AE 330 Rocket Propulsion
Projectiles and Missiles

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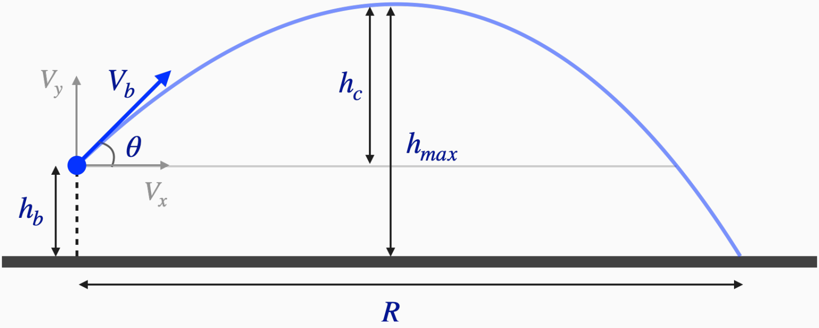
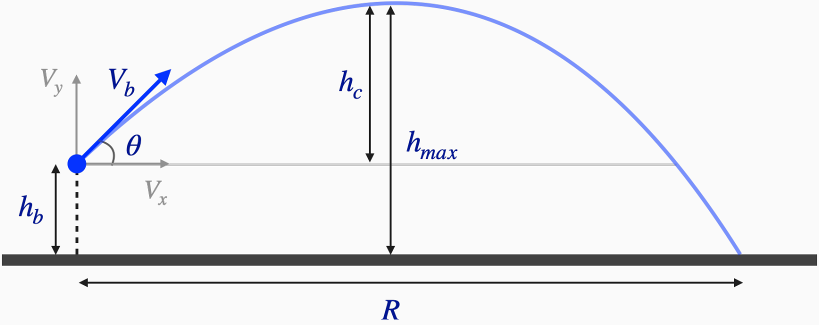
Projectile Basics

Projectile launched at an angle



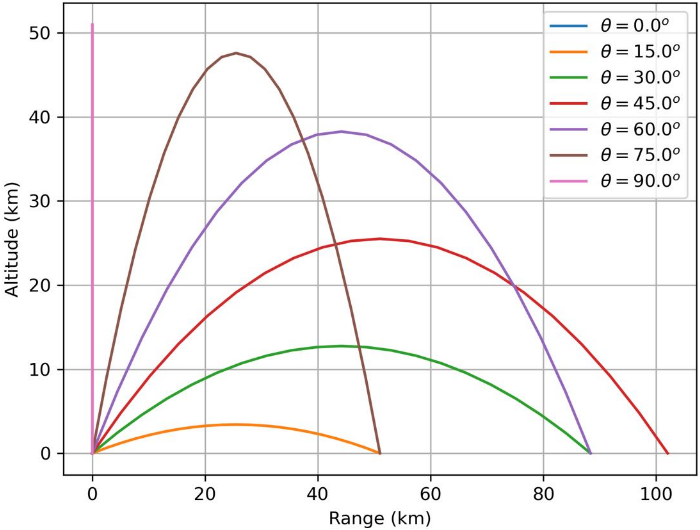
Projectile launched at an angle



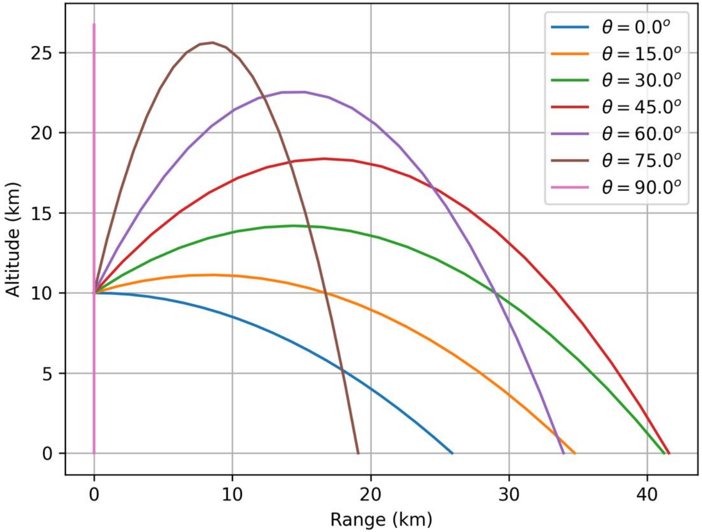
$$\frac{dV_x}{dt} = 0 \text{ and } \frac{dx}{dt} = V_x \equiv V_o \cos\theta$$

$$\frac{dV_y}{dt} = -g_o \text{ and } \frac{dy}{dt} = V_y \equiv V_o \sin\theta$$

Trajectory without drag $(h_b = 0)$



Trajectory without drag $(h_b > 0)$

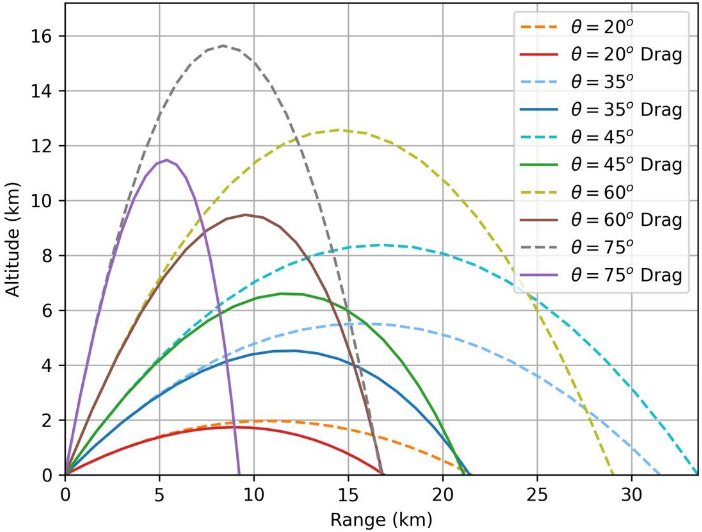


What happens if we consider drag?

Two options:

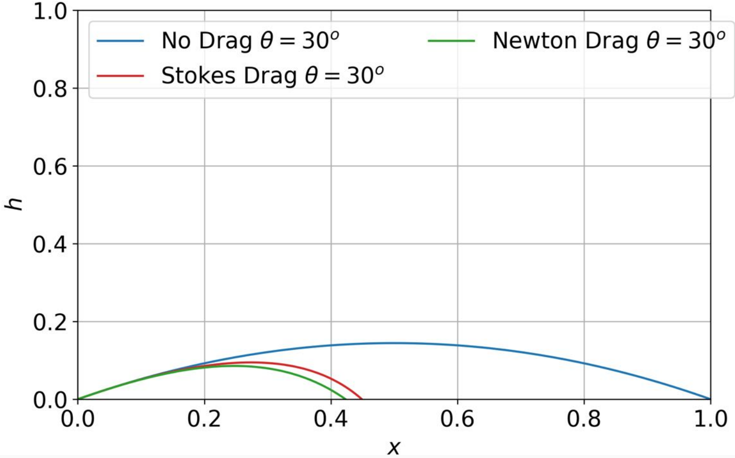
- Stokes Drag: $\propto \nu V$
- Newtonian Drag: $\propto \alpha V^2$

Stokes Drag

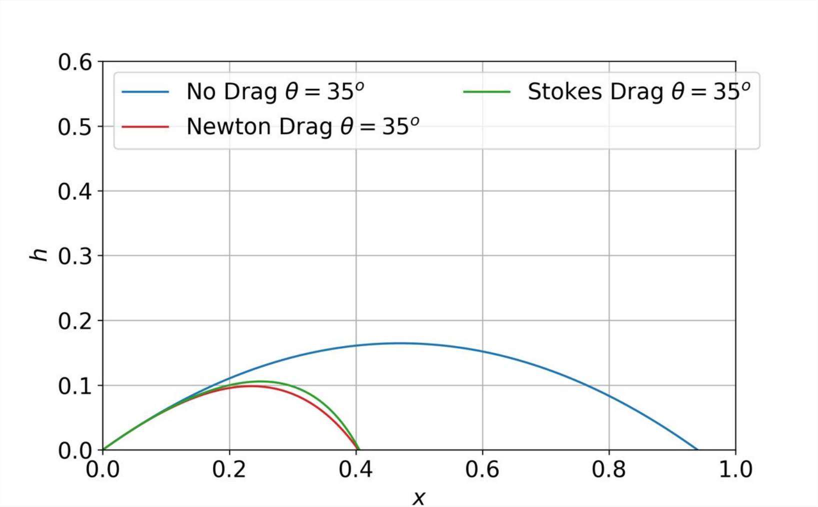


$\theta = 20^o$
$\theta = 20^o$ Drag
$\theta = 35^o$
$\theta = 35^o$ Drag
$\theta = 45^o$
$\theta = 45^o$ Drag
$\theta = 60^o$
$\theta = 60^o$ Drag
$\theta = 75^o$
$\theta = 75^o$ Drag
Altitude (km)
Range (km)
0
2
4
6
8
10
12
14
16
0
5
10
15
20
25
30

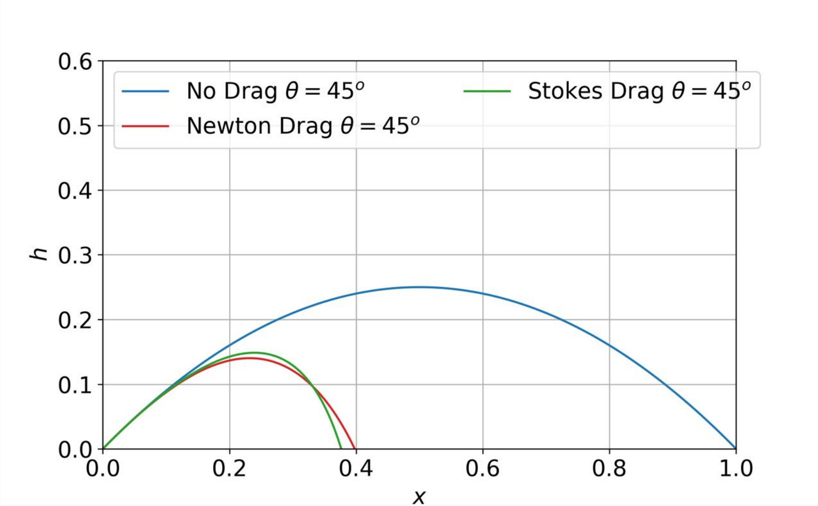
Newtonian Drag $(\theta = 30^o)$



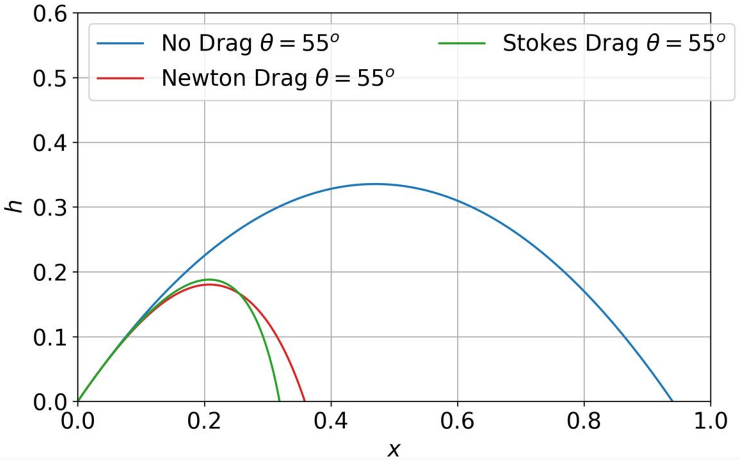
Newtonian Drag $(\theta = 35^o)$



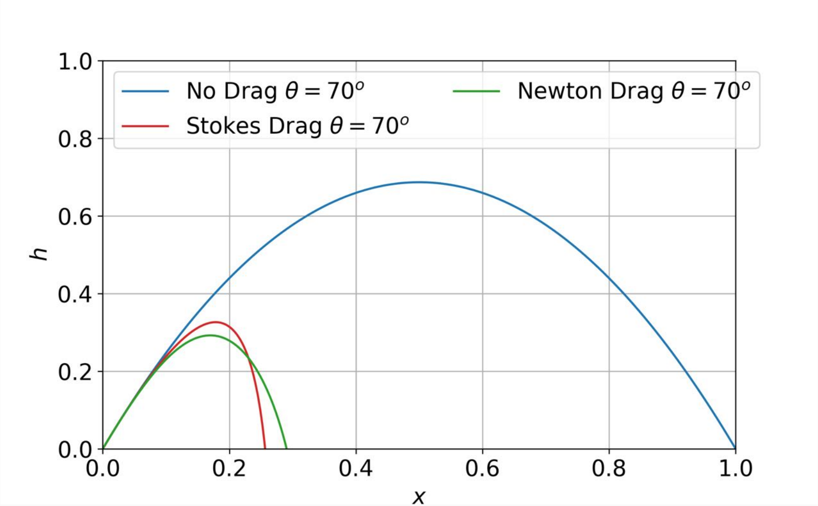
Newtonian Drag $(\theta = 45^o)$



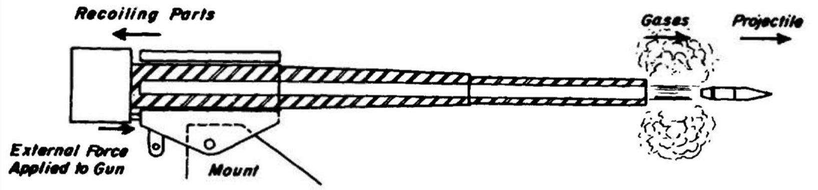
Newtonian Drag $(\theta = 55^o)$



Newtonian Drag $(\theta = 70^o)$



Generating V_b

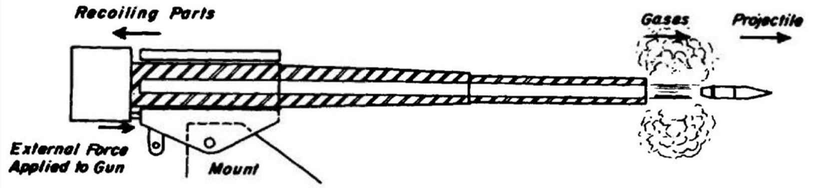


$$\mathcal{T} = \underbrace{\dot{m}u_e}_{\text{rocket}} + \underbrace{(p_e - p_a)\,A_e}_{\text{projectile}}$$

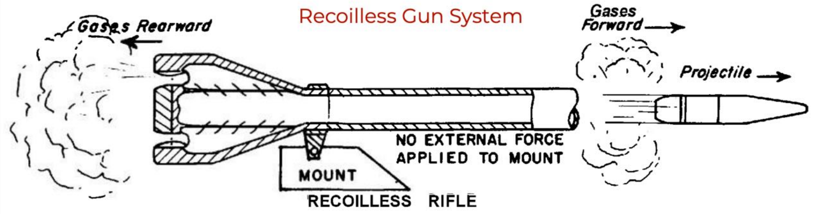
image from Smith, "Internal Ballistics of Guns"

Generating V_b

Gun System with Recoil



Recoilless Gun System



images from Smith, "Internal Ballistics of Guns"

Classification of Guns

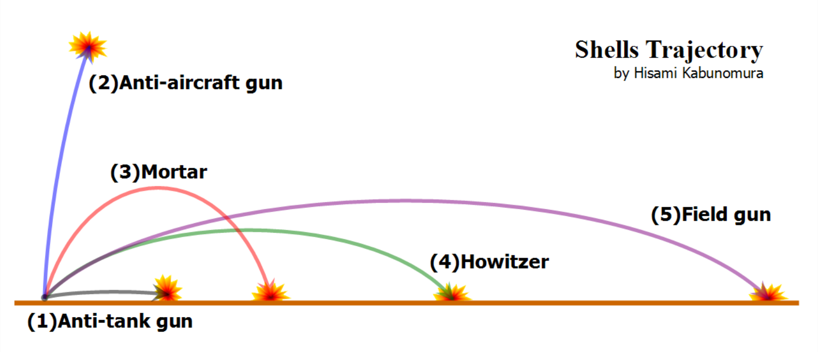


image from wikipedia

Ballistic Missiles

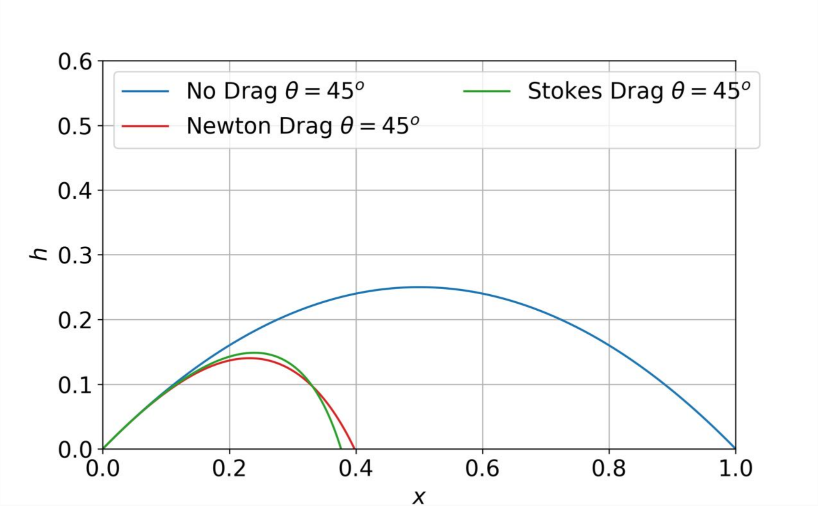
Classification

	Range (km)	
SRBM	<1,000	Short Range Ballistic Missiles
MRBM	1,000 - 3,000	Medium Range Ballistic Missiles
IRBM	3,000 - 5,500	Intermediate Range Ballistic Missiles
ICBM	>5,500	Intercontinental Ballistic Missiles

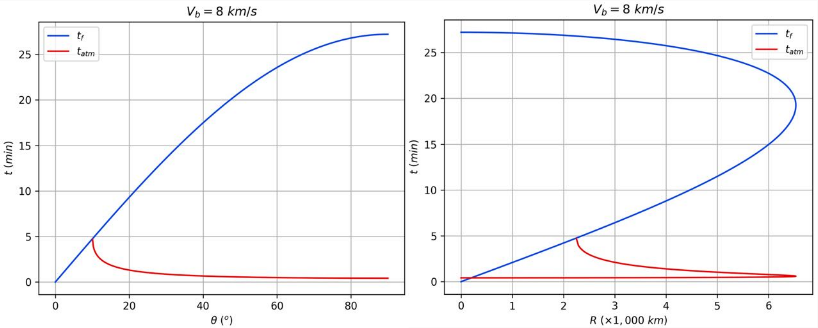
Missile Range: $V_b = \sqrt{Rg_o}$ for $\theta = 45^o$

	Range (km)	$V_b\,(km/s)$
SRBM	<1,000	3.13
MRBM	1,000 - 3,000	$3.13 - 5.4$
IRBM	3,000 - 5,500	$5.4 - 7.3$
ICBM	>5,500	> 7.3

Missile Trajectories: Drag



Avoiding Drag



ICBM Trajectories

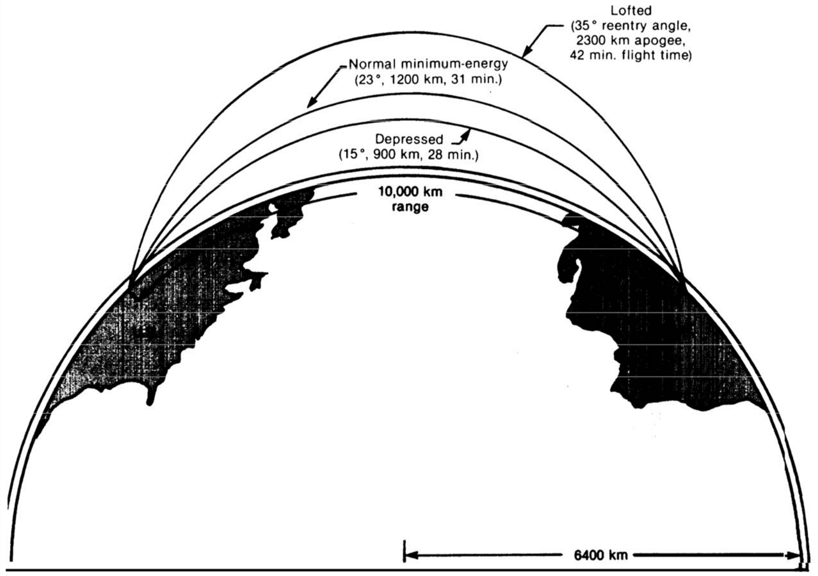
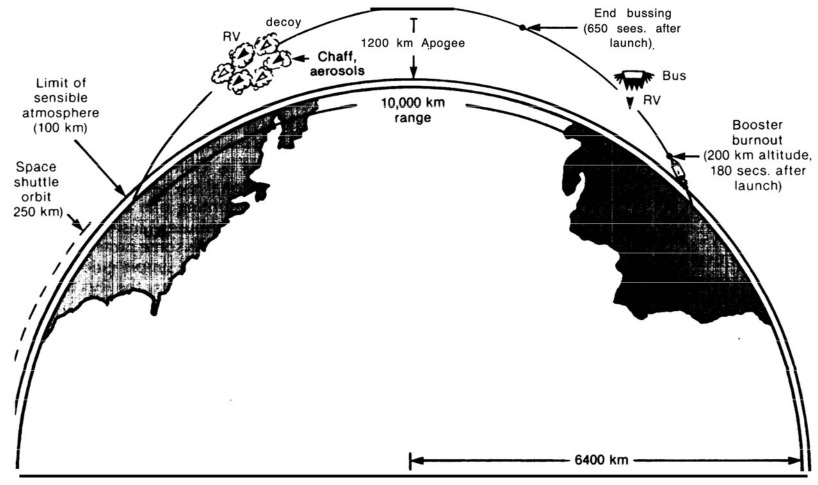


image from Carter, "Directed Energy Missile Defense in Space"

ICBM Trajectory



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ICBM Trajectory

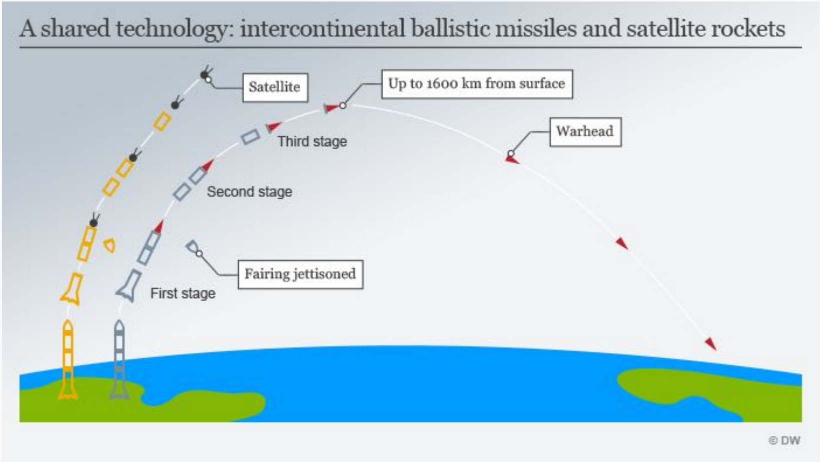

image from dw.com

Atmospheric Re-entry

Empirical Correlations for stagnation region heat flux

$$q'' = C\sqrt{\frac{\rho_\infty}{R_c}}V_\infty^3\left(1 - \frac{h_w}{h_o}\right)$$

Blunt bodies have lower heat flux (Allen's "Blunt Body Theory")
$q'' \sim 600\ W/cm^2$ for manned mission reentry capsules.

Atmospheric Re-entry

Empirical Correlations for stagnation region heat flux

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Entry	V_b (km/s)	$h_o \sim V_b^2/2$ (MJ/kg)
Apollo	11.4	66
Mars Return	14.0	98

Water boils at $\sim 2.3\ MJ/kg$

Carbon vaporizes at $\sim 60.5\ MJ/kg$

data from Akin

Re-entry Vehicle Shape Evolution

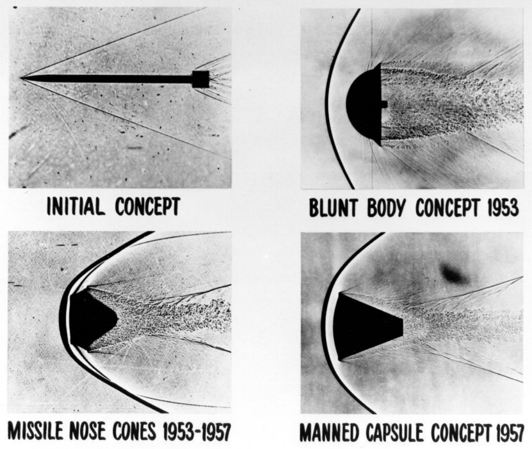
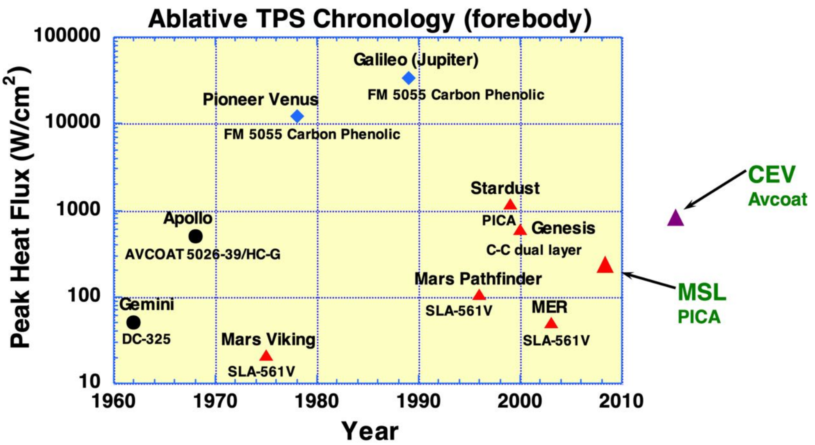


image from wikipedia

Blunt bodies have lower heat flux (Harvey Allen's "Blunt Body Theory")

$q'' \sim 600\ W/cm^2$ for manned mission reentry capsules.

Re-entry Thermal Protection System (TPS)



No Human Rated Ablative TPS Available Today!
CEV/Orion is working to develop Avcoat, for a human rated system - Very Close to Achieving This Goal!

image from Wright, Dec and Laub

Re-entry Thermal Protection System (TPS)

Material Name	Manufacturer	Density (kg/m³)	Limit (W/cm²)	
SLA-561V	Lockheed-Martin	256	~ 200	Not viable for high shear
FM 5055 Carbon Phenolic	Fibercote (formerly US Polymeric), Hitco Inc.	1450	> 10,000	No source of heritage Rayon
MX4926N Carbon Phenolic	Cytec (pre-preg), ATK, HITCO	1450	> 10,000	Flown on Shuttle SRM, never as a heat shield
PhenCarb-20,24,32	Applied Research Associates (ARA)	320-512	~ 750	Never flown
PICA (Phenolic Impregnated Carbon Ablator)	Fiber Materials, Inc. (FMI)	265	> 1500	Must be tiled above 1m diameter
Avcoat 5026 (Apollo)	Textron Systems	513	~1000	Recreated for CEV
ACC	Lockheed-Martin	1890	~ 1500	Heavy, not readily extendible above 2m

image from Wright, Dec and Laub

Indian Ballistic Missiles

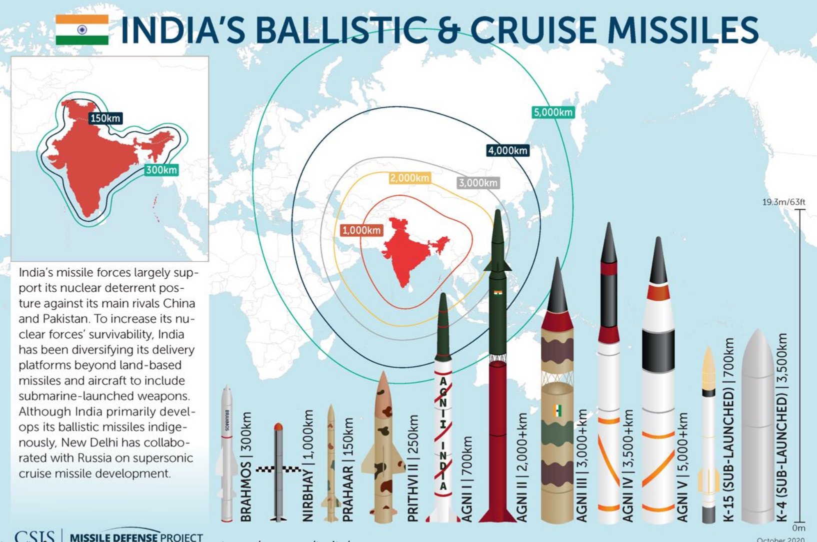


image from https://missilethreat.csis.org/country/india/

Hypersonic Missiles

Motivation

Course correction not possible for ballistic missiles in the terminal phase

Air-breathing propulsion at similar speeds $(M > 6)$ would give the advantage of control

Low altitude flight $\implies$ Less chance of detection

Hypersonic vs Ballistic Missiles

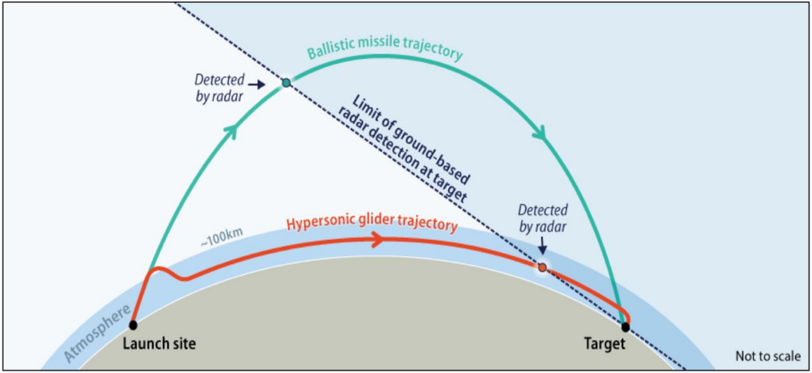


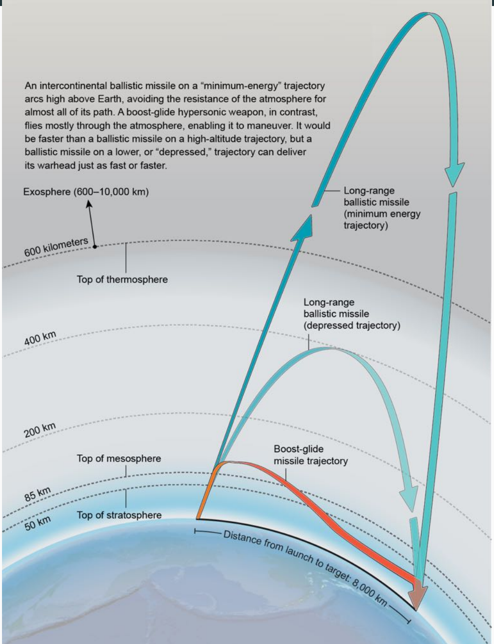
image from economist.com

Hypersonic “Boost-Glide” vs Ballistic Missiles

Trajectory at a lower altitude than even “Depressed-trajectory” ballistic missiles

Equally fast, and more difficult to detect

Image from Scientific American



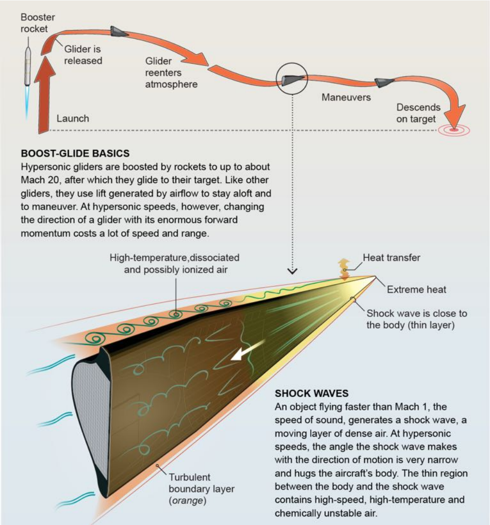
Hypersonic "Boost-Glide" Missiles

"Boost" phase using a rocket (may reach $M \sim 20$)

Drag and heating are serious problems

High Temperature may reduce material strength!

Image from Scientific American



Hypersonic Vehicles

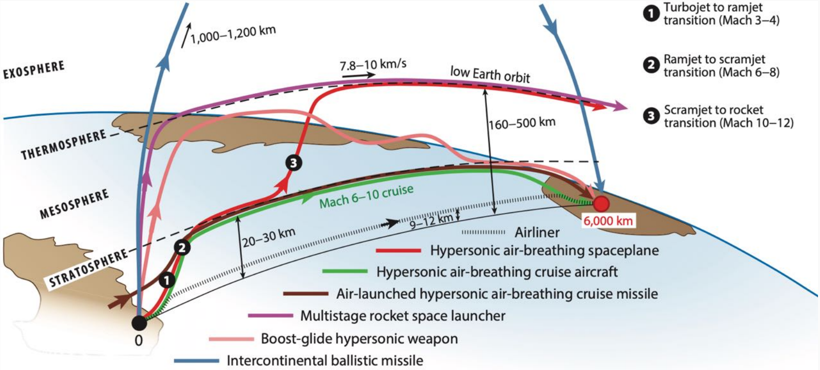
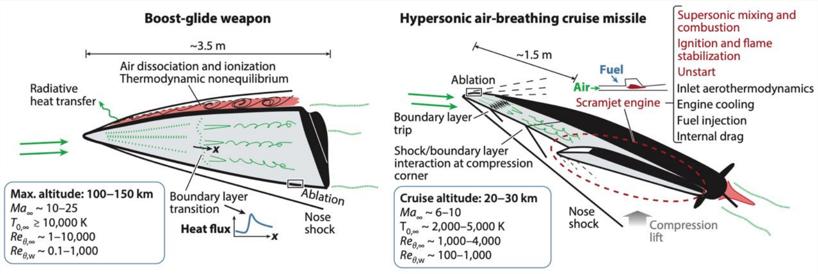


image from Urzay, Ann. Rev. FluMech.

Hypersonic Vehicles



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