos \gamma$, $V_y = V \sin \gamma$

$R_x = R \cos \gamma$, $R_y = R \sin \gamma$

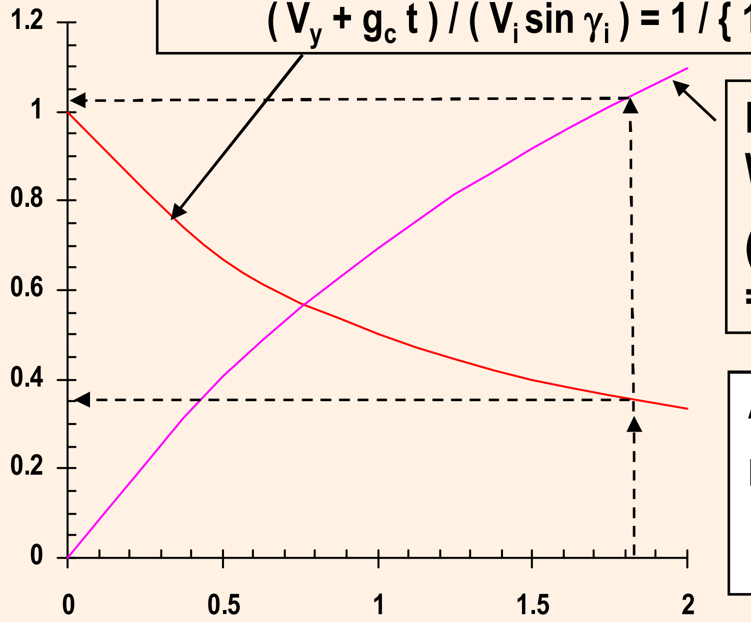
Example for Rocket Baseline:

- W_{BO} = 367 lb, S_{Ref} = 0.349 ft^2, V_{BO} = 2,151 ft / sec, γ = 0 deg, C_{D_0} = 0.9, h = 20,000 ft (ρ = 0.00127 slugs / ft^3), t = 10 sec
- $t / [2 W_{BO} / (g_c \rho S_{Ref} C_{D_0} V_{BO})] = 10 / \{ 2 (367) / [32.2 (0.00127) (0.349) (0.9) (2151)]\} = 10 / 26.6 = 0.376$
- $V / V_{BO} = 0.727$, V = 0.727 x 2151 = 1564 ft / sec, $R / [2 W_{BO} / (g_c \rho S_{Ref} C_{D_0})] = 0.319$, R = 18,300 ft or 3.0 nm

For Long Range Ballistic Flight, Maximize Initial Velocity

$V_x / (V_i \cos \gamma_i) = 1 / \{ 1 + t / \{ 2 W_{BO} / [g_c \rho_{AVG} S_{Ref} (C_{D_0})_{AVG} V_i]\}\}$

$(V_y + g_c t) / (V_i \sin \gamma_i) = 1 / \{ 1 + t / \{ 2 W_{BO} / [g_c \rho_{AVG} S_{Ref} (C_{D_0})_{AVG} V_i]\}$



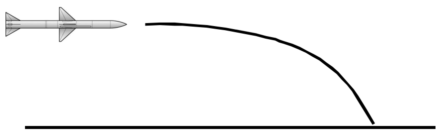
$R_x / \{ 2 W_{BO} \cos \gamma_i / [g_c \rho_{AVG} S_{Ref} (C_{D_0})_{AVG}]\} = \ln \{ 1 + t / \{ 2 W_{BO} / [g_c (\rho)_{AVG} S_{Ref} (C_{D_0})_{AVG} V_i]\}\}$

$(h - h_i + g_c t^2 / 2) / \{ 2 W_{BO} \sin \gamma_i / [g_c \rho_{AVG} S_{Ref} (C_{D_0})_{AVG}]\} = \ln \{ 1 + t / \{ 2 W_{BO} / [g_c \rho_{AVG} S_{Ref} (C_{D_0})_{AVG} V_i]\}$

Assumptions: $T = 0$, $\alpha = 0$ deg, $D > W \sin \gamma$, flat earth

Nomenclature: V = velocity during ballistic flight, V_i = initial velocity, R_x = horizontal range, h = altitude, h_i = initial altitude, V_x = horizontal velocity, V_y = vertical velocity

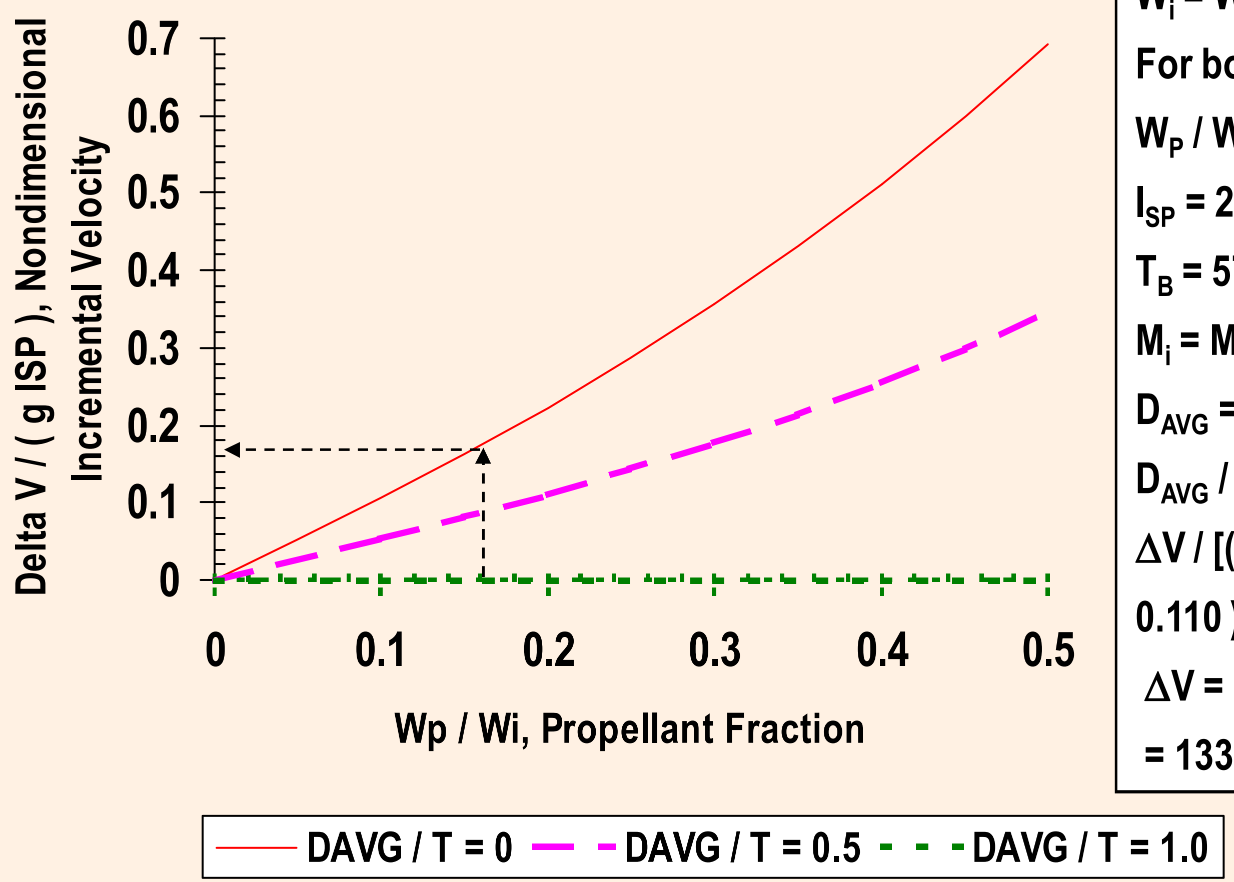
Example for Rocket Baseline:



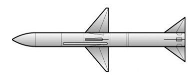
- W_{BO} = 367 lb, S_{Ref} = 0.349 ft^2, $V_i = V_{BO}$ = 2,151 fps, γ_i = 0 deg, $(C_{D_0})_{AVG}$ = 0.9, h_i = 20,000 ft, ρ_{AVG} = 0.001755 slugs / ft^3, t = 35 sec
- $t / [2 W_{BO} / (g_c \rho S_{Ref} C_{D_0} V_i)] = 35 / \{ 2 (367) / [32.2 (0.001755) (0.349) (0.9) (2151)]\} = 35 / 19.22 = 1.821$
- $V_x / (V_i \cos \gamma_i) = 0.354 \Rightarrow V_x$ = 762 ft / sec, $(V_y + 32.2 t) / (V_i \sin \gamma_i) = 0.354 \Rightarrow V_y$ = - 1127 ft / sec, $R_x / [2 W_i \cos \gamma_i / (g_c \rho S_{Ref} C_{D_0})] = 1.037 \Rightarrow R_x$ = 42,900 ft or 7.06 nm, $(h - h_i + 16.1 t^2) / [2 W_{BO} \cos \gamma_i / (g_c \rho S_{Ref} C_{D_0})] = 1.037 \Rightarrow h = 0$ ft

High Propellant Weight and High Thrust Provide High Burnout Velocity

$$\Delta V / (g_c I_{SP}) = - (1 - D_{AVG} / T) \ln (1 - W_p / W_i)$$



Example for Rocket Baseline:

$W_i = W_L = 500$ lb 

For boost, $W_P = 84.8$ lb

$W_P / W_L = 0.1696$

$I_{SP} = 250$ sec

$T_B = 5750$ lb

$M_i = M_L = 0.8$, $h_i = h_L = 20{,}000$ ft

$D_{AVG} = 635$ lb

$D_{AVG} / T = 0.110$

$\Delta V / [(32.2) (250)] = - (1 - 0.110) \ln (1 - 0.1696) = 0.1654$

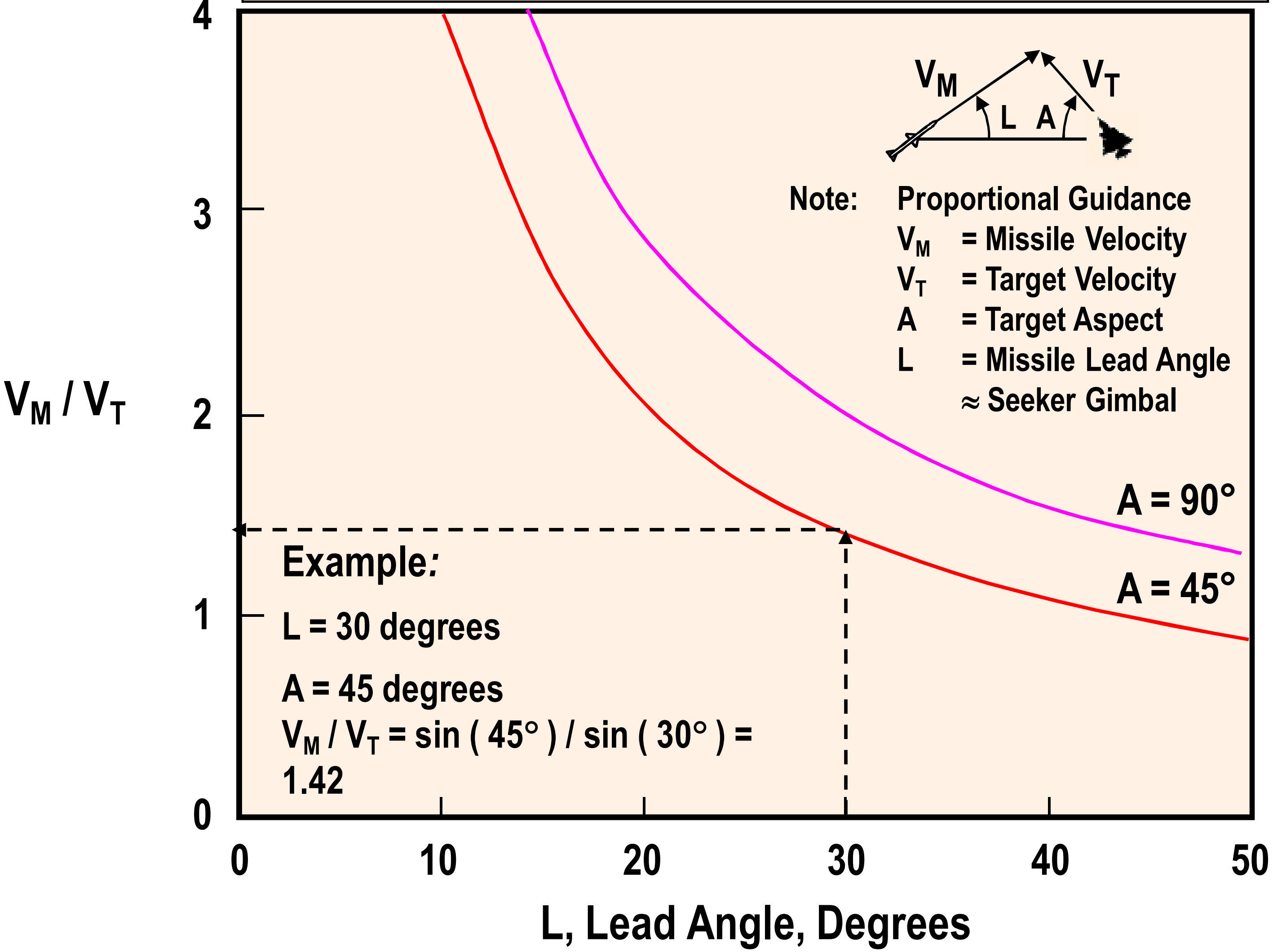
$\Delta V = (0.1654) (32.2) (250) = 1331$ ft / sec

Note: 1 DOF Equation of Motion with $\alpha \approx 0$ deg, γ = constant, and $T > W \sin \gamma$, W_i = initial weight, W_P = propellant weight, I_{SP} = specific impulse, T = thrust, M_i = initial Mach number, h_i = initial altitude, D_{AVG} = average drag, ΔV = incremental velocity, g_c = gravitation constant, $V_x = V \cos \gamma$, $V_y = V \sin \gamma$, $R_x = R \cos \gamma$, $R_y = R \sin \gamma$

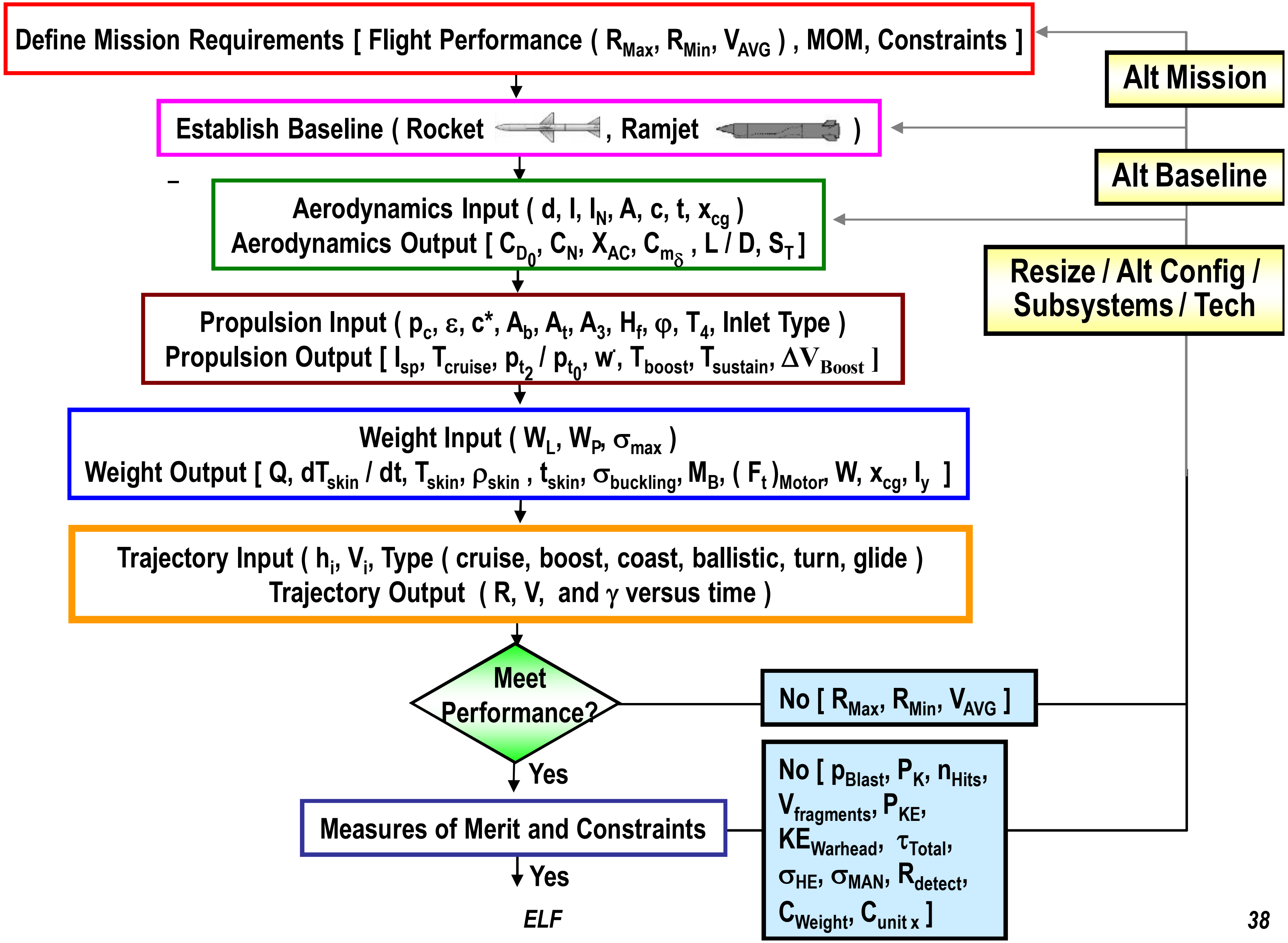
Note: $R = (V_i + \Delta V / 2) t_B$, where R = boost range, V_i = initial velocity, t_B = boost time

High Missile Velocity and Lead Are Required to Intercept High Speed Crossing Targets

$V_M \sin L = V_T \sin A$, Proportional Guidance Trajectory



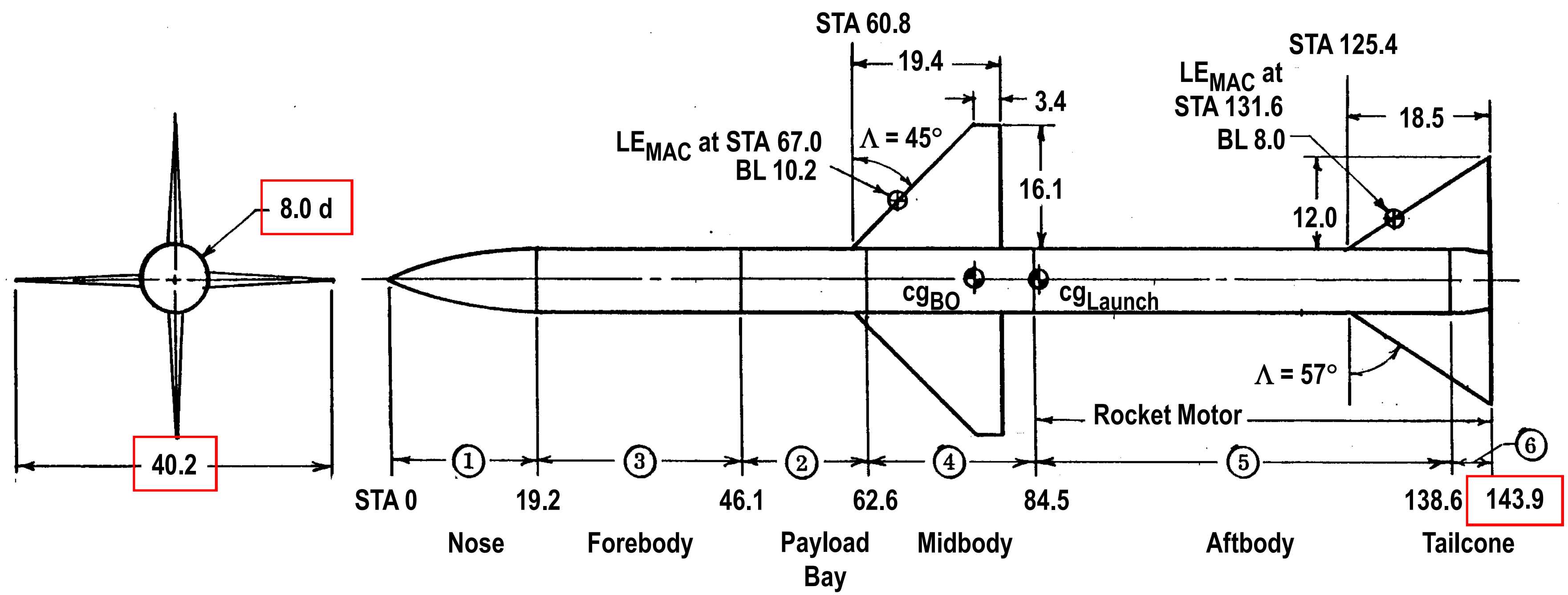
Example of Spreadsheet Based Conceptual Sizing Computer Code - TMD Spreadsheet



Outline

- Examples of Parameters and Technologies That Drive Missile Flight Performance
- Missile Flight Performance Prediction
- Examples of Maximizing Missile Flight Performance (Workshop)
- Summary

Rocket Baseline Missile Configuration



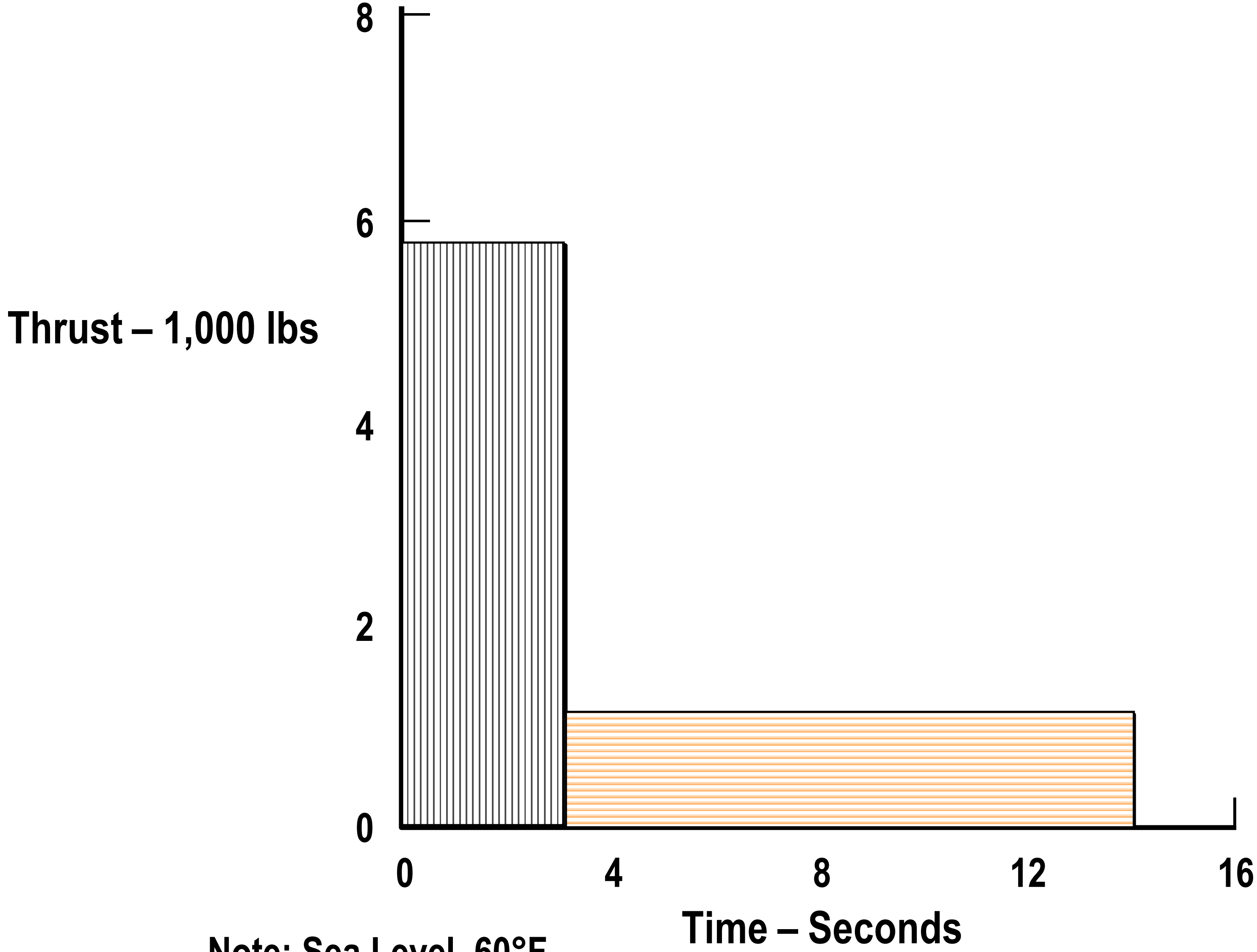
Note: Dimensions in inches

Source: Bithell, R.A. and Stoner, R.C., "Rapid Approach for Missile Synthesis, Vol. 1, Rocket Synthesis Handbook," AFWAL-TR-81-3022, Vol. 1, March 1982.

Rocket Baseline Missile Propellant Weight Is 27% of the Launch Weight

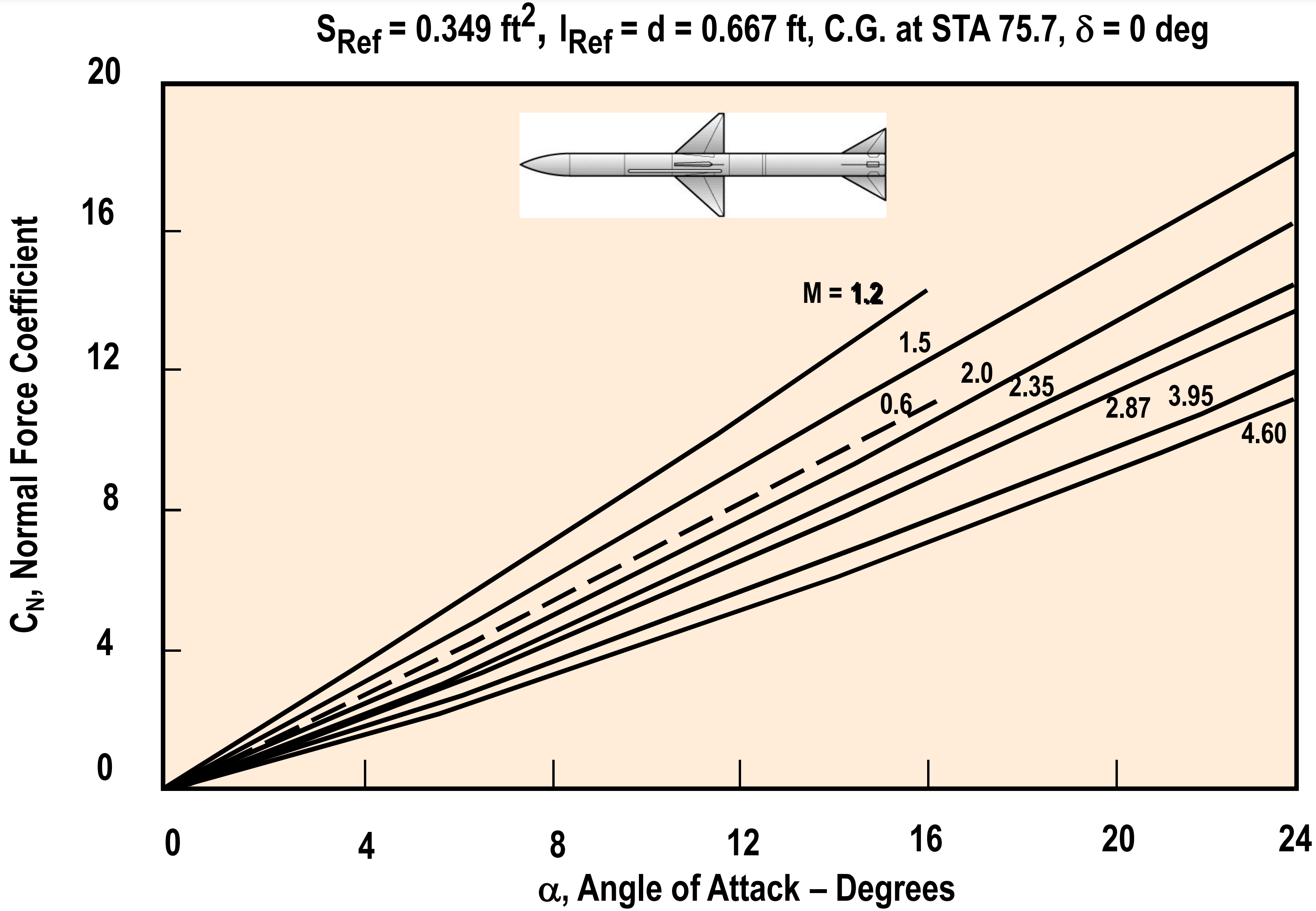
	Component	Weight, lbs.	C.G. STA, In.
1	Nose (Radome)	4.1	12.0
3	Forebody structure	12.4	30.5
	Guidance	46.6	32.6
2	Payload Bay Structure	7.6	54.3
	Warhead	77.7	54.3
4	Midbody Structure	10.2	73.5
	Control Actuation System	61.0	75.5
5	Aftbody Structure	0.0	–
	Rocket Motor Case	47.3	107.5
	Insulation	23.0	117.2
6	Tailcone Structure	6.5	141.2
	Nozzle	5.8	141.2
	Fixed Surfaces	26.2	137.8
	Movable Surfaces	38.6	75.5
	Burnout Total	367.0	76.2
	Propellant	133.0	107.8
	Launch Total	500.0	84.6

Rocket Baseline Missile Has Boost-Sustain Thrust - Time History

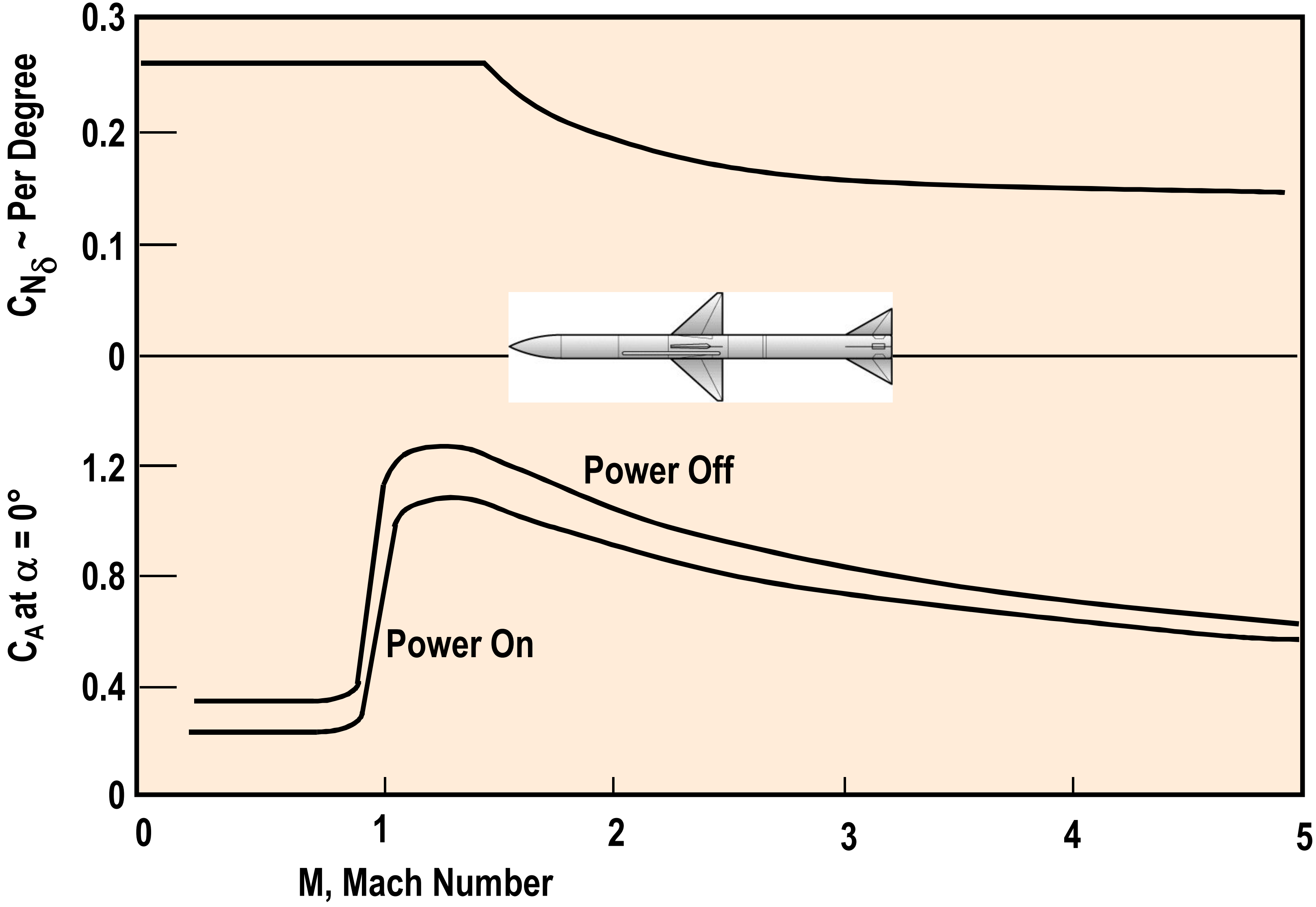


Note: Sea Level, 60°F

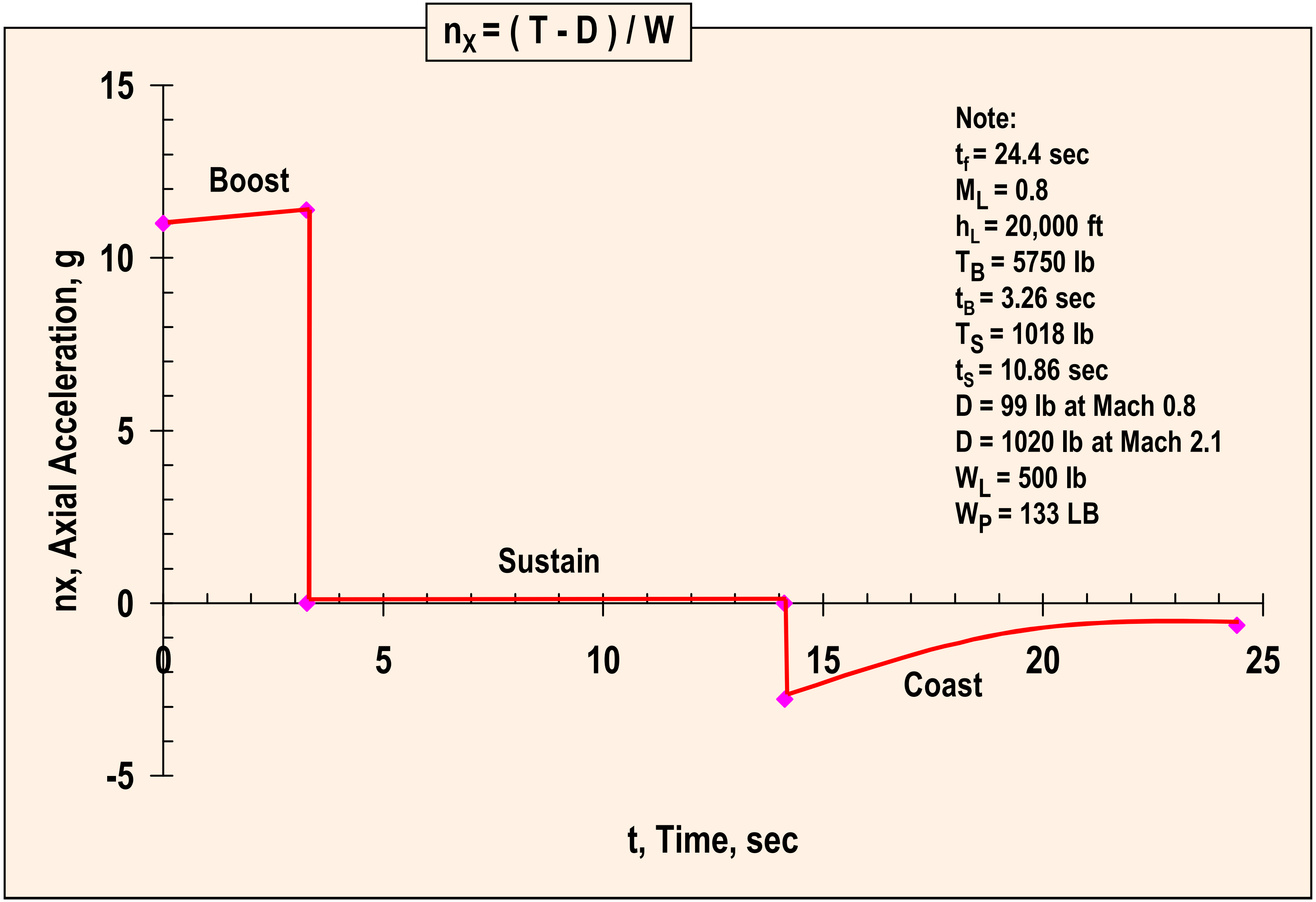
Rocket Baseline Missile Has Higher Maneuverability at High Angle of Attack



Rocket Baseline Missile Control Effectiveness and Drag Are Driven by Mach Number



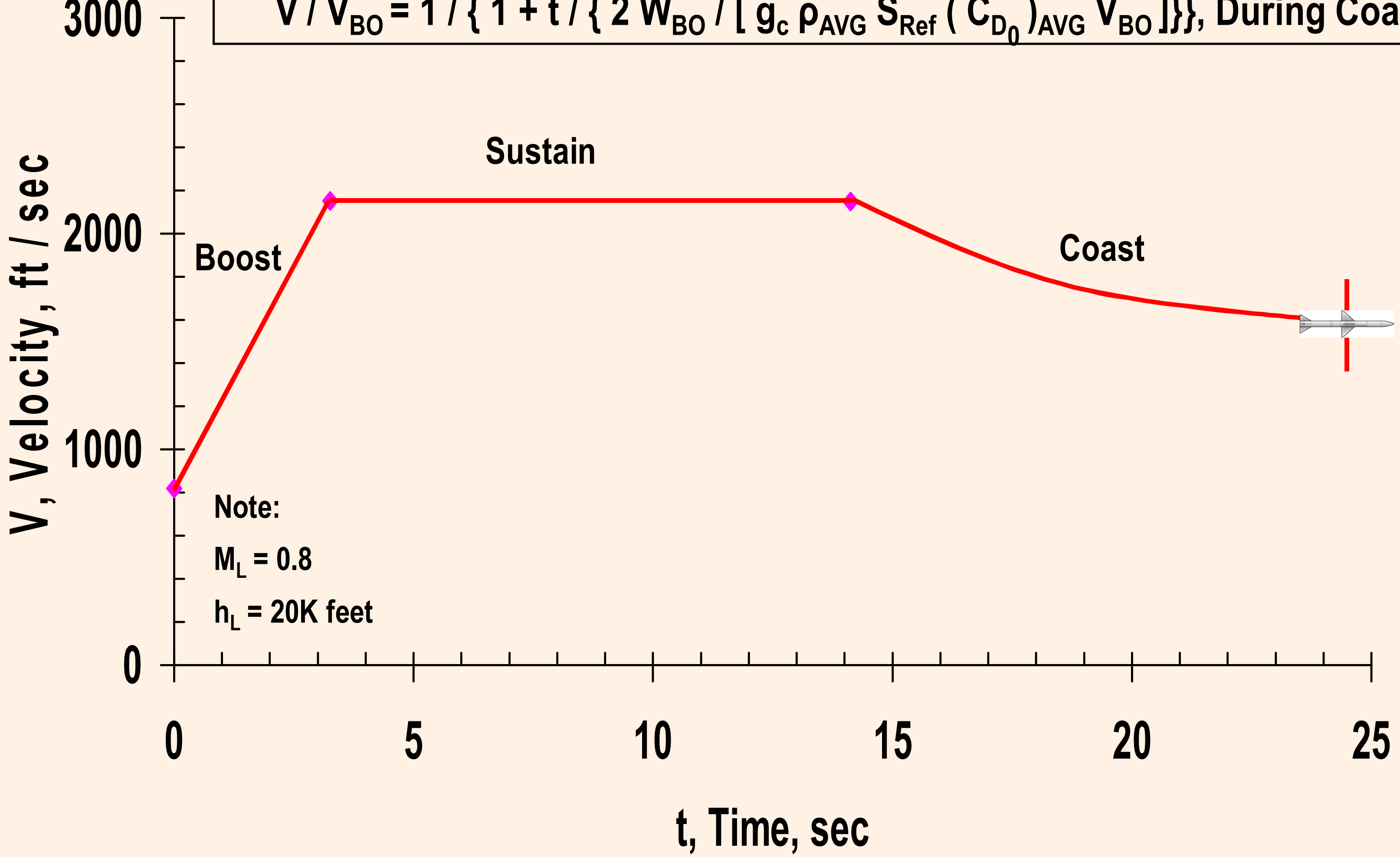
Rocket Baseline Has High Boost Acceleration



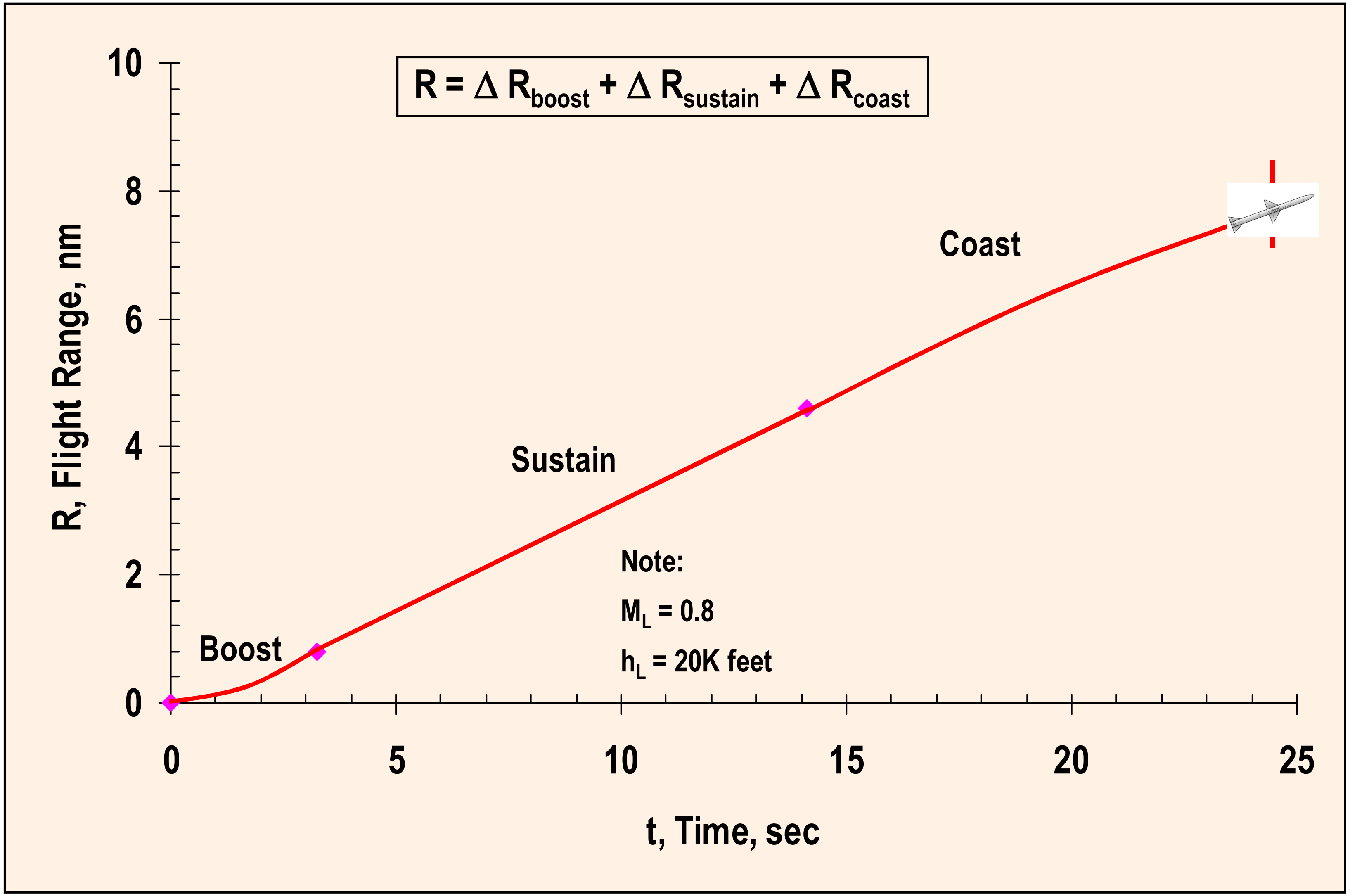
Rocket Baseline Missile Has Nearly Constant Velocity During Sustain

$$\Delta V / (g_c I_{SP}) = - (1 - D_{AVG} / T) \ln (1 - W_p / W_i), \text{ During Boost}$$

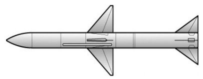
$$V / V_{BO} = 1 / \{ 1 + t / \{ 2 W_{BO} / [g_c \rho_{AVG} S_{Ref} (C_{D_0})_{AVG} V_{BO}]\}\}, \text{ During Coast}$$



Rocket Baseline Missile Maximum Range Is About Eight Nautical Miles



Rocket Baseline Missile Has About 30 G Maneuverability

- $(n_Z) = (n_Z)_{Body} + (n_Z)_{Wing} + (n_Z)_{Taill}$
- Rocket Baseline @ 
  - •Mach 2
  - •20,000 ft altitude
  - •367 lb weight (burnout)
- Compute

  $\alpha_{Wing} = \alpha'_{Max} = (\alpha + \delta)_{Max}$ = 22 deg for rocket baseline

  $\alpha = 0.75\delta$, $\alpha_{Body} = \alpha_{Tail}$ = 9.4 deg

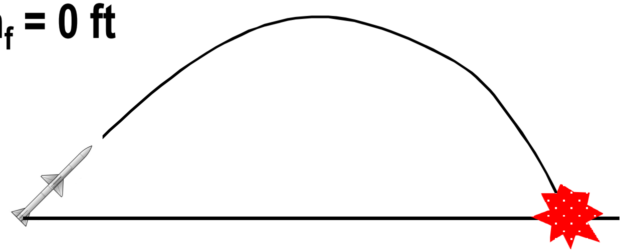
  $(n_Z)_{Body} = q\ S_{Ref}\ (C_N)_{Body} / W$ = 2725 (0.35) (1.1) / 367 = 2.9 g (from body)

  $(n_Z)_{Wing} = q\ S_{Wing}\ [(C_N)_{Wing}\ (S_{Ref} / S_{Wing})] / W$ = 2725 (2.55) (1.08) / 367 = 20.4 g (from wing)

  $(n_Z)_{Tail} = q\ S_{Tail}\ [(C_N)_{Tail}\ (S_{Ref} / S_{Tail})] / W$ = 2725 (1.54) (0.50) / 367 = 5.7 g (from tail)
- n_Z = 2.9 + 20.4 + 5.7 = 29 g

Example of Boost Climb - Ballistic Trajectory

- Assume Rocket Baseline @ γ_i = 45 deg, $h_i = h_f$ = 0 ft



- Velocity, Horizontal Range, and Altitude During Initial Boost @ γ = 45 deg
  - $\Delta V = - g_c I_{SP} (1 - D_{AVG} / T) \ln (1 - W_p / W_i) = -32.2 (250) (1 – 419 / 5750) \ln (1 – 84.8 / 500)$ = 1,387 ft / sec
  - $\Delta R = (V_i + \Delta V / 2) t_B = (0 + 1387 / 2) 3.26$ = 2,260 ft
  - $\Delta R_x = \Delta R \cos \gamma_i = 2260 (0.707)$ = 1,598 ft
  - $\Delta R_y = \Delta R \sin \gamma_i = 2260 (0.707)$ = 1,598 ft
  - $h = h_i + \Delta R_y = 0 + 1598$ = 1,598 ft
- Velocity, Horizontal Range, and Altitude During Sustain @ γ = 45 deg
  - $\Delta V = - g_c I_{SP} (1 - D_{AVG} / T) \ln (1 - W_p / W_i) = -32.2 (230.4) (1 – 650 / 1018) \ln (1 – 48.2 / 415.2)$ = 585 ft / sec
  - V_{BO} = 1387 + 585 = 1,972 ft / sec
  - $\Delta R = (V_i + \Delta V / 2) t_B = (1387 + 585 / 2) 10.86$ = 18,239 ft
  - $\Delta R_x = \Delta R \cos \gamma_i = 18239 (0.707)$ = 12,895 ft
  - $\Delta R_y = \Delta R \sin \gamma_i = 18239 (0.707)$ = 12,895 ft
  - $h = h_i + \Delta R_y = 1598 + 12895$ = 14,493 ft

Example of Boost Climb - Ballistic Trajectory (cont)

- **Velocity, Horizontal Range, and Altitude During Ballistic Flight**

  $h_f = h_i = 0$ ft $\Rightarrow t_{ballistic} = 59$ sec)

  $V_x = V_i \cos \gamma_i / \{ 1 + t / \{ 2 W_{BO} / [g_c \rho_{AVG} S_{Ref} (C_{D_0})_{AVG} V_{BO}]\}\} = 1972 (0.707) / \{ 1 + 59 / \{ 2 (367) / [32.2 (0.001496) (0.349) (0.95) (1972)]\}\} = 395$ ft / sec

  $V_y = V_i \sin \gamma_i / \{ 1 + t / \{ 2 W_{BO} / [g_c \rho_{AVG} S_{Ref} (C_{D_0})_{AVG} V_{BO}]\} - 32.2 t = 1972 (0.707) / \{ 1 + 59 / \{ 2 (367) / [32.2 (0.001496) (0.349) (0.95) (1972)]\}\} - 32.2 (59) = - 1{,}505$ ft / sec

  $R_x = \{ 2 W_{BO} \cos \gamma_i / [g_c \rho_{AVG} S_{Ref} (C_{D_0})_{AVG}]\} \ln \{ 1 + t / \{ 2 W_{BO} / [g_c \rho_{AVG} S_{Ref} (C_{D_0})_{AVG} V_{BO}]\}\} = \{ 2 (367) (0.707) / [32.2 (0.001496) (0.349) (0.95)]\} \ln \{ 1 + 59 / \{ 2 (367) / [32.2 (0.001496) (0.349) (0.95) (1972)]\}\} = 40{,}991$ ft

  $h = h_i + \{ 2 W_{BO} \sin \gamma_i / [g_c \rho_{AVG} S_{Ref} (C_{D_0})_{AVG}]\} \ln \{ 1 + t / \{ 2 W_{BO} / [g_c \rho_{AVG} S_{Ref} (C_{D_0})_{AVG} V_{BO}]\} - 16.1 t^2 = 14493 + \{ 2 (367) (0.707) / [32.2 (0.001496) (0.349) (0.95)]\} \ln \{ 1 + 59 / \{ 2 (367) / [32.2 (0.001496) (0.349) (0.95) (1972)]\}\} - 16.1 (59)^2 = 0$ ft

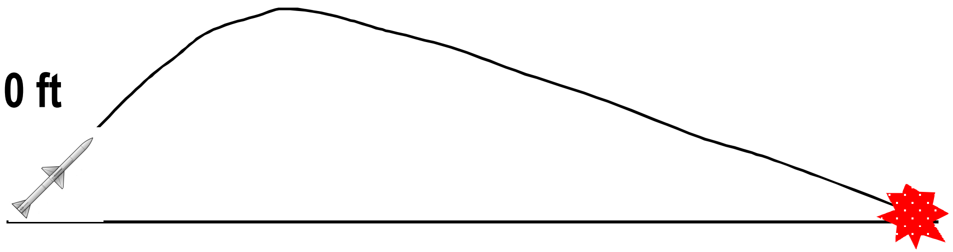
- **Total Time of Flight and Horizontal Range**

  $t = \Sigma\Delta t = \Delta t_{boost} + \Delta t_{sustain} + \Delta t_{ballistic} = 3.26 + 10.86 + 59 = 73$ sec

  $R_x = \Sigma\Delta R_x = \Delta R_{x,boost} + \Delta R_{x,sustain} + \Delta R_{x,ballistic} = 1598 + 12895 + 40991 = 55{,}894$ ft $= 9.2$ nm

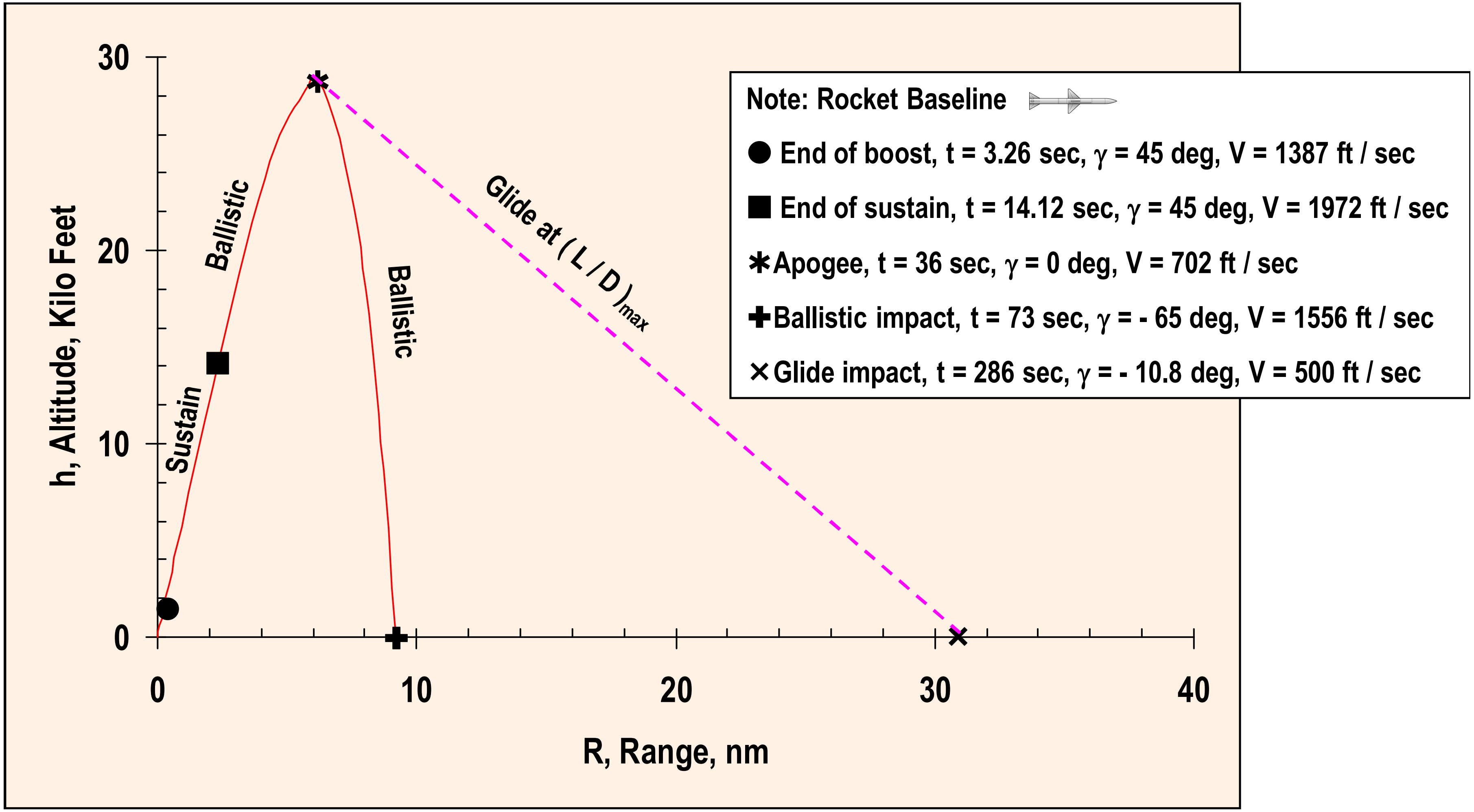
Boost Climb – Ballistic – Glide Trajectory Provides Extended Range

- Rocket Baseline @ γ_i = 45 deg, $h_i = h_f$ = 0 ft



- From Previous Example, the Boost Climb – Ballistic Conditions at Apogee are:
  - t = 36 sec
  - γ = 0 deg
  - V = 702 ft / sec
  - h = 28,994 ft
  - ΔR_x = 36,786 ft
  - q = 227 psf
  - M = 0.7
  - $(L / D)_{max}$ = 5.22
  - $\alpha_{(L / D)max}$ = 5.5 deg
- Incremental Horizontal Range During the $(L / D)_{max}$ Glide from Apogee to the Ground is given by
  - $\Delta R_x = (L / D) \Delta h = 5.22 (28994) = 151,349$ ft
- Total Horizontal Range for a Boost Climb – Ballistic – Glide Trajectory is
  - $R_x = \Sigma\Delta R_x = \Delta R_{x,BoostClimb\text{-}Ballistic} + \Delta R_{x,Glide} = 36786 + 151349 = 188,135$ ft = 31.0 nm

Glide at $(L / D)_{max}$ Provides Extended Range



Soda Straw Rocket Design, Build, and Fly

- Objective – Hands-on Learning of Rocket Physics Based on
  - Design
  - Build
  - Fly
- Furnished Property
  - 1 Launch System
  - 1 Target
  - 1 Weight Scale
- Furnished Material
  - 1 Soda Straw: ¼ in Inside Diameter by 11 in Length
  - 1 Strip Tabbing: ½ in by 6 in
  - 1 Tape Dispenser
  - 1 Wood Dowel: ¼ in Diameter by 1 in Length

Soda Straw Rocket (cont)

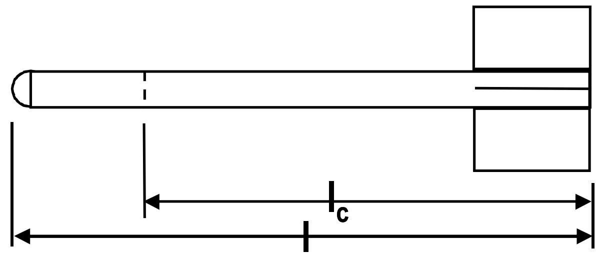
- Design – Soda Straw Rocket
  - Compatible with Furnished Property Launch System
    - Launch tube outside diameter: ¼ in
    - Launch tube length: 6 in
    - Launch static gauge pressure: up to 30 psi
  - Design Body and Tails for
    - Maximum flight range
    - Accurate and stable flight
  - Calculate Aerodynamic Drag Coefficient
    - Skin friction drag
    - Base drag
  - Calculate Thrust and Thrust Duration
  - Measure Weight
    - $\pm$ 0.1 gram accuracy
  - Predict Flight Range and Altitude for Proscribed
    - Launch pressure
    - Elevation angle

Soda Straw Rocket (cont)

- **Build - Soda Straw Rocket Using Either**
  - **Furnished Material**
  - **Or Can Use Own Material**
- **Fly - Soda Straw Rocket**
  - **Proscribed Target Location, Launch Location, Launch Pressure, and Launch Angle**
  - **Compare Flight Test Results for Alternative Concepts**
    - **Highest vertical location of impact**
    - **Smallest horizontal dispersal from impact aim point**
  - **Discuss Reasons for Performance of Alternative Concepts**

Example Baseline Configuration Geometry, Weight, and Balance

- **Example Baseline Configuration**
  - Diameter = d = ¼ in = 0.0208 ft
  - Outside Length = l = 5 in = 0.417 ft
  - Inside Cavity Length Available for Launch Tube = l_c = 4 in = 0.333 ft
  - Hemispherical Nose
  - Reference Area = $S_{Ref} = (\pi / 4)\, d^2 = 0.0491\ in^2 = 0.000341\ ft^2$
  - 4 Tail Panels (Cruciform Tails, $n_T = 2$)
    - Each tail panel ½ in by 1 in
    - Mean aerodynamic chord = c_{mac} = 1 in = 0.0833 ft
    - Exposed area of 2 tail panels = $S_T = 1\ in^2 = 0.00694\ ft^2$
    - Exposed aspect ratio of 2 tail panels = $A = b^2 / S_T = (1)^2 / (1) = 1.0$



- **Example Baseline Weight and Balance**
  - W = 1.9 gram = 0.0042 lb
  - $X_{cg} / l = 0.55$

Example Baseline Boost Performance

- During Boost, Thrust (T) Provided by Pressurized Launch Tube
  - $T = (p - p_0) A = p_{gauge} (1 - e^{-t/\tau}) A$
  - $A = S_{Ref} = 0.0491 \text{ in}^2$, τ = Rise Time to Open Valve
  - Assume $p_{gauge} = 20$ psi, $\tau = 0.2$ sec
  - $T = 20 (1 - e^{-t/0.2}) (0.0491) = 0.982 (1 - e^{-5.00 t})$
  - Actual Thrust Lower (Pressure Loss, Boundary Layer, Launch Tube Friction)
- Acceleration (a), Velocity (V), and Distance (s) During Boost
  - $a \approx 32.2\, T / W = 32.2 (0.982) (1 - e^{-5.00 t}) / 0.0042 = 7528.667 (1 - e^{-5.00 t})$
  - $V = 7528.667\, t + 1505.733\, e^{-5.00 t} - 1505.733$
  - $s = 3764.333\, t^2 - 301.147\, e^{-5.00 t} - 1505.733\, t + 301.147$
- End of Boost Conditions
  - $s = l_c = 0.333 \text{ ft} \Rightarrow t = 0.0382$ sec
  - $V = 25.8$ ft / sec
  - $q = ½ \rho V^2 = ½ (0.002378) (25.8)^2 = 0.791$ psf
  - $M = V / c = 25.8 / 1116 = 0.0231$

Example Baseline Drag Coefficient

- Total Drag Coefficient $C_{D_0} = (C_{D_0})_{Body} + (C_{D_0})_{Tail}$
  - During Coast, $C_{D_0} = (C_{D_0})_{Body,Friction} + (C_{D_0})_{Base,Coast} + (C_{D_0})_{Tail,Friction} = 0.053 (l / d) [M / (q l)]^{0.2} + 0.12 + n_T \{ 0.0133 [M / (q c_{mac})]^{0.2} \} (2 S_T / S_{Ref})$
  - $C_{D_0} = 0.053 (20) \{ 0.0231 / [(0.791)(0.417)]\}^{0.2} + 0.12 + 2 \{ 0.0133 \{ 0.0231 / [(0.791)(0.0833)]\}^{0.2} \} [2 (0.00694) / 0.000341)] = 0.62 + 0.12 + 0.88 = 1.62$
- Above Drag Coefficient Not Exact
  - Based on Assumption of Turbulent Boundary Layer
  - Soda Straw Rocket Is Small Size and Low Velocity $\Rightarrow$ Laminar Boundary Layer

Example Ballistic Flight Performance

- **Horizontal Range Equation**

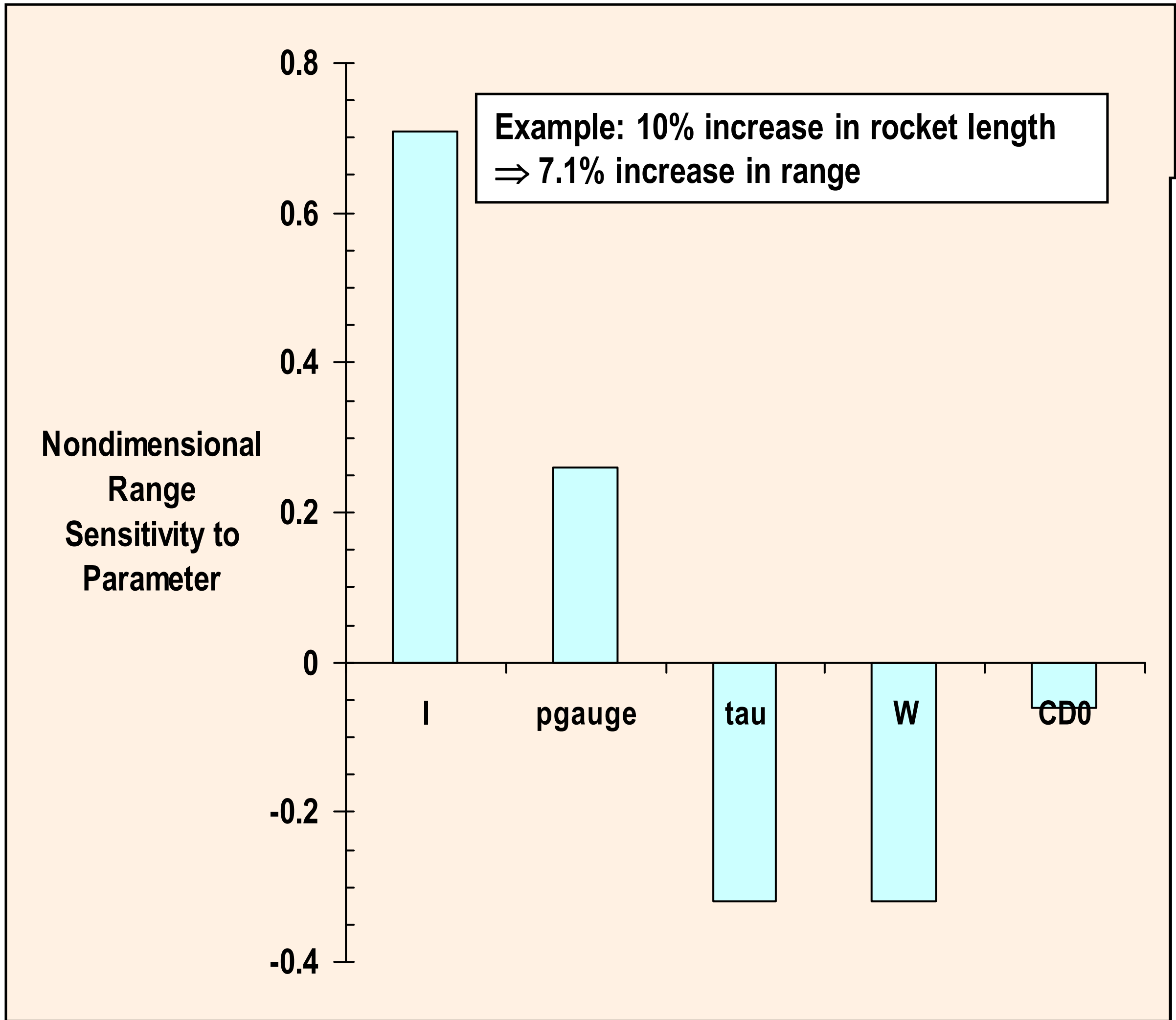
  $R_x = \{ 2 W \cos \gamma_i / [g_c \rho S_{Ref} C_{D_0}]\} \ln \{ 1 + t / \{ 2 W / [g_c \rho S_{Ref} C_{D_0} V_i]\} = \{ 2 (0.0042) \cos \gamma_i / [32.2 (0.002378) (0.000341) (1.62)]\} \ln \{ 1 + t / \{ 2 (0.0042) / [32.2 (0.002378) (0.000341) (1.62) (25.8)]\} = 199 \cos \gamma_i \ln (1 + 0.130 t)$

- **Height Equation**

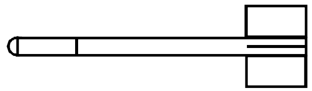
  $h = \{ 2 W \sin \gamma_i / [g_c \rho S_{Ref} C_{D_0}]\} \ln \{ 1 + t / \{ 2 W / [g_c \rho S_{Ref} C_{D_0} V_i]\} + h_i - g_c t^2 / 2 = \{ 2 (0.0042) \sin \gamma_i / [32.2 (0.002378) (0.000341) (1.62)\} \ln \{ 1 + t / \{ 2 (0.0042) / [32.2 (0.002378) (0.000341) (1.62) (25.8)]\} + h_i - 32.2 t^2 / 2 = 199 \sin \gamma_i \ln (1 + 0.130 t) + h_i - 32.2 t^2 / 2$

- **Assume γ_i = 45 deg, t = t_{impact} = 0.9 sec**
  - $R_x = 199 (0.707) \ln [1 + 0.130 (0.9)] = 15.5$ ft
  - $h = 199 (0.707) \ln [1 + 0.130 (0.9)] + h_i - 32.2 (0.9)^2 / 2 = h_i + 2.5$

Soda Straw Rocket Range Driven by Length, Gauge Pressure, Valve Open Time , and Weight



Note: Soda Straw Rocket Baseline:



W = Weight = 0.0042 lb

l = length = 5 in

τ = Time constant to open valve = 0.2 sec

p_{gauge} = gauge pressure = 20 psi

V = Launch Velocity = 25.8 fps

C_{D_0} = Zero-lift drag coefficient = 1.62

γ_i = Initial flight path angle = 45 deg

t_{impact} = Time from launch to impact = 0.9 sec

R_x = Horizontal range = 15.5 ft

Outline

- Examples of Parameters and Technologies That Drive Missile Flight Performance
- Missile Flight Performance Prediction
- Examples of Maximizing Missile Flight Performance (Workshop)
- Summary

Summary

- Flight Performance Analysis Activity in Missile Design and Analysis
  - Compute Range, Velocity, Time-to-Target, Off Boresight
  - Compare with Requirements and Data
- Maximizing Flight Performance Strongly Impacted by
  - Aerodynamics
  - Propulsion
  - Weight
  - Flight Trajectory
- Lecture Topics
  - Aerodynamics Parameters, Prediction and Technologies
    - Drag Coefficient
    - Normal Force Coefficient
  - Propulsion Parameters, Prediction, and Technologies
    - Thrust
    - Specific Impulse

Summary (cont)

- Lecture Topics (continued)
  - Flight Performance Parameters and Technologies
    - Cruise Range
    - High Density Fuel and Packaging
    - Flight Trajectory Shaping
    - Range Sensitivity to Driving Parameters
    - Missile Follow-on Programs
    - Examples of State-of-the-Art Advancements
    - Summary of New Technologies
  - Flight Performance Envelope
  - Videos of Flight Performance
  - Modeling of Degrees of Freedom
  - Equations of Motion and Flight Performance Drivers
  - Steady State Flight Relationships
  - Flight Performance Prediction
    - Steady Climb and Steady Dive Range Prediction
    - Cruise Prediction

Summary (cont)

- Lecture Topics (continued)
  - Flight Performance Prediction (continued)
    - Boost Prediction
    - Coast Prediction
    - Ballistic Flight Prediction
    - Turn Prediction
  - Target Lead for Proportional Homing Guidance
  - Tactical Missile Design Spreadsheet
- Workshop Examples
  - Rocket Boost-Coast Range
  - Rocket Maneuverability
  - Rocket Ballistic Range
  - Rocket Trajectory Optimization
  - Soda Straw Rocket Design, Build, and Fly

Configuration Sizing Criteria for Maximizing Flight Performance

♦ Body Fineness Ratio	$5 < l / d < 25$
♦ Nose Fineness Ratio	$l_N / d \approx 2$ if $M > 1$
♦ Efficient Cruise Dynamic Pressure	$q < 700$ psf
♦ Missile Homing Velocity	$V_M / V_T > 1.5$
♦ Subsystems Packaging	Maximize available volume for fuel / propellant
♦ Trim Control Power	$\alpha / \delta > 1$
♦ Missile Maneuverability	$n_M / n_T > 3$

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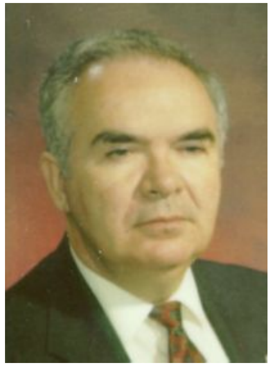
Follow-up Communication

I would appreciate receiving your comments and corrections on this text, as well as any data, examples, or references that you may offer.

Thank you,



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