AE 721 Aerospace Design Laboratory I

Missile Design I

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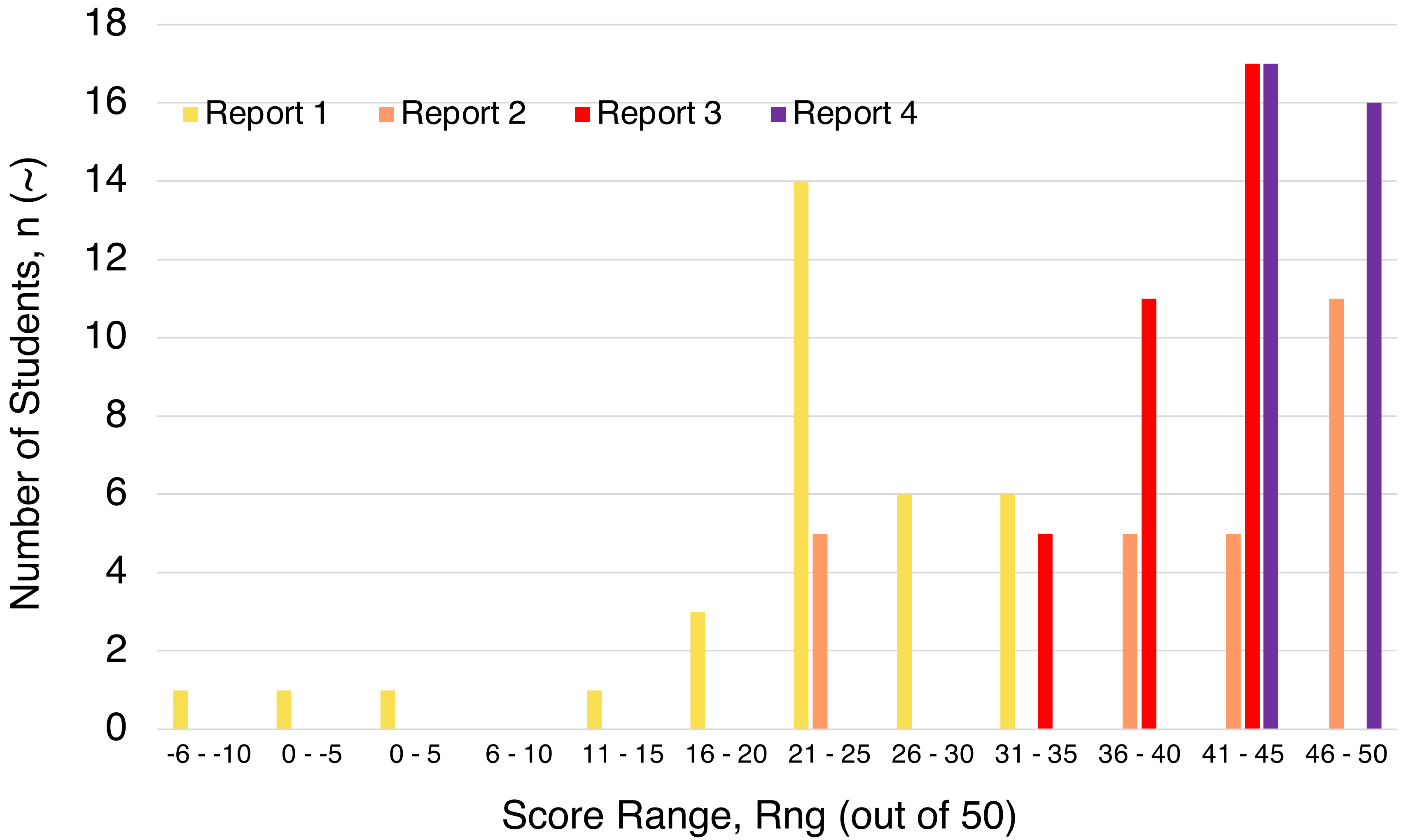
Monday
9 October

Today's Schedule:

- Call roll
- Report 4
- Reading Assignment: Chapter 2 Fleeman
- Fleeman
- Reverse Engineering Methods
- Proverse Engineering of RAIDERs

AE 721 Report Scores

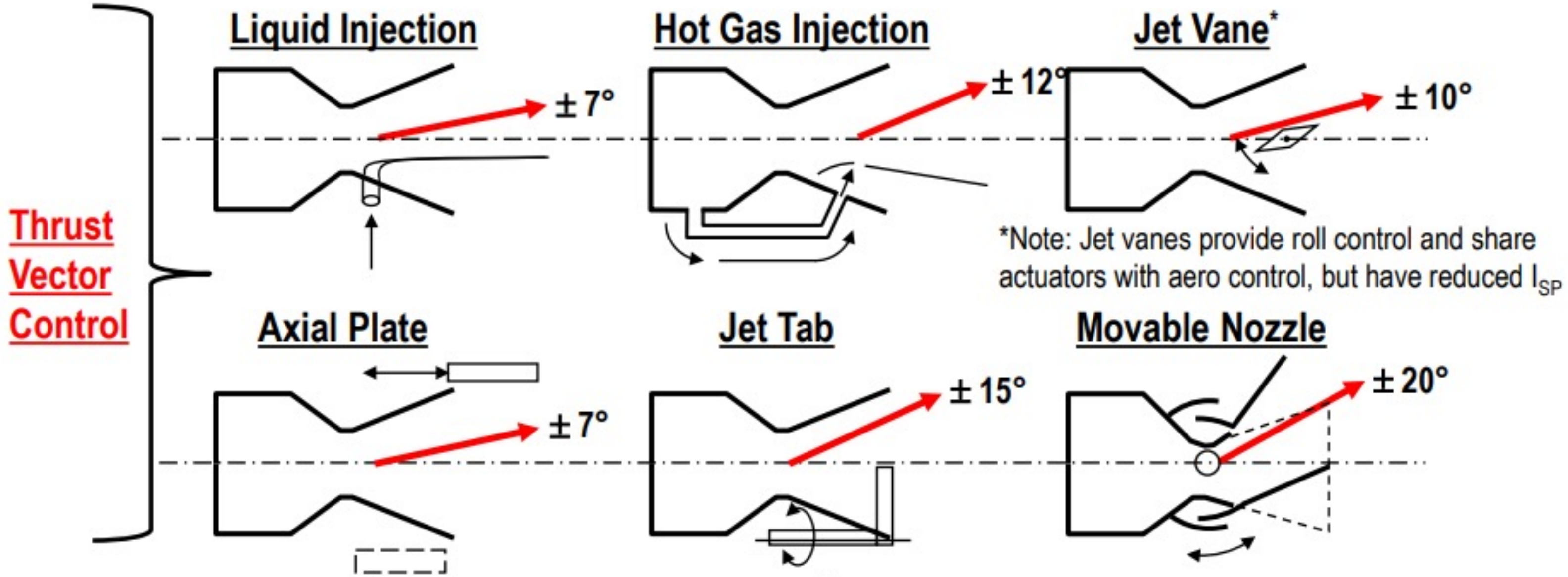


AE 721 Quiz Team Rosters

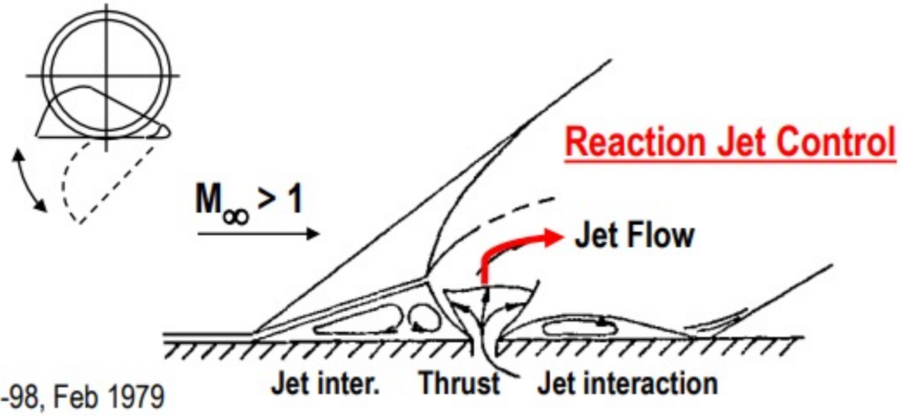
Student	Team
Dargahi,Alex	1
Deng,Keyu	1
Junnare,Nupoor	1
Shah,Dhairya	1
Thorson,Johnathan A	1
Barland,Jack A	2
Dillon,Peter	2
Dodge,Andrew	2
Guzman,Jonathan Alan	2
Mistretta,Anthony J	2
Svoboda,Benjamin C	2
Horst,Evelyn	3
Hunt,Wesley Afra	3
King,Kathryn M	3
Mcmichael,Barrett	3
Waggoner,Alex	3
Wegiel,Jeremy L	3

Student	Team
Braaten,Niels C	6
Dutta,Sap	6
Larsen,Isaac	6
Platt,Charlie M	6
Wall,James Edgar	6
Foster,Dean C	7
Heide,Rhett Gile	7
Marshall,Jeb O	7
Olson,Kadin Lee	7
Russell,Lucas S	7
Ativie,Joseph	8
Kuligowski,Payton M	8
Poznanski,Joshua	8
Richardson,Jake	8
Schneider,Cade W	8
Torres Leon,Hector	8

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



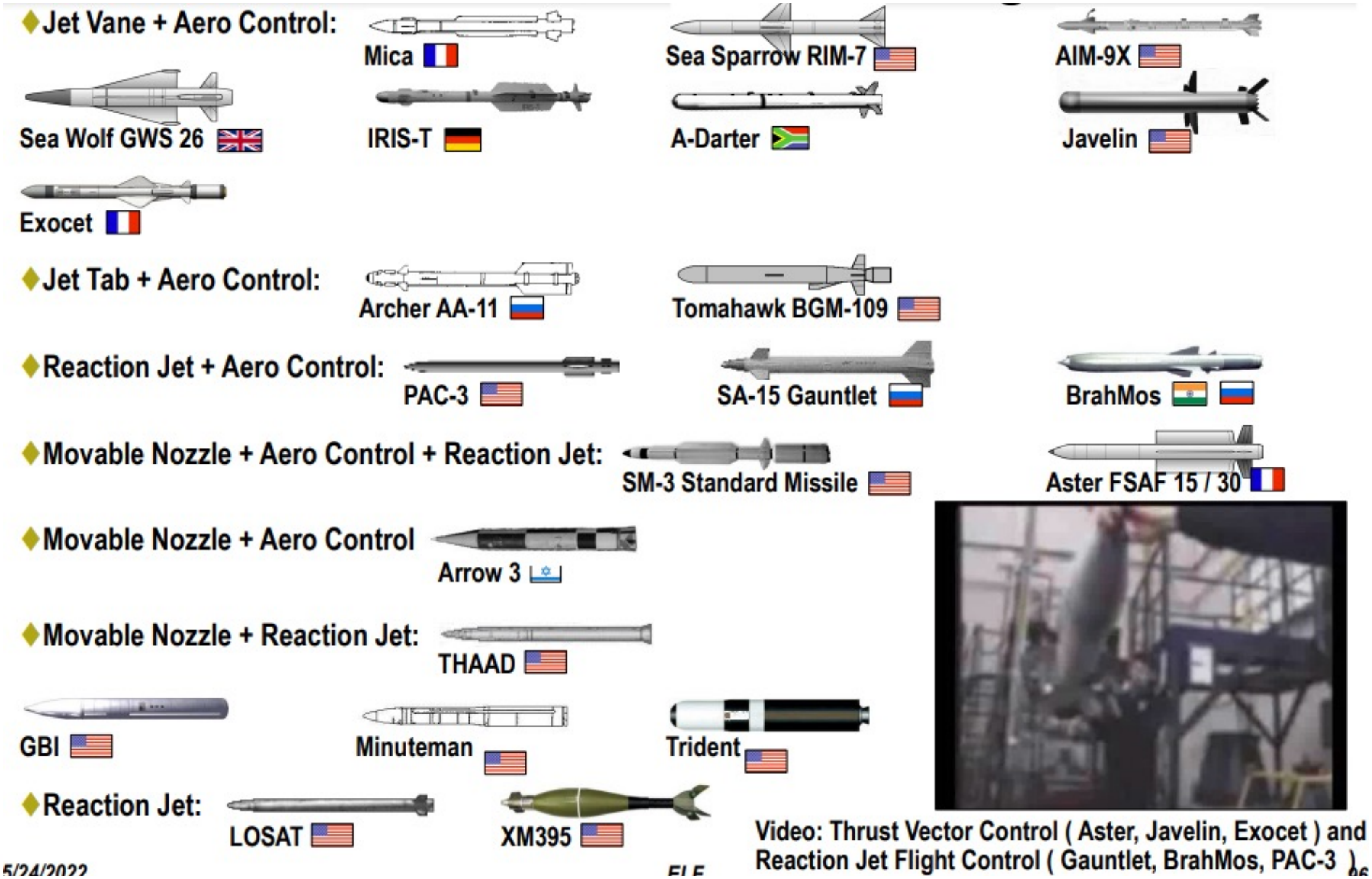
*Note: Jet vanes provide roll control and share actuators with aero control, but have reduced I_{SP}



- •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

Source: Brebner, G. G., "The Control of Missiles," AGARD-LS-98, Feb 1979

Most Missiles with TVC or Reaction Jet Flight Control Also Use Aerodynamic Flight Control



◆ **Jet Vane + Aero Control:**
- Mica
- Sea Sparrow RIM-7
- AIM-9X
- Sea Wolf GWS 26
- IRIS-T
- A-Darter
- Javelin
- Exocet

◆ **Jet Tab + Aero Control:**
- Archer AA-11
- Tomahawk BGM-109

◆ **Reaction Jet + Aero Control:**
- PAC-3
- SA-15 Gauntlet
- BrahMos

◆ **Movable Nozzle + Aero Control + Reaction Jet:**
- SM-3 Standard Missile
- Aster FSAF 15 / 30

◆ **Movable Nozzle + Aero Control**
- Arrow 3

◆ **Movable Nozzle + Reaction Jet:**
- THAAD
- GBI
- Minuteman
- Trident

◆ **Reaction Jet:**
- LOSAT
- XM395

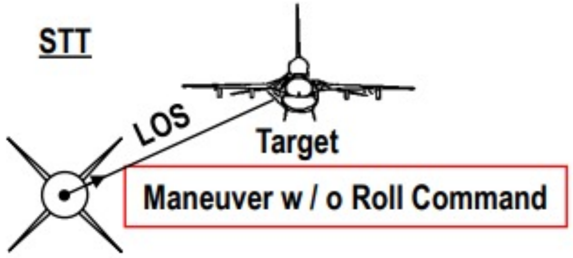
Video: Thrust Vector Control (Aster, Javelin, Exocet) and Reaction Jet Flight Control (Gauntlet, BrahMos, PAC-3)

5/24/2022

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

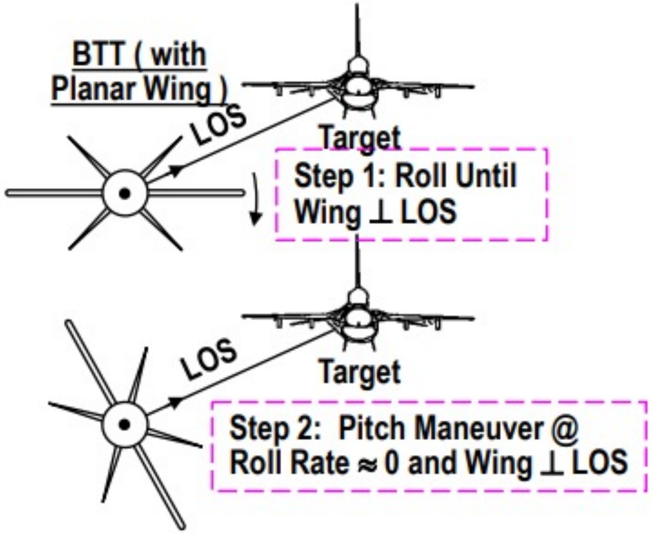
Skid-To-Turn (STT)

- Advantage ☺: Fast response
- Disadvantage ☹: Usually limited to axisymmetric cruciform missiles with low aspect ratio
- Feature:
  - Usually small roll attitude / rate commands from autopilot



Bank-To-Turn (BTT)

- Advantage ☺: 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

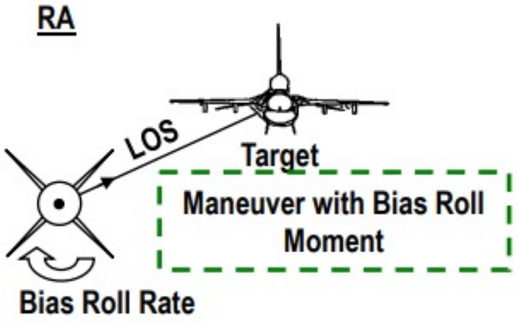


Note: LOS is line-of-sight

Skid-to-Turn is the Most Common Maneuver Law for Missiles (cont)

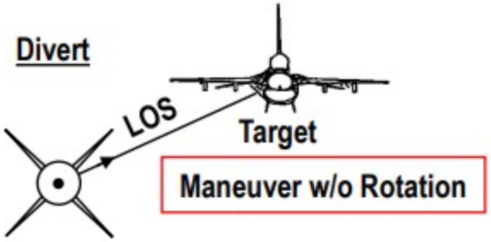
Rolling Airframe (RA)

- Advantages ☺:
  - Requires fewer gyros / accelerometers / actuators
  - Compatible with rosette scan / pseudo Image seeker
- 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
  - Induces radial stress
  - Thrust varies with roll rate
- Features
  - Bias roll rate (~ 10 Hz) from bias roll moment
  - Can use "bang-bang" / impulse steering
  - Compensates for thrust offset



Divert

- Advantages ☺:
  - Lower time constant
  - Less effect of radome error slope
  - Often has smaller miss distance
- Disadvantages ☹:
  - Usually higher cost
  - May not provide sufficient maneuverability
- Features
  - Direct lift / side force w/o rotation
  - Either wing, blended canard – tail, or divert reaction jet control



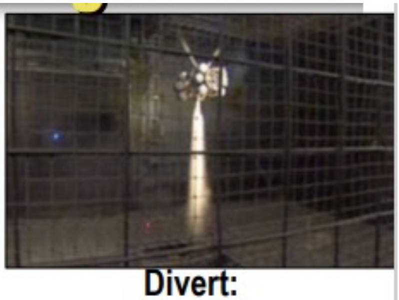
Note: LOS is line-of-sight

Examples of Skid-to-Turn, Bank-to-Turn, Rolling Airframe, and Divert Maneuvering

Skid-To-Turn (STT):
Sea Sparrow

Bank-to-Turn (BTT):
JASSM

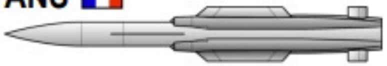
Rolling Airframe (RA):
SeaRAM



Divert:
MKV

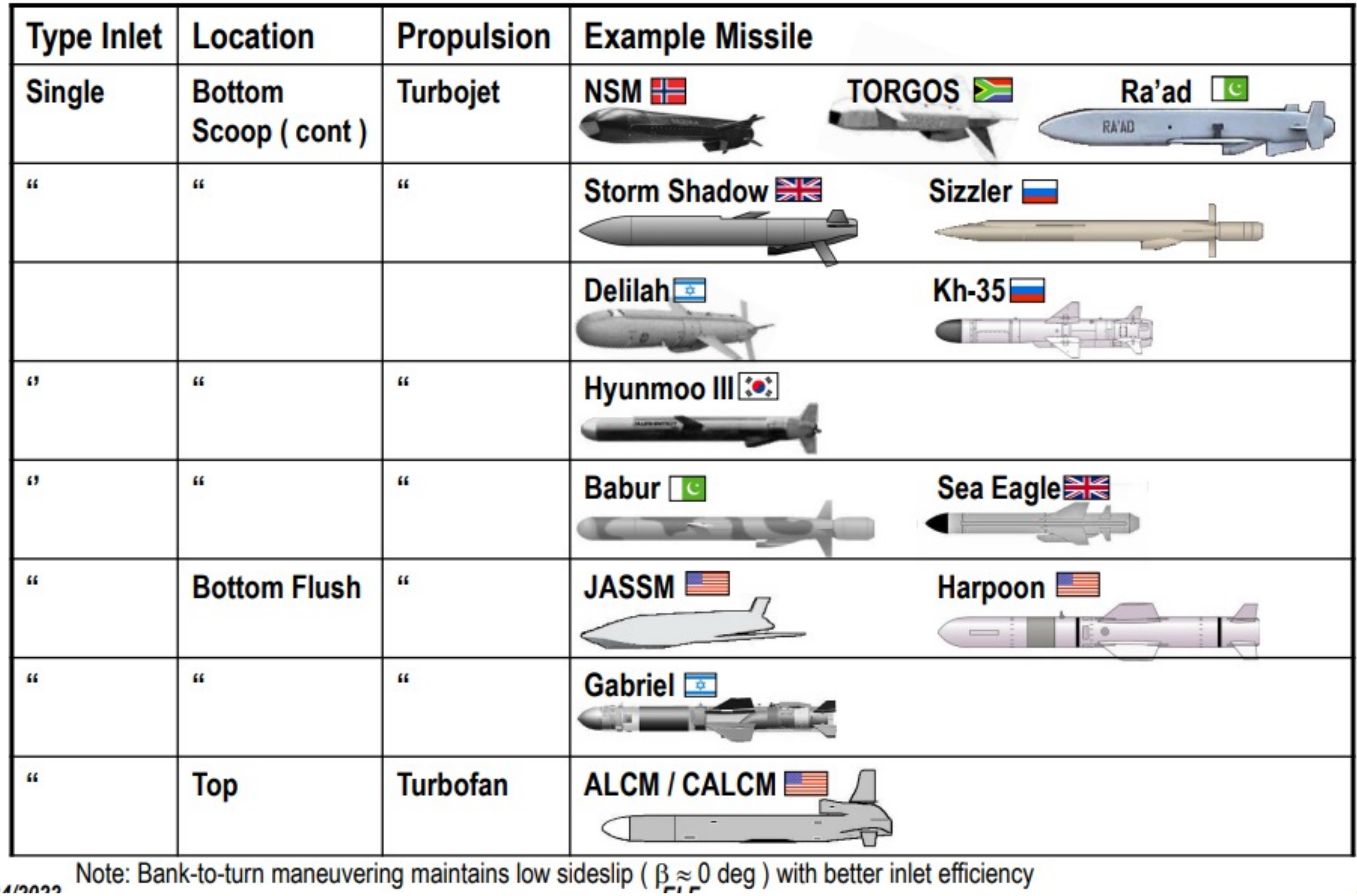
https://www.youtube.com/watch?v=KWA0EcVvgtk

Non-Cruciform Inlets Require Bank-to-Turn Maneuvering

Type Inlet	Location	Propulsion	Example Missile
Twin	Side	Ramjet	ASMP 🇫🇷  ANS 🇫🇷 
"	"	"	C-101 🇨🇳  C-301 🇨🇳 
"	"	Turbojet	Taurus KEPD-350 🇩🇪 🇸🇪 
"	Cheek	Ducted Rocket	HSAD 🇺🇸  Meteor 🇬🇧 
Single	Bottom Scoop	Scramjet	X-51 SED 🇺🇸 
"	"	Ramjet	ASALM 🇺🇸 
"	"	Turbojet	Tomahawk 🇺🇸  RBS-15 🇸🇪  SOM 🇹🇷 

Note: Bank-to-turn maneuvering maintains low sideslip ($\beta \approx 0$ deg) with better inlet efficiency

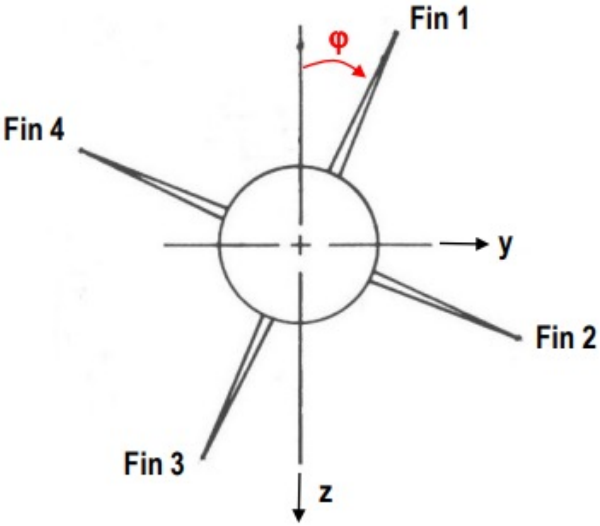
Non-Cruciform Inlets Require Bank-to-Turn Maneuvering (cont)



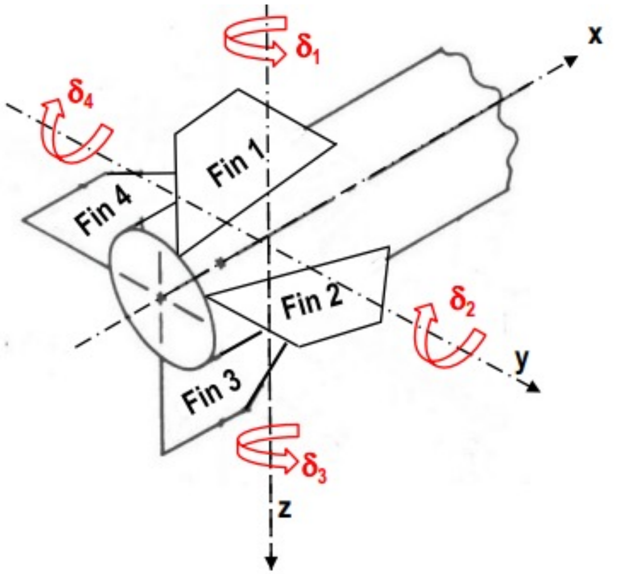
Type Inlet	Location	Propulsion	Example Missile
Single	Bottom Scoop (cont)	Turbojet	NSM 🇳🇴 TORGOS 🇿🇦 Ra’ad 🇵🇰
“	“	“	Storm Shadow 🇬🇧 Sizzler 🇷🇺
			Delilah 🇮🇱 Kh-35 🇷🇺
“	“	“	Hyunmoo III 🇰🇷
“	“	“	Babur 🇵🇰 Sea Eagle 🇬🇧
“	Bottom Flush	“	JASSM 🇺🇸 Harpoon 🇺🇸
“	“	“	Gabriel 🇮🇱
“	Top	Turbofan	ALCM / CALCM 🇺🇸

Note: Bank-to-turn maneuvering maintains low sideslip ($\beta \approx 0$ deg) with better inlet efficiency

Typical Sign Convention for Cruciform Missile Roll Angle and Flight Control Surface Deflection



+ φ looking forward from base



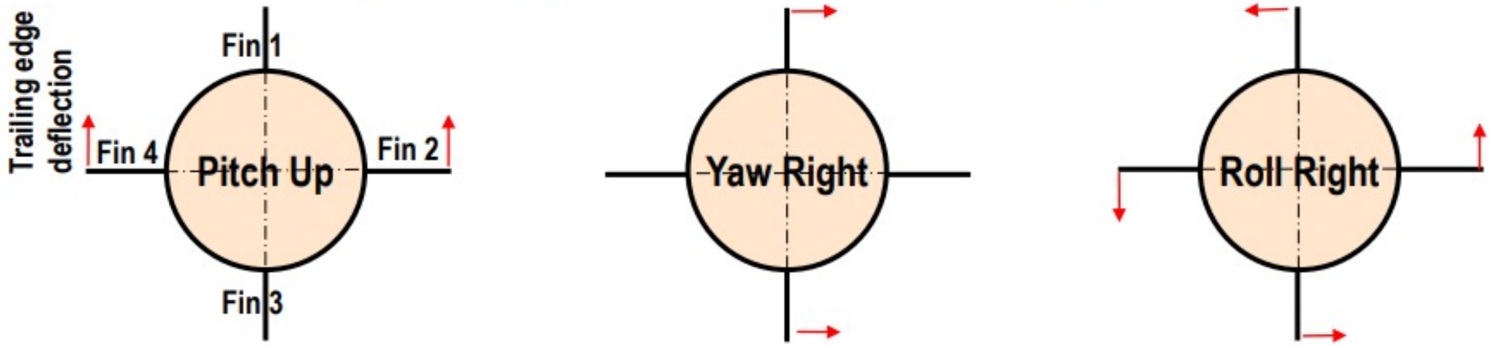
Fins 1 and 3 have trailing edge right for + deflection
Fins 2 and 4 have trailing edge up for + deflection
In above figure Fins 1 and 2 have + deflection

δ_e = Equivalent elevator deflection (+ δ_e produces + (up) pitching moment) = $[(\delta_2 + \delta_4)/2] \cos\varphi - [(\delta_1 + \delta_3)/2] \sin\varphi$
δ_r = Equivalent rudder deflection (+ δ_r produces + (right) yawing moment) = $[(\delta_2 + \delta_4)/2] \sin\varphi + [(\delta_1 + \delta_3)/2] \cos\varphi$
δ_a = Equivalent aileron deflection (+ δ_a produces + (clockwise) rolling moment) = $(\delta_2 + \delta_3 - \delta_1 - \delta_4)/4$

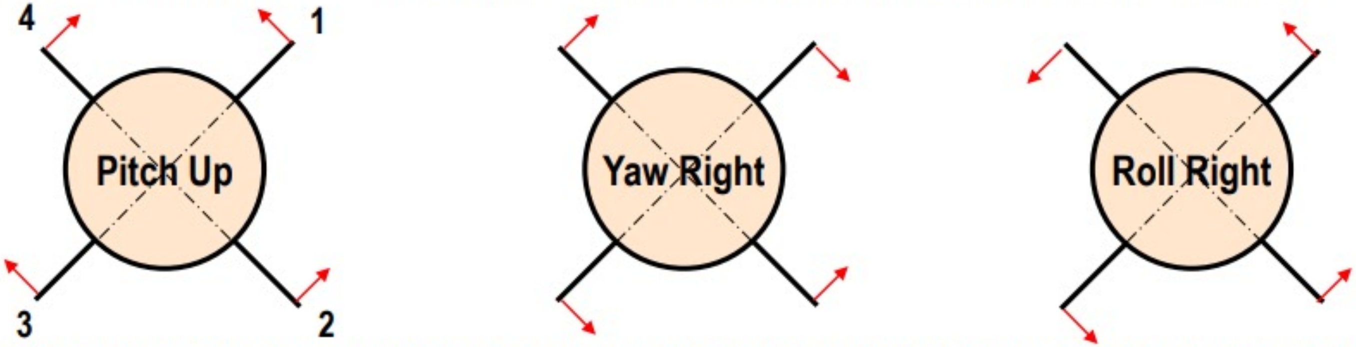
Note: For minimum total fin deflection (⇨ lowest total hinge moment, lowest drag, highest control effectiveness):
$\delta_1 = \delta_r - \delta_a$, $\delta_2 = \delta_e + \delta_a$, $\delta_3 = \delta_r + \delta_a$, $\delta_4 = \delta_e - \delta_a$

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

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



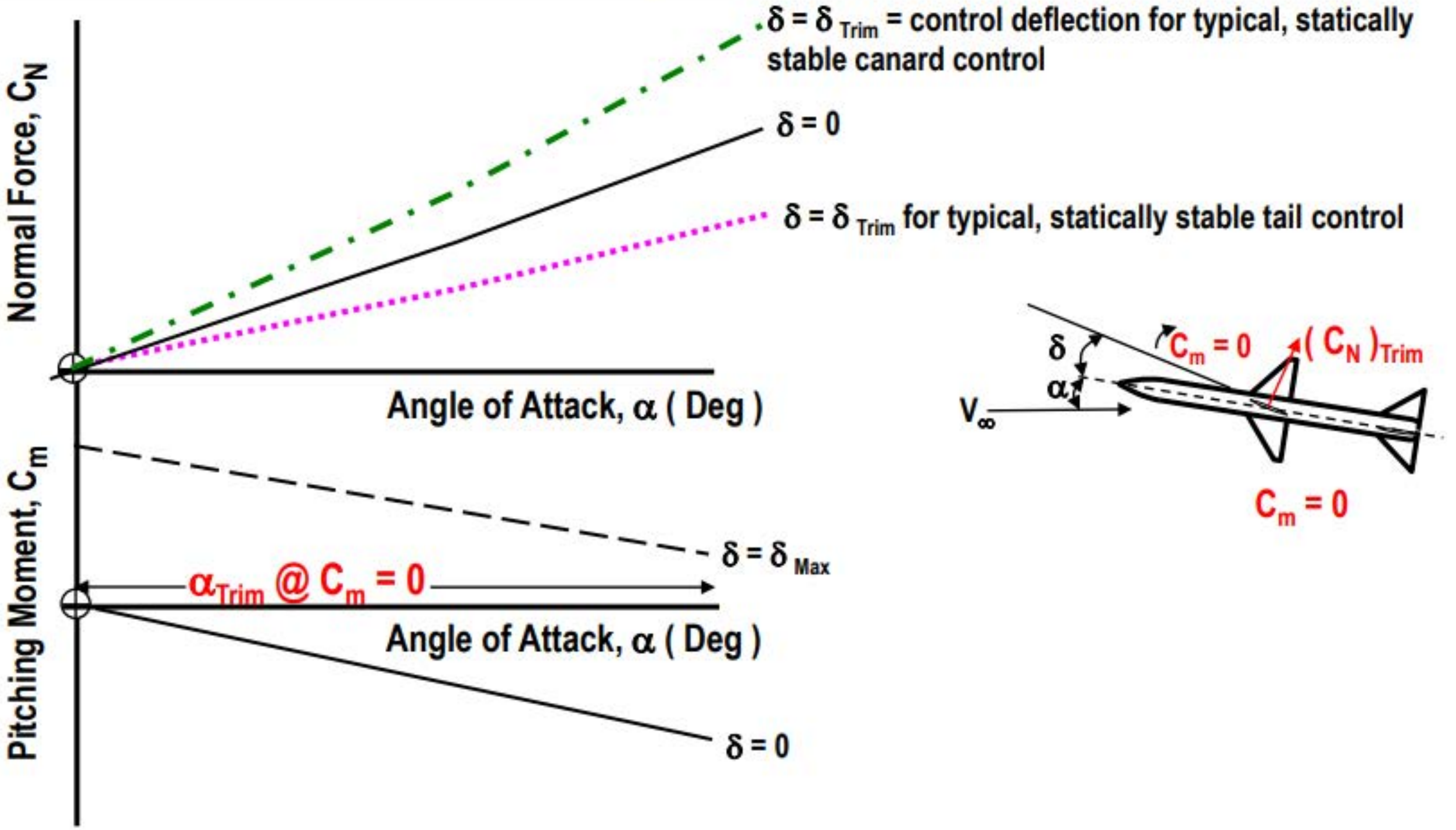
X Roll Orientation ($\varphi = 45$ deg), Cruciform Tail Control, Looking Forward from Base



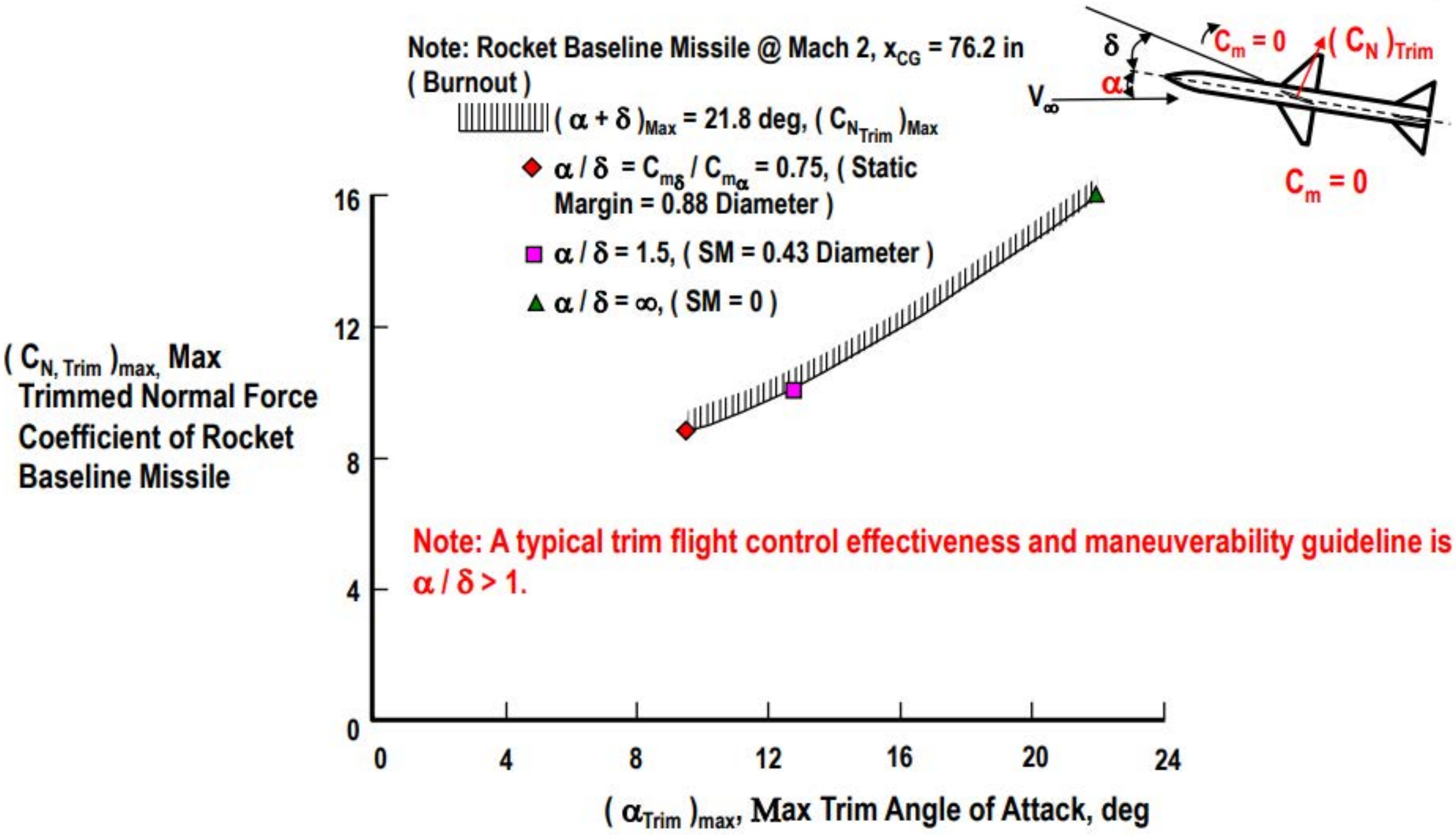
Note: + roll orientation sometimes has lower trim drag and less static stability and control effectiveness in pitch and yaw. + roll often has statically unstable roll moment derivative ($C_{l_\phi} > 0$) in supersonic flight.

X roll orientation usually has better launch platform compatibility, higher lift-to-drag ratio, 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.

Trimmed Normal Force is Defined at Zero Pitching Moment



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



Note: Rocket Baseline Missile @ Mach 2, $x_{CG} = 76.2$ in (Burnout)

Note: A typical trim flight control effectiveness and maneuverability guideline is $\alpha / \delta > 1$.

Note: Based on Data of Chapter 7

SM = Static Margin = Distance Between Aerodynamic Center and Center of Gravity ($x_{AC} - x_{CG}$)

Relaxed Static Stability Margin Reduces Drag

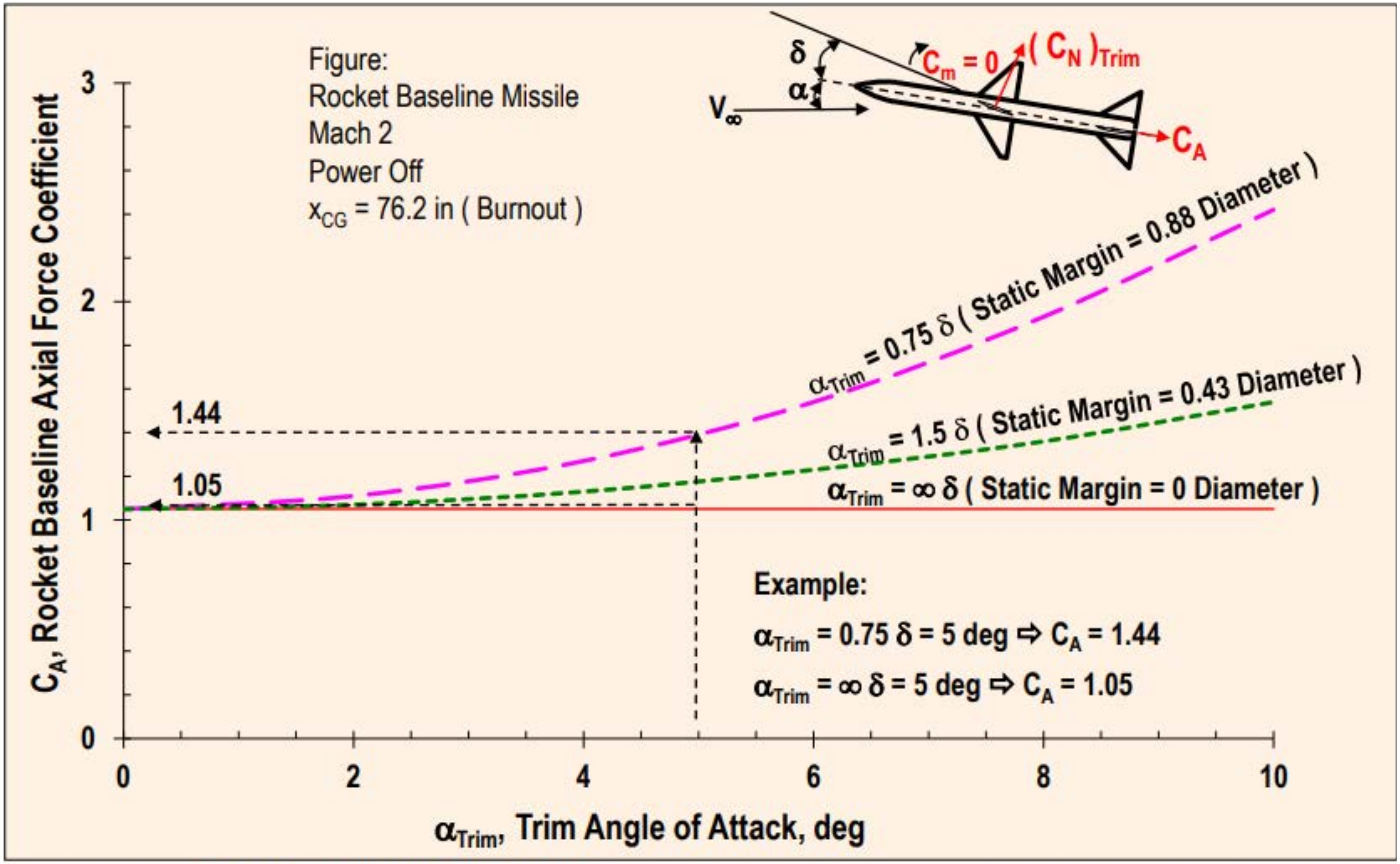


Figure:
Rocket Baseline Missile
Mach 2
Power Off
$x_{CG} = 76.2$ in (Burnout)

Example:

$\alpha_{Trim} = 0.75\ \delta = 5$ deg ⇨ $C_A = 1.44$

$\alpha_{Trim} = \infty\ \delta = 5$ deg ⇨ $C_A = 1.05$

Note: Based on Data of Chapter 7

.SM = Static Margin = Distance Between Aerodynamic Center and Center of Gravity ($x_{AC} - x_{CG}$)

Neutral Stability Tail Area with Mach

$$\frac{X_{AC}-X_{CG}}{d}=\frac{-(C_{N_\alpha})_B\dfrac{[X_{CG}-(X_{AC})_B]}{d}+(C_{N_\alpha})_W\dfrac{[X_{CG}-(X_{AC})_W]}{d}(S_W/S_{Ref})+(C_{N_\alpha})_T\dfrac{[X_{CG}-(X_{AC})_T]}{d}(S_T/S_{Ref})}{(C_{N_\alpha})_B+(C_{N_\alpha})_W\,S_W/S_{Ref}+(C_{N_\alpha})_T\,S_T/S_{Ref}}$$

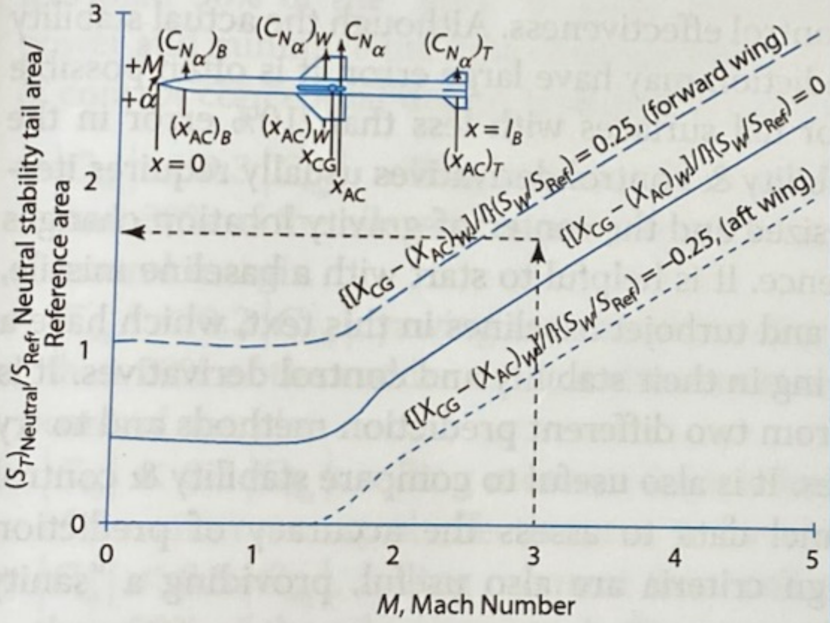


Fig. 2.60

Assumptions for figure ($X_{AC} = X_{CG}$):

- $X_{CG} \approx l/2$, $(X_{AC})_B \approx d$, $(X_{AC})_T \approx l - d$
- $\alpha < 6$ deg, turbulent boundary layer
- $(C_{N_\alpha})_B = 2$ per rad
- $(C_{N_\alpha})_T = (C_{N_\alpha})_W = 4/[M^2-1]^{1/2}$, if $M > \{1+[8/(\pi A)]^2\}^{1/2}$
- $(C_{N_\alpha})_T = (C_{N_\alpha})_W = \pi A/2$, if $A < 3$

and $M < \{1+[8/(\pi A)]^2\}^{1/2}$

Example Rocket Baseline: 

$l = 144$ in, $d = 8$ in, $S_W = 2.55$ ft^2, $S_{Ref} = 0.349$ ft^2, $A_W = 2.82$, $(C_{MAC})_W = 13.3$ in, $X_{MAC} = 67.0$ in from nose tip, burnout ($X_{CG} = 76.2$ in from tip), $M = M_{max} = 3$

$(X_{AC})_W = 0.49\ (13.3) = 6.5$ in from leading edge of MAC

$(X_{AC})_W = 6.5 + 67.0 = 73.5$ in from nose

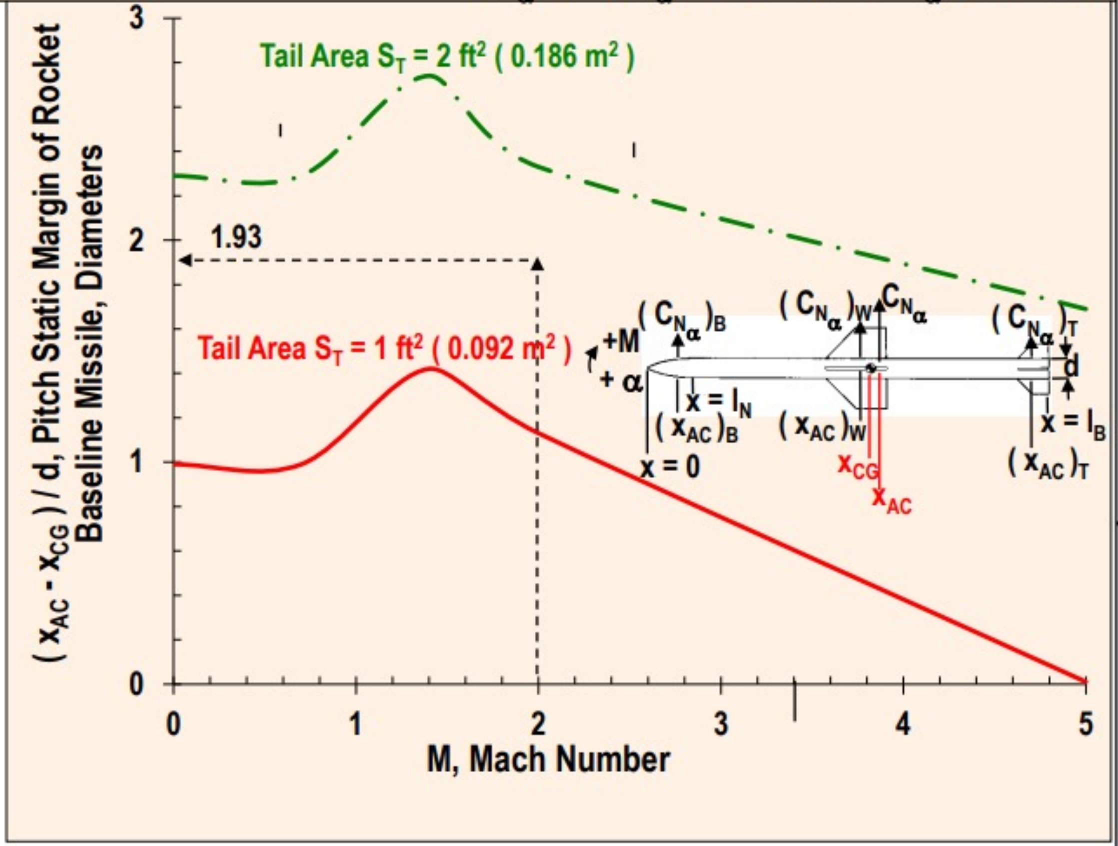
$\{[X_{CG}-(X_{AC})_W]/l\}(S_W/S_{Ref}) = 0.14$ (forward wing)

$(S_T)_{Neutral}/S_{Ref} = 1.69$ provides neutral stability

$(S_T)_{Neutral} = 1.69(0.349) = 0.59$ ft^2

Missile Static Margin is Driven by Tail Area and Static Margin Predicition Has Large Uncertainty

$$x_{AC} - x_{CG} \approx \frac{(C_{N_\alpha})_B[(x_{AC})_B - (x_{CG})] + (C_{N_\alpha})_W[(x_{AC})_W - (x_{CG})](S_W / S_{Ref}) + (C_{N_\alpha})_T[(x_{AC})_T - (x_{CG})](S_T / S_{Ref})}{(C_{N_\alpha})_B + (C_{N_\alpha})_W S_W / S_{Ref} + (C_{N_\alpha})_T S_T / S_{Ref}}$$



Assumptions for Figure:

Rocket Baseline Missile

Body length l = 144 in, Nose length l_N = 19.2 in, d = 8 in, Wing area S_W = 2.55 ft^2, Reference area S_{Ref} = 0.349 ft^2, A_W = 2.82, $(c_{MAC})_W$ = 13.3 in, Burnout x_{CG} = 76.2 in from tip, $\alpha < 6$ deg, turbulent boundary layer.

Using Simplified Prediction Methods:

$(C_{N_\alpha})_B = 2$ per rad, $(x_{AC})_B / l_N = 0.63$, $(C_{N_\alpha})_T = (C_{N_\alpha})_W = 4 / [M^2 - 1]^{1/2}$, if $M > \{1 + [8 / (\pi A)]^2\}^{1/2}$, $(C_{N_\alpha})_T = (C_{N_\alpha})_W = \pi A / 2$, if $A < 3$ and $M < \{1 + [8 / (\pi A)]^2\}^{1/2}$, $(x_{AC})_B = 0.63\, l_N$,

Example Rocket Baseline Tail (S_T = 1.54 ft^2), M = 2 :

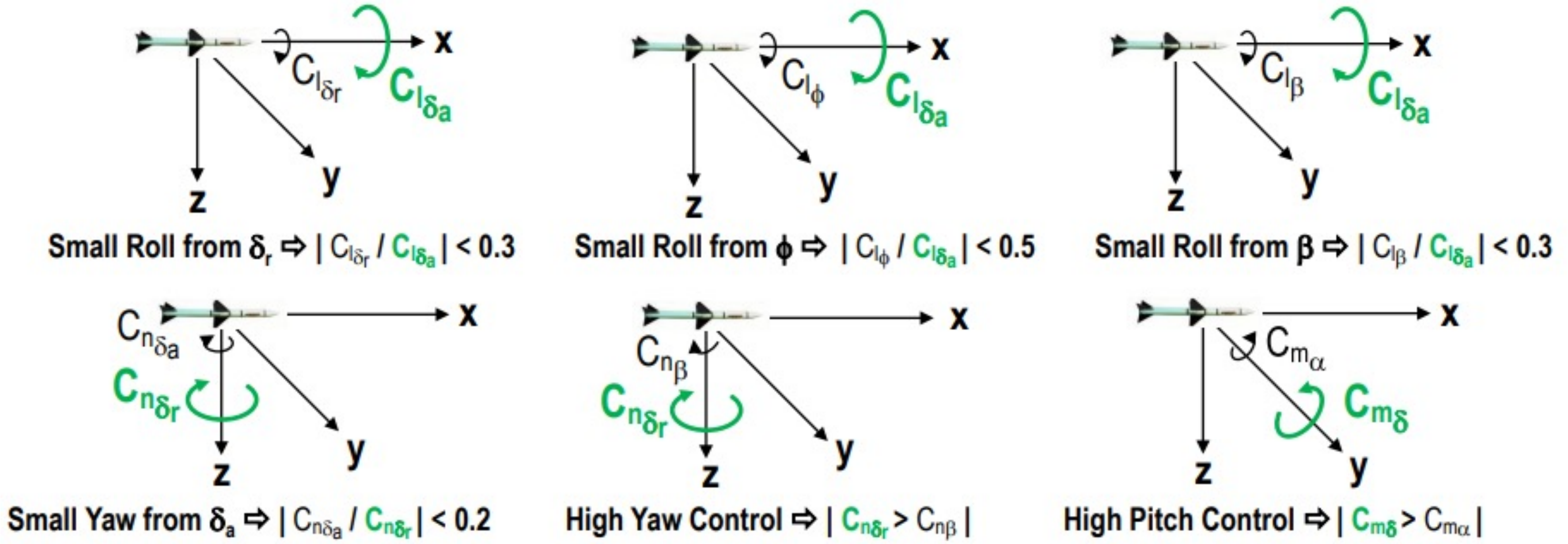
$(C_{N_\alpha})_T = (C_{N_\alpha})_W = 4 / [M^2 - 1]^{1/2} = 2.31$, $(x_{AC})_B / l = 0.084$, $(x_{AC})_W / l = 0.510$, $(x_{AC})_T / l = 0.955$

$(x_{AC} - x_{CG}) / d = 1.93$

From Chapter 7: $(x_{AC} - x_{CG}) / d = 0.88$

There is Typically Large Uncertainty in Conceptual Design Static Margin

Stability & Control Requires High Flight Control Effectiveness



Small Roll from δ_r ⇨ $| C_{l_{\delta_r}} / C_{l_{\delta_a}} | < 0.3$

Small Roll from ϕ ⇨ $| C_{l_\phi} / C_{l_{\delta_a}} | < 0.5$

Small Roll from β ⇨ $| C_{l_\beta} / C_{l_{\delta_a}} | < 0.3$

Small Yaw from δ_a ⇨ $| C_{n_{\delta_a}} / C_{n_{\delta_r}} | < 0.2$

High Yaw Control ⇨ $| C_{n_{\delta_r}} > C_{n_\beta} |$

High Pitch Control ⇨ $| C_{m_\delta} > C_{m_\alpha} |$

Stabilty & Control Cross Coupling is a Concern for Lifting Bodies (S&C Cross Coupling Often > 30%)

M2-F2 Lifting Body

X-24B Lifting Body

https://www.youtube.com/watch?v=QtO5eO9GqtM
https://www.youtube.com/watch?v=50dDWT48b9M

Wednesday
11 October

Today’s Schedule:

- Call roll
- Winners’ Prizes for last quiz
- Florida Trip Classes
- Symposium Attendance & Meals
- Reverse Engineering Methods
- Proverse Engineering of RAIDERs

Winners' Treasure!

	AE 721 Field Trip to Air Armament Symposium November 2023	Conflicting Classes	Not Going	Maybe Going	Going
1	Ativie,Joseph	?			x
2	Barland,Jack A	?			x
3	Bo Xu	?			x
4	Braaten,Niels C	?			x
5	Dillon,Peter	?			x
6	Dutta,Sap	?			x
7	Evelyn Horst	?			x
8	Foster,Dean C	?			x
9	Gerell Miller	?			x
10	Guzman,Jonathan Alan	?			x
11	Heide,Rhett Gile	?			x
12	Hunt,Wesley Afra	?			x
13	Jeremy Wegiel	?			x
14	Justin Clough	?			x
15	King,Kathryn M	?			x
16	Kuligowski,Payton M	?			x
17	Larsen,Isaac	?			x
18	Marshall,Jeb O	?			x
19	Mcmichael,Barrett	?			x
20	Olson,Kadin Lee	?			x
21	Platt,Charlie M	?			x
22	Poznanski,Joshua	?			x
23	Richardson,Jake	?			x
24	Schneider,Cade W	?			x
25	Shanya Dorsey	?			x
26	Svoboda,Benjamin C	?			x
27	Waggoner,Alex	?			x
28	Wall,James Edgar	?			x
29	Dargahi,Alex			x	
30	Deng,Keyu			x	
31	Dodge,Andrew			x	
32	Junnare,Nupoor			x	
33	Mistretta,Anthony J		x		
34	Olivia Caudillo		x		
35	Russell,Lucas S		x		
36	Shah,Dhairya			x	
37	Thorson,Johnathan A		x		

Eglin AFB Loop

Friday 11/3 After Class Depart?
Saturday 11/4 En Route?
Sunday 11/5 En Route?
Monday 11/6 Setup & Secret Sessions
Tuesday 11/7 Symposium
Wednesday 11/8 Symposium
Thursday 11/9 USAF Armament Museum
Friday 11/10 Naval Air Museum, Pensacola
Saturday 11/11 Return
Sunday 11/12 Return

Improved Weapon Design with RAIDER Powerplant Configurations

Reverse Engineering of Baseline Missiles & Proverse Engineering of RAIDER Missiles

Improved Weapon Design with RAIDER Powerplant Configurations

1. Reverse Engineering

1.1 Get baseline missile data

1.2 Construct design Mission Profile

1.3 Assemble Payload-Range Diagram

1.4 Get Weight of Propellant

1.5 Approximate I_{sp} & TSFC

1.6 Estimate Time of Flight (TOF) with live engine

1.7 Update Mission Profile with derived values

1.8 Solve for mission L/D values

1.9 Solve for W_e/W_{launch}

1.10 Solve for Lift & Drag expressions with Mach

1.11 Solve for Mach and α at L/D Cruise

1.12 Solve for $C_{Lcruise}$, L/D_{cruise} and α_{cruise}

1.13 Solve for cruise mid-point air density

1.14 Find mid-cruise point altitude for standard atmosphere

1.15 Update Mission Profile to include mid-point cruise details

General Performance -- Reverse Engineering

Step 1 Get as much general information as possible

Air-to-Air Missile

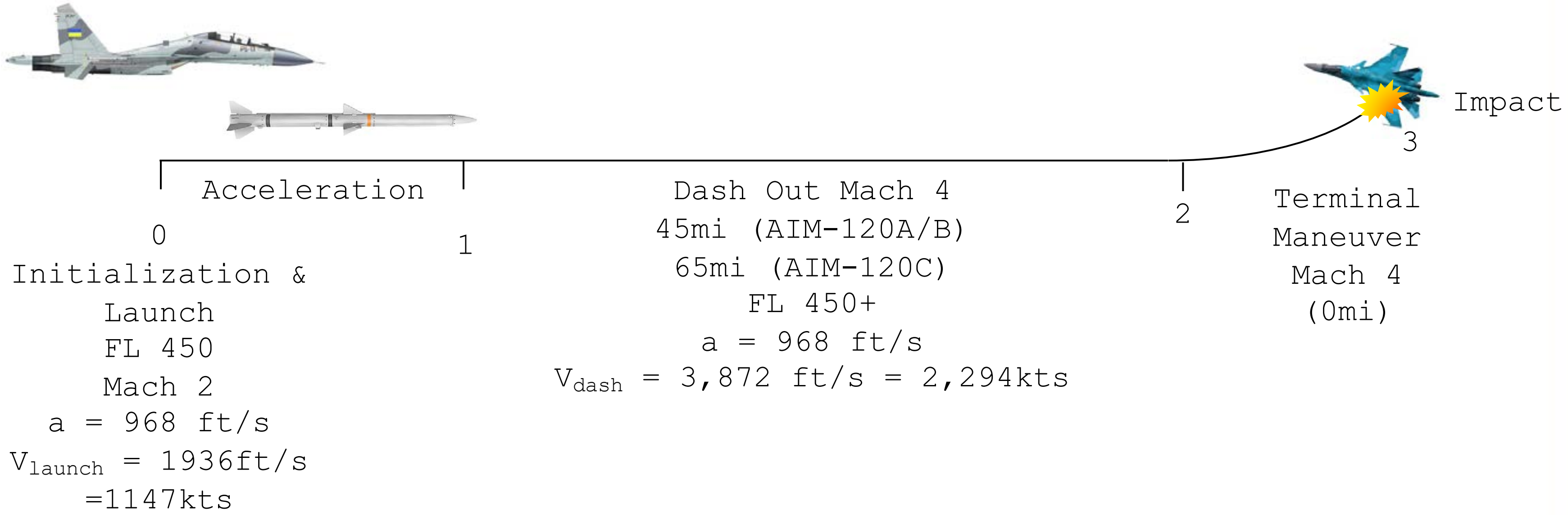
AIM-120 Example:

(from public sources)
https://www.designation-systems.net/dusrm/m-120.html

	AIM-120A/B	AIM-120C-5
Length	3.66 m (12 ft)	
Wingspan	53.3 cm (21 in)	44.7 cm (17.6 in)
Finspan	63.5 cm (25 in)	44.7 cm (17.6 in)
Diameter	17.8 cm (7 in)	
Weight	157 kg (345 lb)	
Speed	Mach 4	
Range	50-70 km (30-45 miles)	> 105 km (65 miles)
Propulsion	Hercules/Aerojet solid-fueled rocket	
Warhead	23 kg (50 lb) WDU-33/B blast-fragmentation	18 kg (40 lb) WDU-41/B blast-fragmentation
Max. Thrust	3,700lbf	

General Performance -- Reverse Engineering

Step 2 Construct Mission Profile



Acceleration

0
Initialization &
Launch
FL 450
Mach 2
$a = 968$ ft/s
$V_{launch} = 1936$ft/s
=1147kts

Dash Out Mach 4
45mi (AIM-120A/B)
65mi (AIM-120C)
FL 450+
$a = 968$ ft/s
$V_{dash} = 3{,}872$ ft/s = 2,294kts

Terminal
Maneuver
Mach 4
(0mi)

General Performance -- Reverse Engineering

Step 2 Construct Mission Profile

Acceleration

Dash Out Mach 4
45mi (AIM-120A/B)
65mi (AIM-120C)
FL 450+
a = 968 ft/s
V_{dash} = 3,872 ft/s = 2,294kts

2

Terminal
Maneuver
Mach 4
(0mi)

0
Initialization &
Launch
FL 450
Mach 2
a = 968 ft/s
V_{launch} = 1936ft/s
=1147kts

1

T_{max} ~ 3700 lbf
$A_{acceleration}$ = T/m = 3700lbf/345lbm ~ 11gs

Vo = 1936 ft/s
V1 = 3872 ft/s

General Performance -- Reverse Engineering

Step 2 Construct Mission Profile

0
Initialization &
Launch
FL 450
Mach 2
a = 968 ft/s
V_{launch} = 1936ft/s
=1147kts

Dash Out Mach 4
45mi (AIM-120A/B)
65mi (AIM-120C)
FL 450+
a = 968 ft/s
V_{dash} = 3,872 ft/s = 2,294kts

Terminal
Maneuver
Mach 4
(0mi)

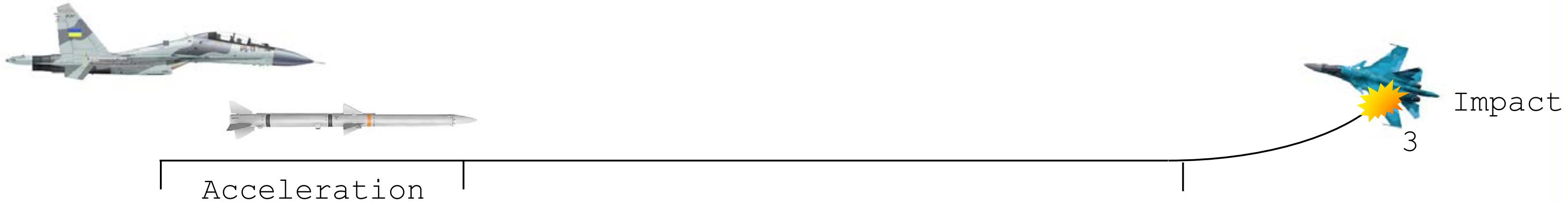
T_{max} ~ 3700 lbf
$A_{acceleration}$ = T/m = 3700lbf/345lbm ~ 11gs

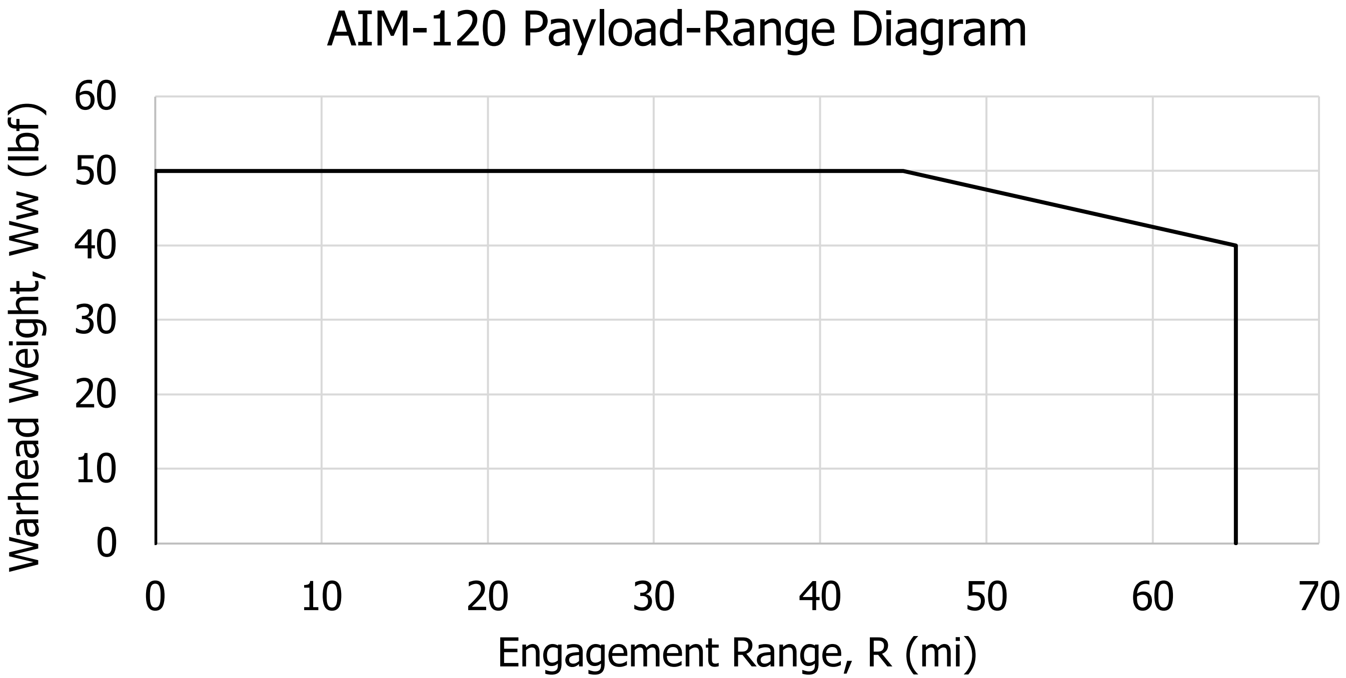
Vo = 1936 ft/s
V1 = 3872 ft/s

$$A_{acceleration} = \frac{dV}{dt} \therefore \ \Delta t \cong \frac{dV}{A_{acceleration}} = \frac{3872-1936\,ft/s}{11\times 32.2\,ft/s^2} = 5.46\text{s}$$

General Performance -- Reverse Engineering

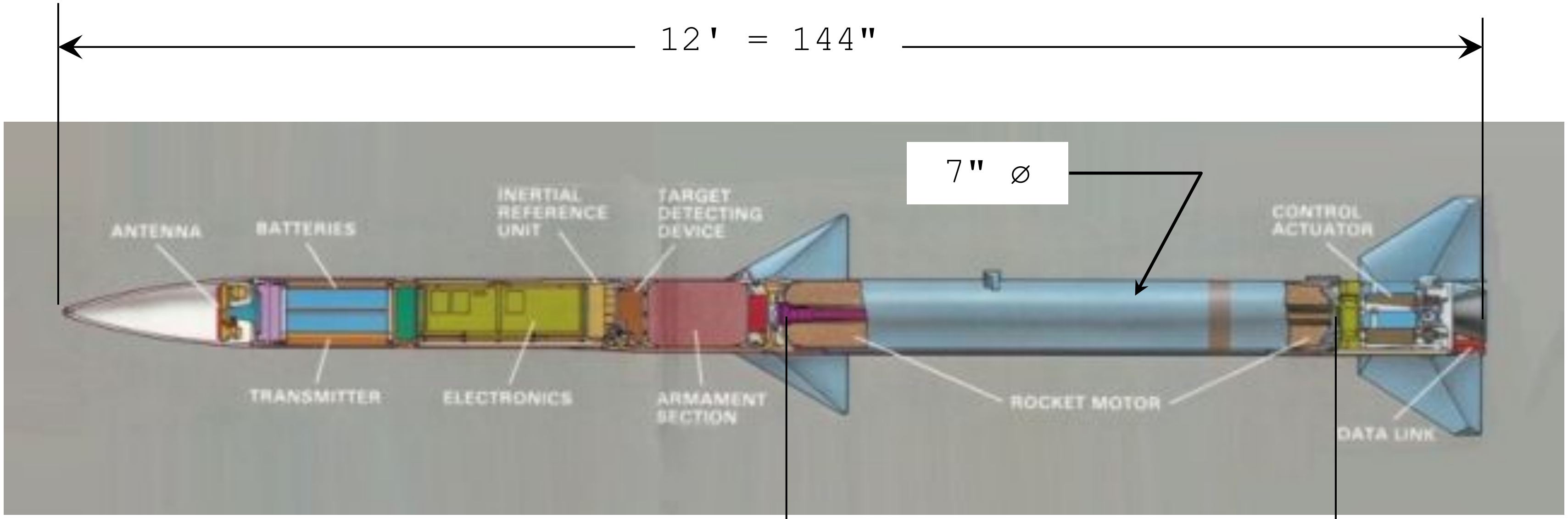
Step 3 Assemble Payload-Range Diagram





General Performance -- Reverse Engineering

Step 4 Get Approximate Weight of Propellant



By simple geometry:

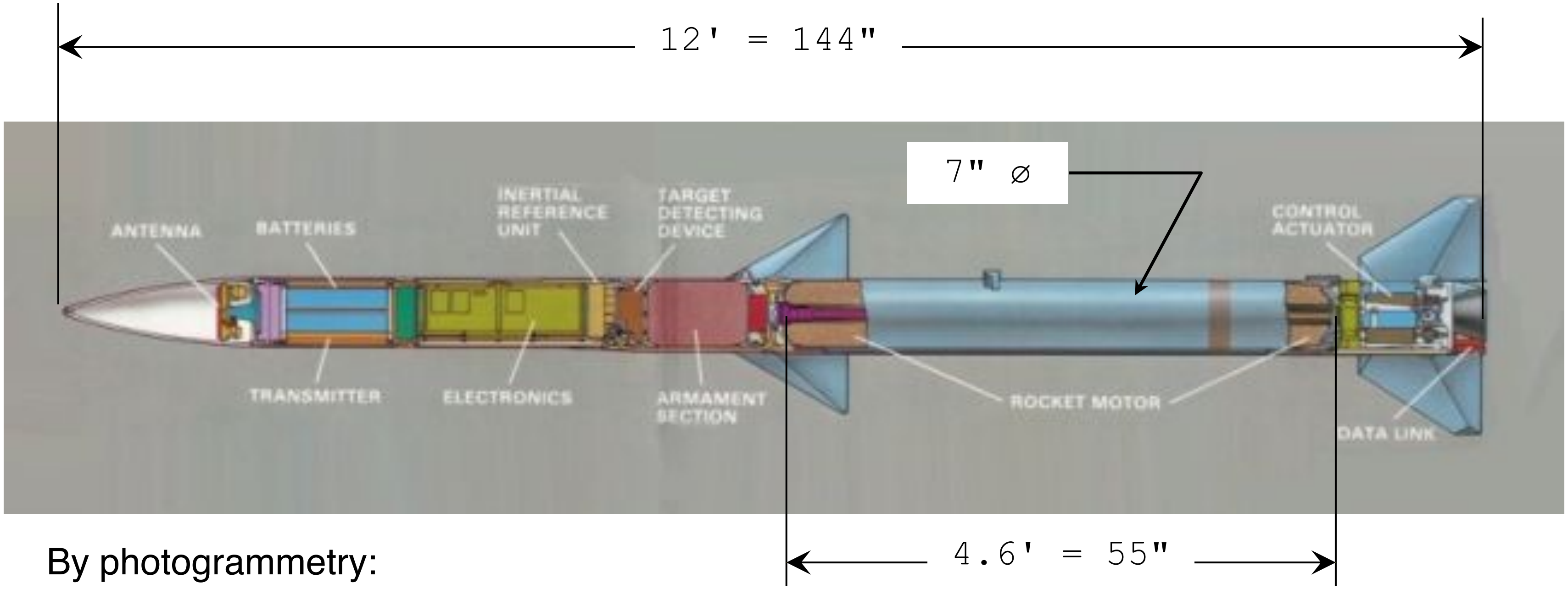
$L_{propellant} \sim$ 55"

$D_{opropellant} \sim$ 6.8"
$D_{ipropellant} \sim$ 1.5"

$$Vol \cong \pi \left(\frac{D_o^2 - D_i^2}{4}\right) L_{propellant} = \pi \left(\frac{6.8in^2 - 1.5in^2}{4}\right) 55" = 1900 in^3$$

General Performance -- Reverse Engineering

Step 4 Get Approximate Weight of Propellant



By photogrammetry:

$L_{propellant} \sim 55''$

$D_{opropellant} \sim 6.8''$
$D_{ipropellant} \sim 1.5''$

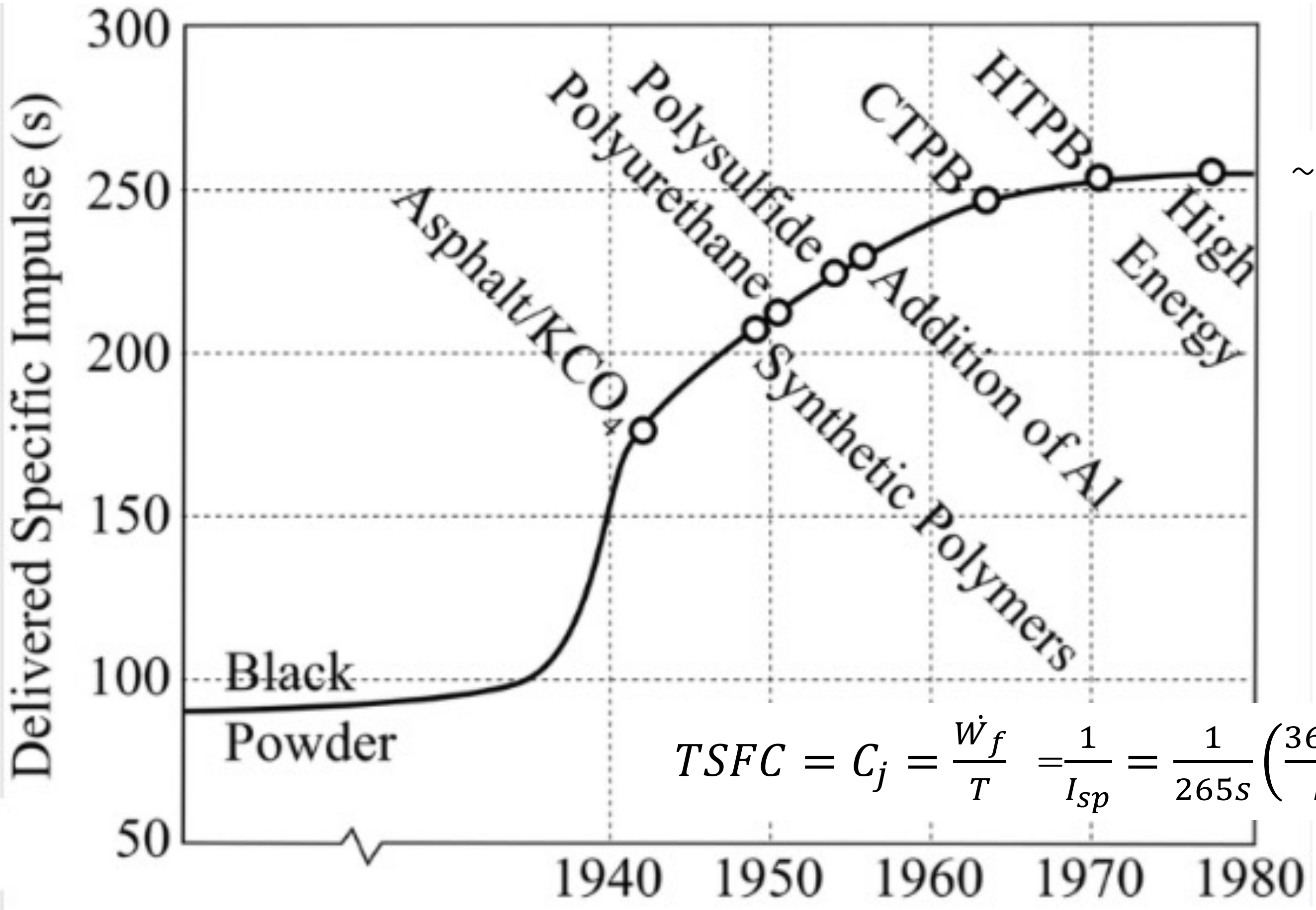
$$Vol \cong \pi\left(\frac{D_o^2 - D_i^2}{4}\right) L_{propellant} = \pi\left(\frac{6.8in^2 - 1.5in^2}{4}\right) 55'' = 1900in^3$$

$$W_{propellantA/B} \cong Vol * \rho = 0.058\left({}^{lb}/_{in^3}\right) 1900in^3 = 110lbf$$

$$W_{propellantC} \cong W_{propellantA/B} + 10lbf = 120lbf$$

General Performance -- Reverse Engineering

Step 5 Get Approximate Specific Impulse of Propellant & Convert



~ 265 s

$$TSFC = C_j = \frac{\dot{W}_f}{T} = \frac{1}{I_{sp}} = \frac{1}{265s}\left(\frac{3600s}{hr}\right) = 13.6\,\frac{lbf}{lbf-hr}$$

General Performance -- Reverse Engineering

Step 6 Estimate Time of Flight (TOF) with Live Engine @ Max. Thrust

$$TSFC = C_j = \frac{\dot{W}_f}{T} = \frac{\Delta W_f}{T\Delta t} = 13.6\,\frac{lbf}{lbf-hr}$$

$$\Delta t = \frac{\Delta W_f}{T13.6\frac{lbf}{lbf-hr}} = \frac{110lbf}{3{,}700lbf13.6\frac{lbf}{lbf-hr}} = 0.00219hr\,\frac{3{,}600s}{hr} = 7.9sec$$

$$\dot{W}_{f\,\mathrm{max}\,thrust} = \frac{110lb}{7.9s} = 13.9\,\frac{lbf}{s}$$

General Performance -- Reverse Engineering

Step 7 Update the Mission Profile with Derived Values

Acceleration

FL 450

Mach 2

a = 968 ft/s

V_{launch} = 1936ft/s =1147kts

5.46s

$\Delta R = V_{av} \Delta t_{accel}$= 2904 ft/s*5.46s = 15,856ft = 3mi

Dash Out Mach 4

45mi total (AIM-120A/B)

65mi total (AIM-120C)

FL 450+

a = 968 ft/s

V_{dash} = 3,872 ft/s = 2,640mph = 2,294kts

R_{dash} = 45 – 3mi = 42mi (AIM-120A/B)

R_{dash} = 65 – 3mi = 62mi (AIM-120C)

Terminal Maneuver

Mach 4

(0mi)

General Performance -- Reverse Engineering

Step 7 Update the Mission Profile with Derived Values

Acceleration

FL 450
Mach 2
$a = 968$ ft/s
$V_{launch} = 1936$ft/s
=1147kts
5.46s
$\Delta R = V_{av}\Delta t_{accel} = 2904$ ft/s*5.46s = 15,856ft = 3mi

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$R_{dash} = 45 - 3$mi = 42mi (AIM-120A/B)
$R_{dash} = 65 - 3$mi = 62mi (AIM-120C)

Terminal
Maneuver
Mach 4
(0mi)

Solve for remaining flight times:

$t_{dashA/B}$ =42mi*5280ft/mi*/3872ft/s = 57s

t_{dashC} = 62mi*5280ft/mi/3872ft/s = 85s

General Performance -- Reverse Engineering

Step 7 Update the Mission Profile with Derived Values

0 Acceleration 1

FL 450
Mach 2
a = 968 ft/s
V_{launch} = 1936ft/s
=1147kts
5.46s
$\Delta R = V_{av}\Delta t_{accel}$= 2904 ft/s*5.46s = 15,856ft = 3mi

Dash Out Mach 4 2
45mi total (AIM-120A/B)
65mi total (AIM-120C)
FL 450+
a = 968 ft/s
V_{dash} = 3,872 ft/s = 2,640mph = 2,294kts
R_{dash} = 45 – 3mi = 42mi (AIM-120A/B)
R_{dash} = 65 – 3mi = 62mi (AIM-120C)

Terminal
Maneuver
Mach 4
(0mi)

Solve for remaining flight times:

$t_{dashA/B}$ =42mi*5280ft/mi*/3872ft/s = 57s t_{dashC} = 62mi*5280ft/mi/3872ft/s = 85s

Solve for remaining fuel weight in each case:

$W_{fdashA/B}$ = 110lbf – 5.46s*13.9lbf/s = 34lbf W_{fdashC} = 120lbf – 5.46s*13.9lbf/s = 44lbf

General Performance -- Reverse Engineering

Step 7 Update the Mission Profile with Derived Values

Dash Out Mach 4
45mi total (AIM-120A/B)
65mi total (AIM-120C)
FL 450+
a = 968 ft/s
V_{dash} = 3,872 ft/s = 2,640mph = 2,294kts
R_{dash} = 45 - 3mi = 42mi (AIM-120A/B)
R_{dash} = 65 - 3mi = 62mi (AIM-120C)

Terminal
Maneuver
Mach 4
(0mi)

FL 450
Mach 2
a = 968 ft/s
V_{launch} = 1936ft/s
=1147kts
5.46s
$\Delta R = V_{av}\Delta t_{accel}$= 2904 ft/s*5.46s = 15,856ft = 3mi

Solve for remaining flight times:

$t_{dashA/B}$ =42mi*5280ft/mi*/3872ft/s = 57s t_{dashC} = 62mi*5280ft/mi/3872ft/s = 85s

Solve for remaining fuel weight in each case:

$W_{fdashA/B}$ = 110lbf - 5.46s*13.9lbf/s = 34lbf W_{fdashC} = 120lbf - 5.46s*13.9lbf/s = 44lbf

$$T_{dashA/B} = \frac{\dot{W}_{f\,dash}}{c_j} = I_{sp}\dot{W}_{f\,dash} = 265s\,\frac{34lbf}{57s} = 158\text{lbf}$$

$$T_{dashC} = \frac{\dot{W}_{f\,dash}}{c_j} = I_{sp}\dot{W}_{f\,dash} = 265s\,\frac{44lbf}{85s} = 137\text{lbf}$$

General Performance -- Reverse Engineering

Step 8 Solve for L/D's

Recall that for jets (which also goes for rockets & missiles):

$$R(nmi) = \left(\frac{V(kts)}{c_j\left({}^{lbf}/_{lbf-hr}\right)}\right)\left(\frac{L}{D}\right)\text{Ln}\left(\frac{W_i}{W_{i+1}}\right)$$

But... Things are much simpler for air-to-air missiles...

Assume that induced drag ~ 0, wave drag dominates

For acceleration leg: $T = D_{aero} + D_{D'Alembert's} \sim D_{D'Alembert's}$

So from dash segment: $L/D \sim W/D = W_{dash}/T_{dash}$

$L/D_{A/B}$ ~ ((345lb – 34/2lbf)/158lbf = 2.08

L/D_{C}~ ((345lb – 44/2lbf)/137lbf = 2.35

Contemplate the ways to get a 13% boost in L/D...

Friday
13 October

Today's Schedule:

- Call roll
- Reverse Engineering Methods
- Proverse Engineering of RAIDERs
- Report 6
- Quiz

General Performance -- Reverse Engineering Missiles

Step 9 Solve for W_e/W_{launch}:

$\mathbf{W_e/W}_{launchA/B} = (W_{launch} - W_{warhead} - W_{propellant})/W_{launch} = (345 - 50 - 110lb)/345lb = 54\%$

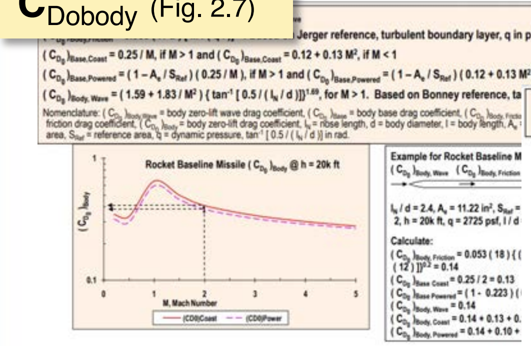
$\mathbf{W_e/W}_{launchA/B} = (W_{launch} - W_{warhead} - W_{propellant})/W_{launch} = (345 - 40 - 120lb)/345lb = 54\%$

General Performance -- Reverse Engineering Missiles

Step 10 Solve for Normal Force & Drag expressions with Mach and α:

$$C_D(\alpha,M) = C_{Dobody}(\alpha,M) + C_{surface,friction}(\alpha,M) + C_{Dosurface,wave}(\alpha,M)$$

C_{Dobody} (Fig. 2.7)



Jerger reference, turbulent boundary layer, q in psf, l in ft.

$(C_{D_0})_{Base,Coast} = 0.25 / M$, 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 $(C_{D_0})_{Base,Powered} = (1 - A_e / S_{Ref})(0.12 + 0.13 M^2)$

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

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

Example for Rocket Baseline M

$l_N / d = 2.4$, $A_e = 11.22$ in², S_{Ref} = 2, h = 20k ft, q = 2725 psf, l / d

Calculate:

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

$(C_{D_0})_{Base,Coast} = 0.25 / 2 = 0.13$

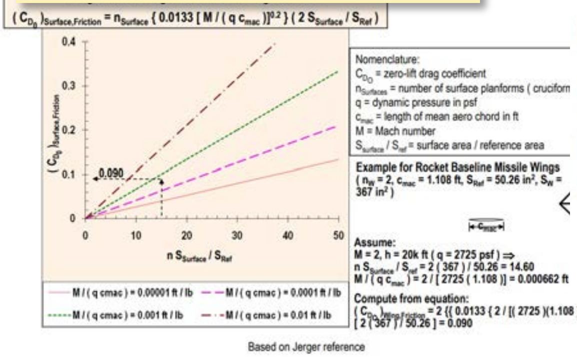
$(C_{D_0})_{Base,Powered} = (1 - 0.223)($

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

$(C_{D_0})_{Body,Coast} = 0.14 + 0.13 + 0.$

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

$C_{dosurface,skinfriction}$ (Fig. 2.29)



$(C_{D_0})_{Surface,Friction} = n_{Surface} \{0.0133 [M / (q c_{mac})]^{0.2}\} (2 S_{Surface} / S_{Ref})$

Nomenclature:

C_{D_0} = zero-lift drag coefficient

$n_{Surfaces}$ = number of surface planforms (cruciform

q = dynamic pressure in psf

c_{mac} = length of mean aero chord in ft

M = Mach number

$S_{Surface} / S_{Ref}$ = surface area / reference area

Example for Rocket Baseline Missile Wings ($n_W = 2$, $c_{mac} = 1.108$ ft, $S_{Ref} = 50.26$ in², $S_W = 367$ in²)

Assume:

M = 2, h = 20k ft (q = 2725 psf) ⇒

$n S_{Surface} / S_{Ref} = 2 (367) / 50.26 = 14.60$

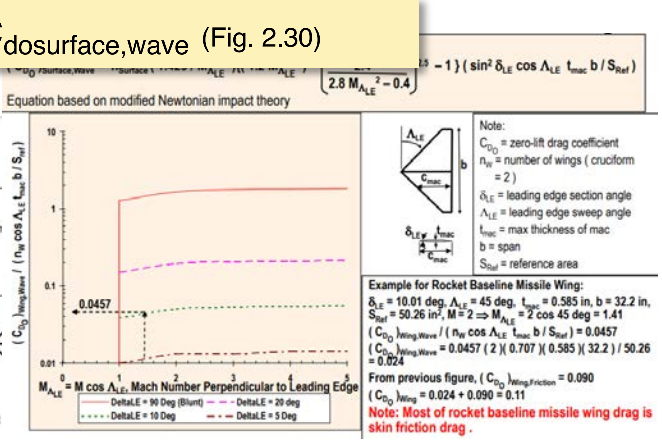
$M / (q c_{mac}) = 2 / [2725 (1.108)] = 0.000662$ ft

Compute from equation:

$(C_{D_0})_{Wing,Friction} = 2 \{\{0.0133 \{2 / [(2725)(1.108)]\}^{0.2}\}$ $[2 (367) / 50.26] = 0.090$

Based on Jerger reference

$C_{dosurface,wave}$ (Fig. 2.30)



$\dfrac{}{2.8 M_{\Lambda_{LE}}{}^2 - 0.4}$ ${}^{2.5} - 1\} (\sin^2 \delta_{LE} \cos \Lambda_{LE}\ t_{mac}\ b / S_{Ref})$

Equation based on modified Newtonian impact theory

Note:

C_{D_0} = zero-lift drag coefficient

n_W = number of wings (cruciform = 2)

δ_{LE} = leading edge section angle

Λ_{LE} = leading edge sweep angle

t_{mac} = max thickness of mac

b = span

S_{Ref} = reference area

Example for Rocket Baseline Missile Wing:

$\delta_{LE} = 10.01$ deg, $\Lambda_{LE} = 45$ deg, $t_{mac} = 0.585$ in, b = 32.2 in, $S_{Ref} = 50.26$ in², M = 2 ⇒ $M_{\Lambda_{LE}} = 2 \cos 45$ deg = 1.41

$(C_{D_0})_{Wing,Wave} / (n_W \cos \Lambda_{LE}\ t_{mac}\ b / S_{Ref}) = 0.0457$

$(C_{D_0})_{Wing,Wave} = 0.0457 (2)(0.707)(0.585)(32.2) / 50.26 = 0.024$

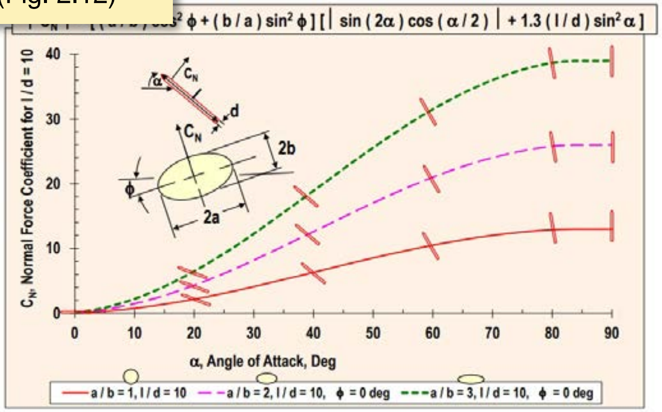
From previous figure, $(C_{D_0})_{Wing,Friction} = 0.090$

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

Note: Most of rocket baseline missile wing drag is skin friction drag .

$$C_N(\alpha,M) = C_{Nbody}(\alpha,M) + C_{Nsurface}(\alpha,M)$$

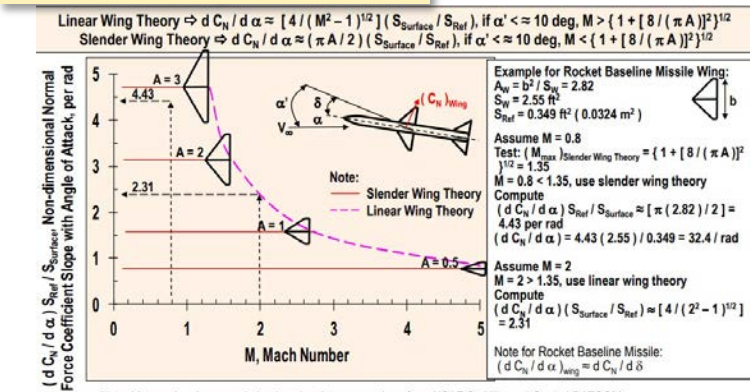
C_{Nbody} (Fig. 2.12)



$\phi + (b / a) \sin^2 \phi] [| \sin (2\alpha) \cos (\alpha / 2) | + 1.3 (l / d) \sin^2 \alpha]$

Note: Based on slender body theory (Pitts, et al) and cross flow theory (Jorgensen) references. Valid for $l / d > 5$. $d = 2 (a b)^{1/2}$

$C_{N\alpha canard,wing,tail}$ (Fig. 2.25)



Linear Wing Theory ⇨ $d C_N / d \alpha \approx [4 / (M^2 - 1)^{1/2}] (S_{Surface} / S_{Ref})$, if $\alpha' < \approx 10$ deg, $M > \{1 + [8 / (\pi A)]^2\}^{1/2}$

Slender Wing Theory ⇨ $d C_N / d \alpha \approx (\pi A / 2)(S_{Surface} / S_{Ref})$, if $\alpha' < \approx 10$ deg, $M < \{1 + [8 / (\pi A)]^2\}^{1/2}$

Example for Rocket Baseline Missile Wing:

$A_W = b^2 / S_W = 2.82$

$S_W = 2.55$ ft²

$S_{Ref} = 0.349$ ft² (0.0324 m²)

Assume M = 0.8

Test: $(M_{max})_{Slender\ Wing\ Theory} = \{1 + [8 / (\pi A)]^2\}^{1/2} = 1.35$

M = 0.8 < 1.35, use slender wing theory

Compute

$(d C_N / d \alpha) S_{Ref} / S_{Surface} \approx [\pi (2.82) / 2] = 4.43$ per rad

$(d C_N / d \alpha) = 4.43 (2.55) / 0.349 = 32.4$ / rad

Assume M = 2

M = 2 > 1.35, use linear wing theory

Compute

$(d C_N / d \alpha)(S_{Surface} / S_{Ref}) \approx [4 / (2^2 - 1)^{1/2}] = 2.31$

Note for Rocket Baseline Missile:

$(d C_N / d \alpha)_{wing} \approx d C_N / d \delta$

Note: Linear wing theory and slender wing theory equations from USAF Stability and Control DATCOM

Note: Slender wing theory good accuracy limited to A < ≈ 2 for small effects of compressibility, wing sweep, and taper ratio

Nomenclature: A = Aspect ratio, $S_{Surface}$ = Surface planform area, S_{Ref} = Reference area, α = Angle of attack

General Performance -- Reverse Engineering Missiles

Step 10 Solve for C_L & C_A with Mach and α:

Recall:

$$C_L(\alpha, M) = C_N(\alpha, M)Cos\alpha - C_A(\alpha, M)Sin\alpha$$

$$C_D(\alpha, M) = C_N(\alpha, M)Sin\alpha + C_A(\alpha, M)Cos\alpha$$

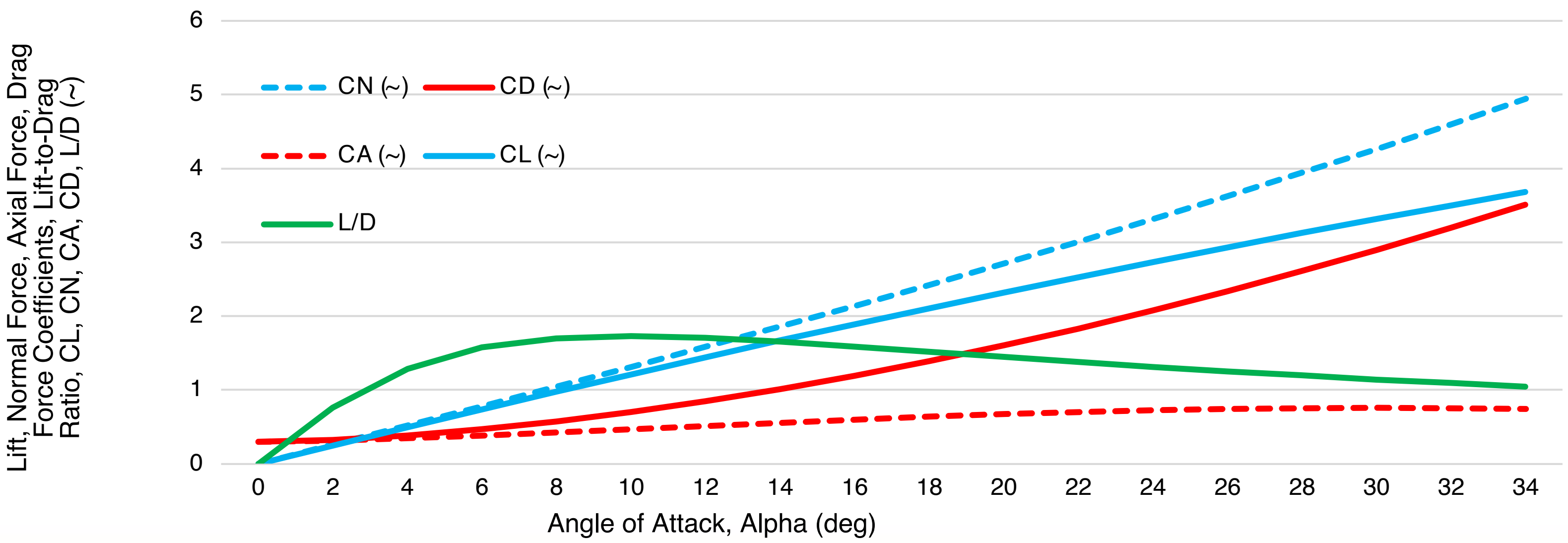
Rearranging:

$$C_A(\alpha, M) = \frac{C_D(\alpha, M) - C_N(\alpha, M)Sin\alpha}{Cos\alpha}$$

Substituting:

$$C_L(\alpha, M) = C_N(\alpha, M)Cos\alpha - \frac{C_D(\alpha, M) - C_N(\alpha, M)Sin\alpha}{Cos\alpha}Sin\alpha$$

Plot C_N, C_L, C_A, C_D & L/D for each relevant Mach number



General Performance -- Reverse Engineering Missiles

Step 11 Solve for Mach and α at L/D cruise (from Step 8)

i. If Cruise Mach is known: Sweep through α to get α_{cruise}
ii. If Cruise Mach is not known: Sweep through α and M_{cruise} to get α_{cruise} at highest Mach

Step 12 Solve for $C_{Lcruise}$ at M_{cruise}, L/D_{cruise} and α_{cruise}

Step 13 Assuming mid-cruise point, solve for cruise air density

Assuming a
50% fuel load:

$$\rho_{cruise} \sim \frac{2(W_{TO} - 0.5W_F)}{V^2 C_{Lcruise} S_{ref}}$$

Step 14 Find mid-cruise point altitude from standard atmospheric data

Step 15 Update mission profile to account for mid-point cruise altitude

General Performance -- Reverse Engineering Ballistics

Steps 1 – 5 Get all Engineering-Level Data as done for missiles

Step 6 Get TOF, (t) and ranges, R, apogee, h for baseline missile system

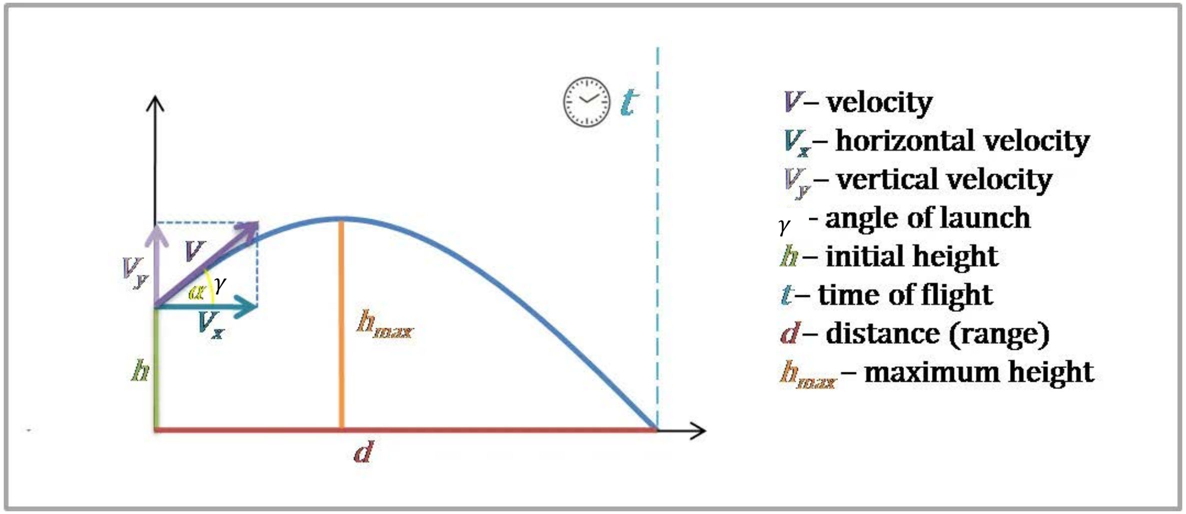
Step 7 Consider a dragless launch with unknown muzzle velocity, V_m

Horizontal Velocity:

$$V_x = V_m Cos\gamma$$

Vertical Velocity:

$$V_y = V_m Sin\gamma - gt$$



Max. Height:

$$h_{max} = h + \frac{V_{yo}^2}{2g}$$

Time of Flight:

$$t = \frac{1}{g}\left[V_{ym} + \sqrt{V_{ym}^2 + 2gh}\right]$$

Range:

$$R = \frac{V_x}{g}\left[V_{ym} + \sqrt{V_{ym}^2 + 2gh}\right]$$

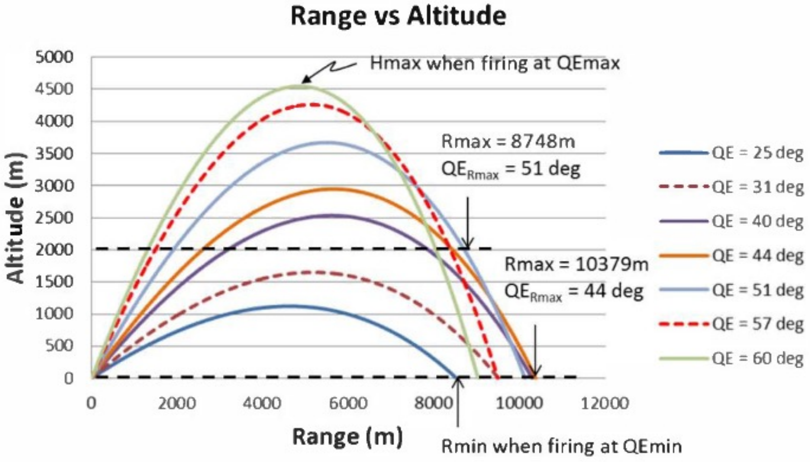
General Performance -- Reverse Engineering Ballistics

Step 8 Gather range-altitude info. for baseline

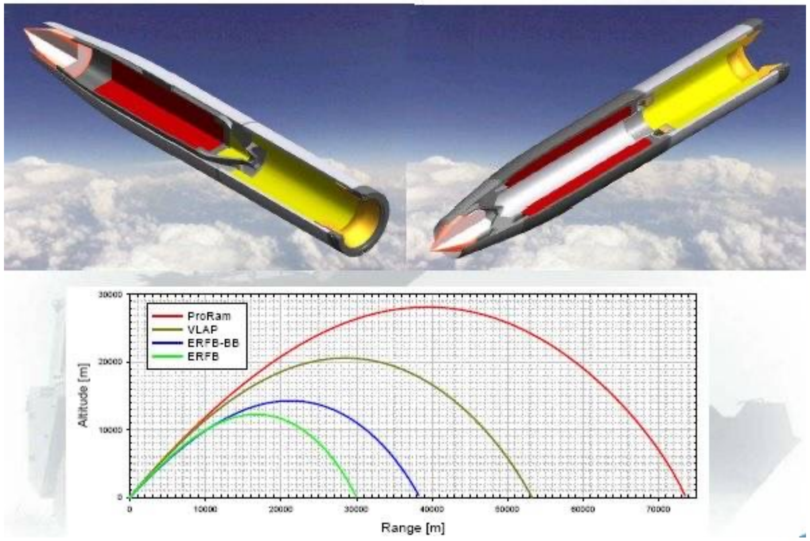
Knowns: R, t(sometimes), h(sometimes)

Unknowns: γ, V_m, t(sometimes), h(sometimes)

GMLRS:

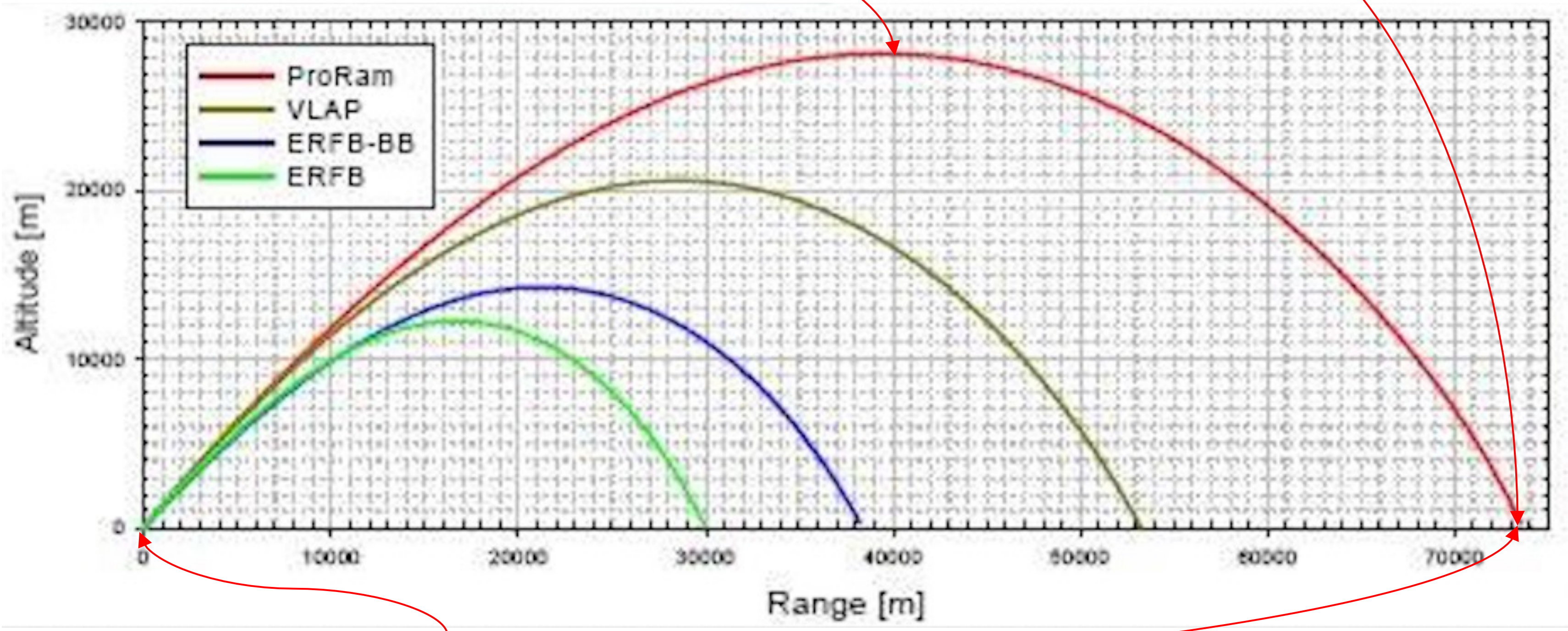


Boeing/Nammo



General Performance -- Reverse Engineering Ballistics

Step 8 Gather range-altitude info. For baseline



Knowns: h_{max} = 28km

R = 73.5km

Knowns: h = 0

General Performance -- Reverse Engineering Ballistics

Step 9 If h_{max} known, solve for V_{ym}:

$$V_{ym} = \sqrt{2g(h_{max} - h)}$$

Step 10 Solve for V_{xm}& V_m:

$$V_{xm} = \frac{Rg}{V_{ym} + \sqrt{V_{ym}^2 + 2gh}}$$

$$V_m = \sqrt{V_{ym}^2 + V_{ym}^2}$$

Step 11 Solve for Barrel Elevation Angle, γ:

$$\gamma = atan\left(\frac{V_{ym}}{V_{xm}}\right)$$

Step 12 Estimate Total Potential Energy at Apogee:

$$PE = mgh_{max}$$

Step 13 Estimate Mid-Terminal Flight Speed

$$V_{midterm} \sim \sqrt{gh_{max}}$$

General Performance – Proverse Engineering

Step 1 Get All Performance and Geometric Data for Baseline Weapon

-Easy, just look at previous info. & tabulate

Step 2 Establish Geometric and/or Performance Goal(s)

2.1 If improved performance in the same form factor is asked:
Determine the desired improved performance vector (range, PL, maneuverability, etc. .)
-GMLRS rounds, optimize range
-NAMMO/Boeing rounds, optimize range

2.2 If better packing volume/lower weight is asked:
Update all aerodynamic and propulsion with new technologies & get new L/Dmax, new TSFC or Isp, new Wf, Wpl etc.
-AIM-120 & AIM-9 minimize total missile volume, shrinking symmetrically in all directions, save the warhead. Preserve warhead volume.

General Performance – Proverse Engineering Missiles

Step 3 Solve for New Size

3.1 New performance in same form factor is easy: solve with new, updated L/D’s and TSFCs

3.2 Smaller size takes a bit more work as it’s iterative:

  3.2.1 Assume a smaller size by as much as 50%, then solve for performance

  3.2.2 If performance doesn’t measure up, solve again with 75%

  3.2.3 If it’s too much performance, reduce to 62.5%, it it’s not enough, go to 87.5%

  etc. etc. till closure

General Performance – Proverse Engineering GMLRS & Nammo/Boeing

Step 3 Solve for New Range

3.1 Assume mid-terminal flight speed is average for the flight, estimate time of flight using baseline munition flight (plus a little bit more):

$$t_{est} \sim (1.?)t = \frac{1.?}{g}\left[V_{ym} + \sqrt{V_{ym}^2 + 2gh}\right]$$

3.2 Determine the mass of the fuel on board and I_{sp}(1300s), TSFC(2.77lbf/(lbf-hr)) for ramjets

3.3 Given test and TSFC, estimate mid-terminal thrust:

$$T_{midterm} \sim \frac{W_f}{TSFC\ \ t_{est}}$$

3.4 Estimate Additional Power:

$$P_{add} \sim V_{midterm}\ T_{midterm}$$

3.5 Estimate Additional Energy added to the total flight:

$$E_{add} \sim t_{est} P_{add}$$

3.6 Estimate Ratio, ER of the new projectile energy to baseline projectile energy:

$$ER = \frac{mgh_{max} + t_{est} P_{add}}{mgh_{max}}$$

3.7 Estimate the new range: $R_{new} \sim R_0 ER$

Physical Model Preparation: Bill of Materials (BOM)

Part No.	Part Name & Mfg no.	Material	Qty. Rq'd	Cost Ea.	Source/Supplier (URL)	Component Weight (lb)	Weight Fraction (%)
1	Main Gear Tires – 30 x 6.5 SBR	n/a	2 ea.	$476	Goodyear	87	2.2
2	Nose Gear Tire – 18 x 4 SBR	n/a	1 ea.	$320	Goodyear	23	0.58
3	Main gear oleo strut	stainless steel 15PH	2 ea.	$19k	n/a	234	5.85
4	Nose gear oleo strut	stainless steel 15PH	1 ea.	$2.6k	n/a	112	2.8
5	Main gear retraction actuator	n/a	2 ea.	$3.9k	Textron Actuator Division	27	0.68
6	Aileron sections 1, 2, 3	Kevlar	2 ea.	$8.7k	GKN Composites Inc.	3.2	0.08
7	Elevator sections 1, 2	Kevlar	1 ea.	$3.3k	GKN Composites Inc.	4.8	0.12
8	Rudder sections 1, 2, 3	Kevlar	1 ea.	$5.9k	GKN Composites Inc.	3.7	0.09
9	FJ44-4 Powerplants	n/a	2 ea.	$6.9M	Williams International	460	11.5
10	Mk17 Ejection Seat	n/a	1 ea.	$220k	Martin Baker	83	2.1
11	Upper wing skin	APC-2 PEEK/graphite	1 ea	$390k	GKN Composites, Inc.	113	2.8
12	Lower wing skin	APC-2 PEEK/graphite	1 ea	$280k	GKN Composites, Inc.	108	2.7
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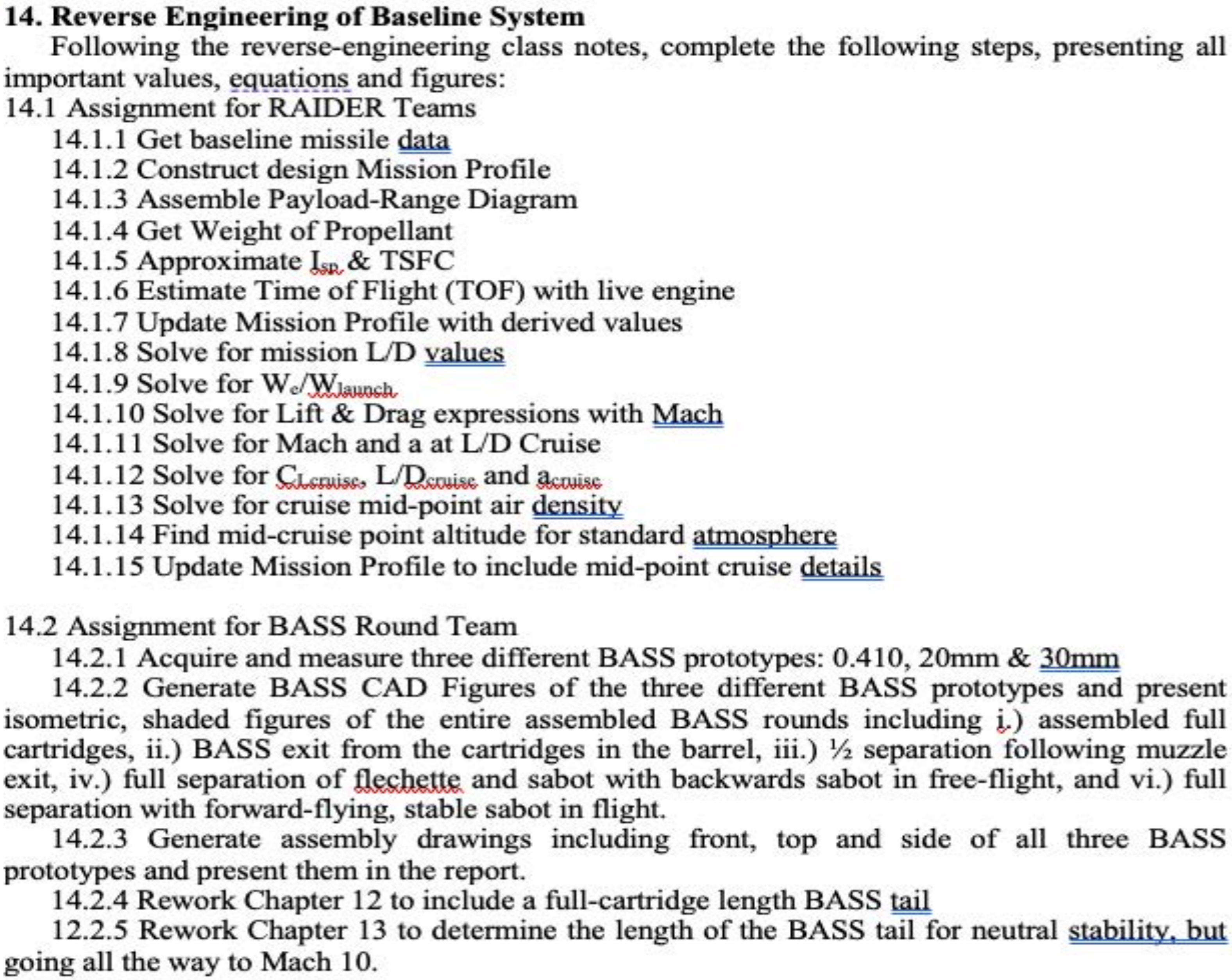


14. Reverse Engineering of Baseline System

Following the reverse-engineering class notes, complete the following steps, presenting all important values, equations and figures:

14.1 Assignment for RAIDER Teams

14.1.1 Get baseline missile data
14.1.2 Construct design Mission Profile
14.1.3 Assemble Payload-Range Diagram
14.1.4 Get Weight of Propellant
14.1.5 Approximate I_{sp} & TSFC
14.1.6 Estimate Time of Flight (TOF) with live engine
14.1.7 Update Mission Profile with derived values
14.1.8 Solve for mission L/D values
14.1.9 Solve for W_e/W_{launch}
14.1.10 Solve for Lift & Drag expressions with Mach
14.1.11 Solve for Mach and a at L/D Cruise
14.1.12 Solve for $C_{L cruise}$, L/D_{cruise} and a_{cruise}
14.1.13 Solve for cruise mid-point air density
14.1.14 Find mid-cruise point altitude for standard atmosphere
14.1.15 Update Mission Profile to include mid-point cruise details

14.2 Assignment for BASS Round Team

14.2.1 Acquire and measure three different BASS prototypes: 0.410, 20mm & 30mm

14.2.2 Generate BASS CAD Figures of the three different BASS prototypes and present isometric, shaded figures of the entire assembled BASS rounds including i.) assembled full cartridges, ii.) BASS exit from the cartridges in the barrel, iii.) ½ separation following muzzle exit, iv.) full separation of flechette and sabot with backwards sabot in free-flight, and vi.) full separation with forward-flying, stable sabot in flight.

14.2.3 Generate assembly drawings including front, top and side of all three BASS prototypes and present them in the report.

14.2.4 Rework Chapter 12 to include a full-cartridge length BASS tail

12.2.5 Rework Chapter 13 to determine the length of the BASS tail for neutral stability, but going all the way to Mach 10.

15. Proverse Engineering Advanced System

Following the proverse engineering class notes, complete the following steps, presenting all important values, equations and figures:

15.1. Assignment for RAIDER Teams

15.1.1 Tabulate all known aerodynamic & inertial info. for baseline weapon

15.1.2 Note changes in Sref, L/D and TSFC that will come from the RAIDER configuration

15.1.3 Optimize designs in different ways depending on chosen system:

15.1.3.1 RAIDER AIM-120 AMRAAM Replacement
Match AMRAAM seeker, warhead & range, design tube-launched variant
Work to minimize size

15.1.3.2 RAIDER AIM-9 Sidewinder Replacement
Match AIM-9 seeker, warhead & range, design tube-launched variant
Work to minimize size

15.1.3.3 RAIDER Long-Range GMLRS Replacement
Match GMLRS seeker & warhead, design tube-launched variant
Work to maximize range.

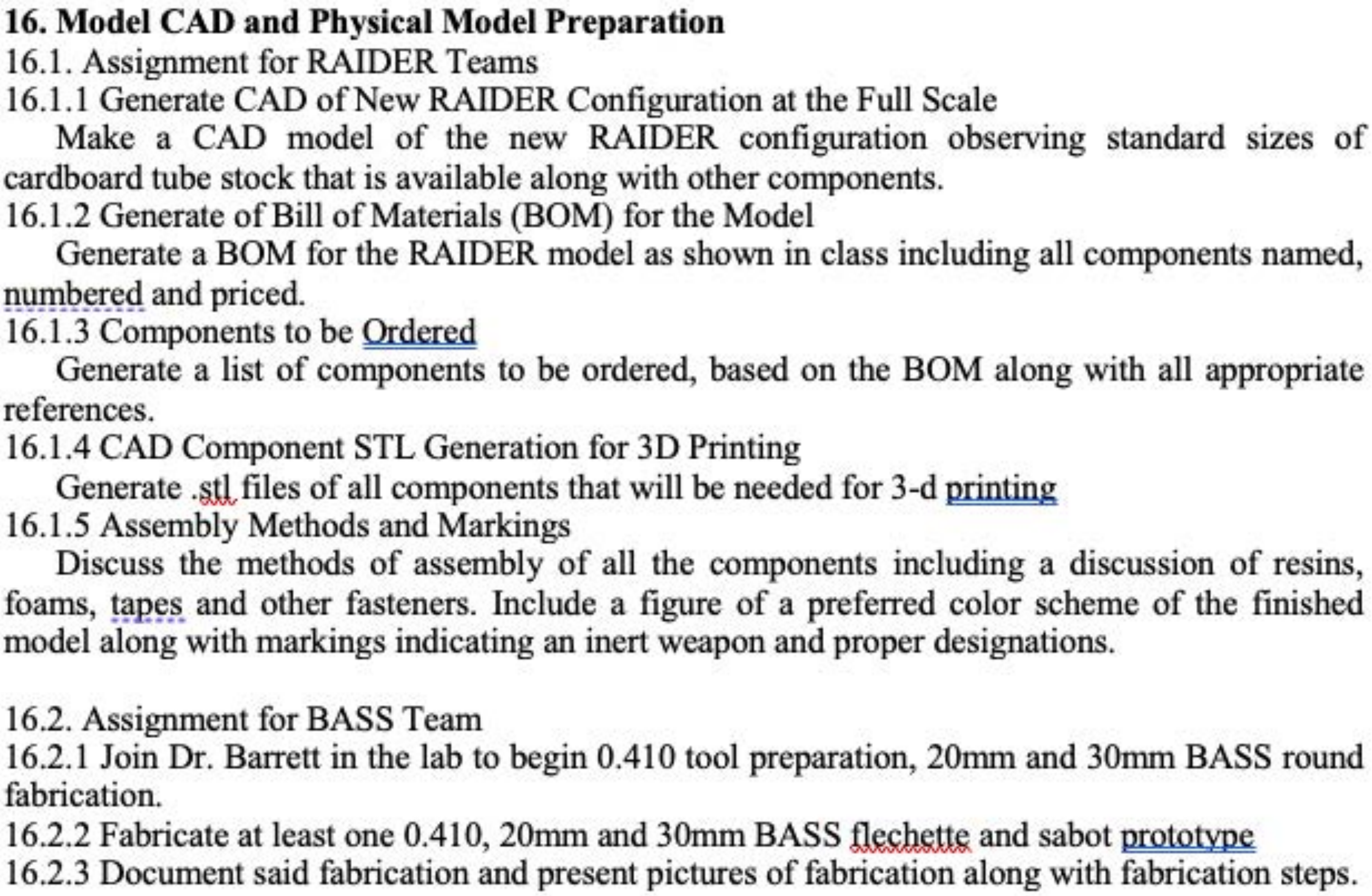
15.1.3.4 RAIDER 155mm Boeing/Nammo Ramjet Artillery Shell Replacement
Match Boeing/Nammo 155mm munition GNC package & warhead
Work to maximize range

15.1.3.5 RAIDER 105mm Boeing/Nammo Ramjet Artillery Shell Replacement
Match Boeing/Nammo 105mm munition GNC package & warhead
Work to maximize range

15.2. Assignment for BASS Team:

15.2.1 Enter the 0.410, 20mm and 30mm BASS flechette-sabot combinations into PATRAN/Nastran, oriented nose up with a constant pressure load on the base of the sabot.

15.2.2 Increase the density of the flechettes to 10,000x the density of tungsten and apply a suitable pressure on the surface of the sabot to balance the force. Plot the Von Mises stresses in the sabot.



16. Model CAD and Physical Model Preparation

16.1. Assignment for RAIDER Teams

16.1.1 Generate CAD of New RAIDER Configuration at the Full Scale

Make a CAD model of the new RAIDER configuration observing standard sizes of cardboard tube stock that is available along with other components.

16.1.2 Generate of Bill of Materials (BOM) for the Model

Generate a BOM for the RAIDER model as shown in class including all components named, numbered and priced.

16.1.3 Components to be Ordered

Generate a list of components to be ordered, based on the BOM along with all appropriate references.

16.1.4 CAD Component STL Generation for 3D Printing

Generate .stl files of all components that will be needed for 3-d printing

16.1.5 Assembly Methods and Markings

Discuss the methods of assembly of all the components including a discussion of resins, foams, tapes and other fasteners. Include a figure of a preferred color scheme of the finished model along with markings indicating an inert weapon and proper designations.

16.2. Assignment for BASS Team

16.2.1 Join Dr. Barrett in the lab to begin 0.410 tool preparation, 20mm and 30mm BASS round fabrication.

16.2.2 Fabricate at least one 0.410, 20mm and 30mm BASS flechette and sabot prototype

16.2.3 Document said fabrication and present pictures of fabrication along with fabrication steps.