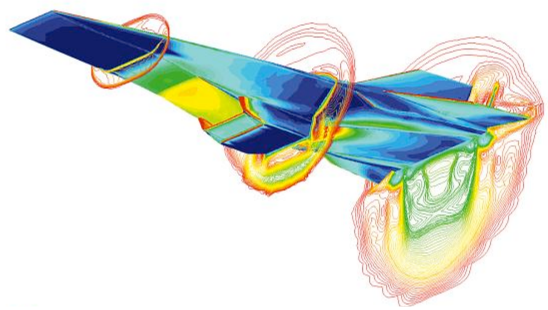
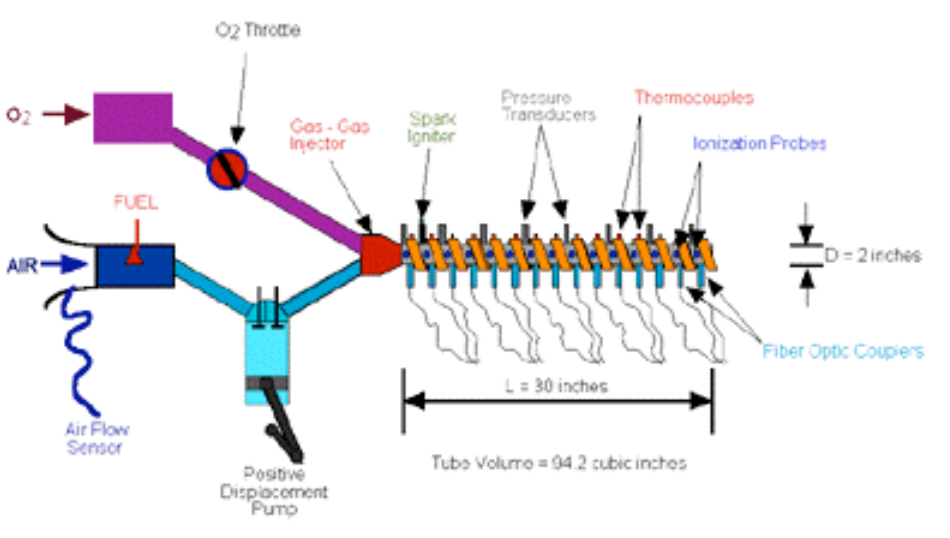
Section 9.4

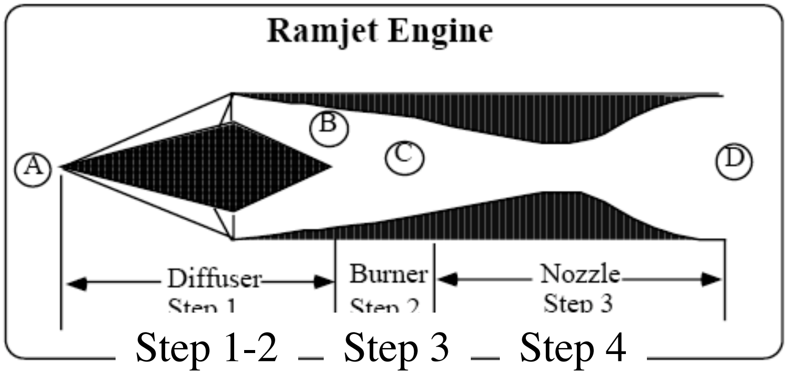
Supersonic Combustion Ramjets (SCRAMjets) and Combined Cycle Engines

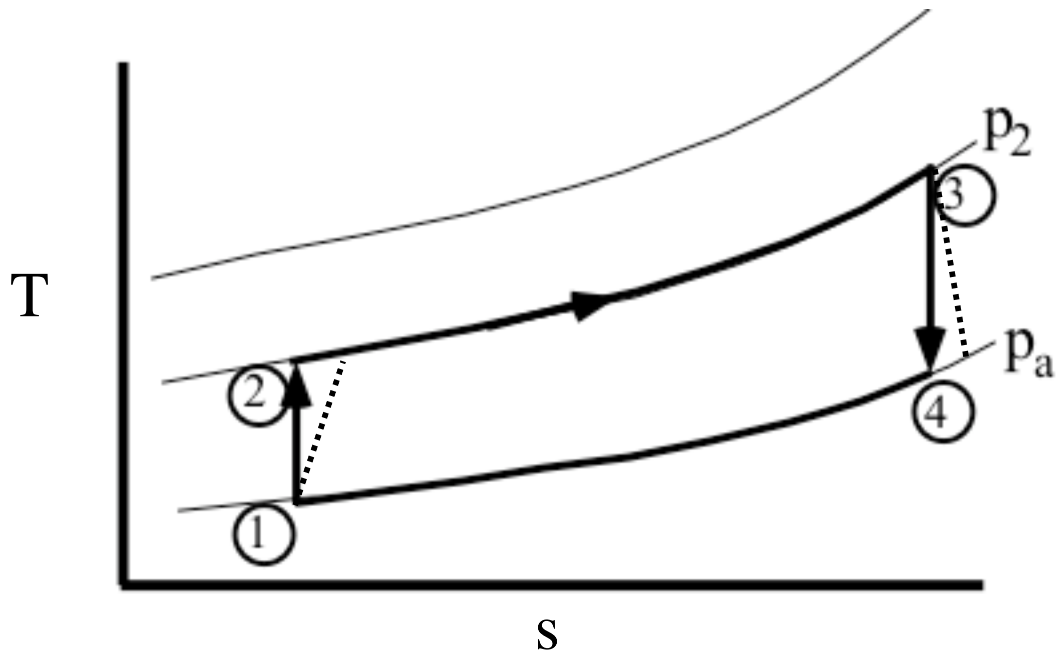




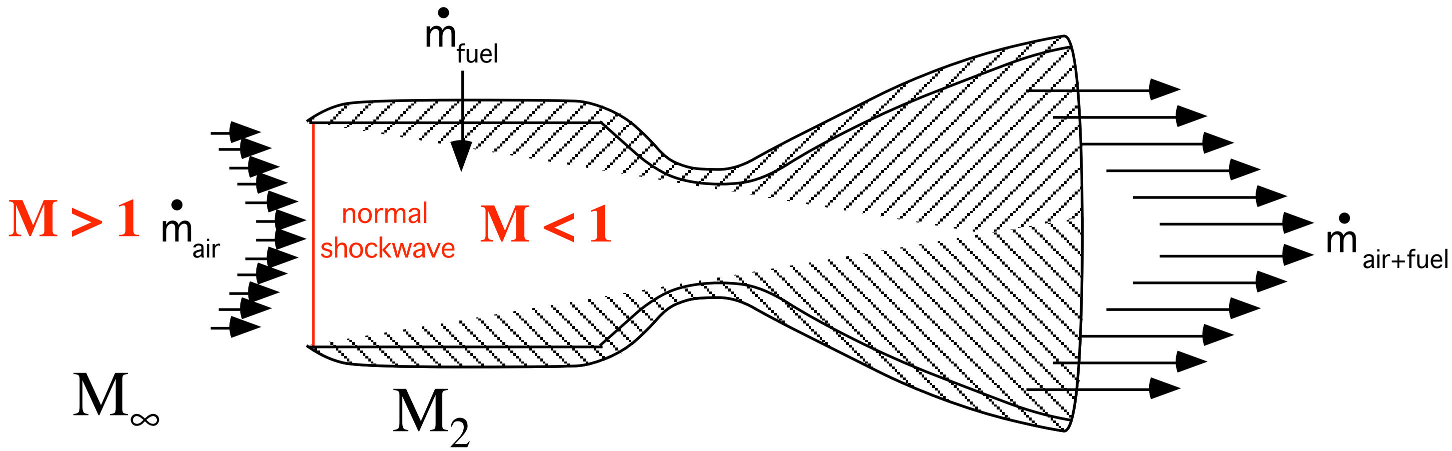
Ideal Ramjet Cycle Analysis

T-s Diagram





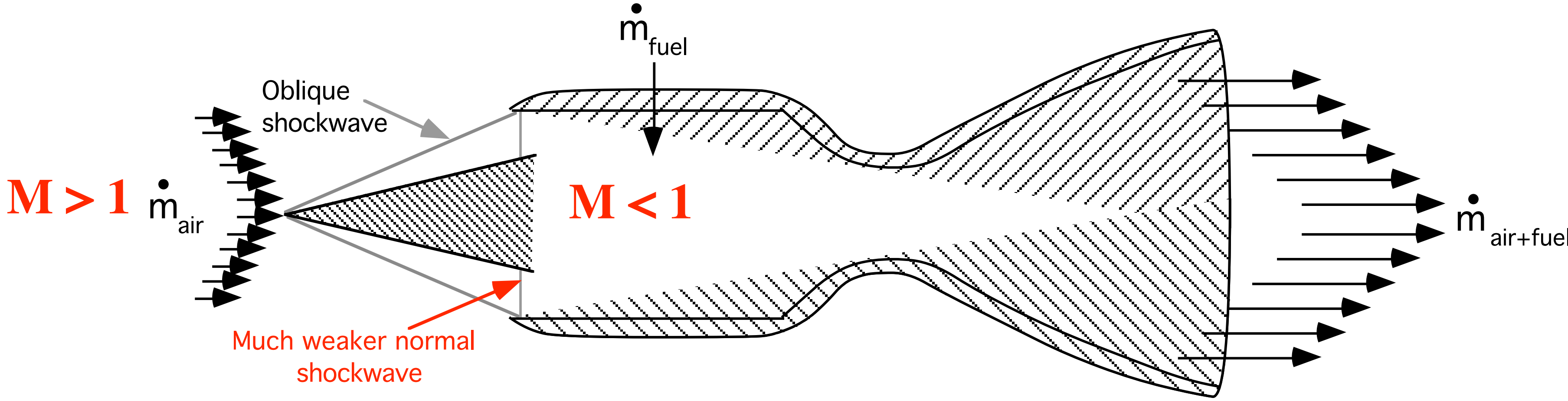
Ideal Ramjet: *Inlet and Diffuser with normal shock*

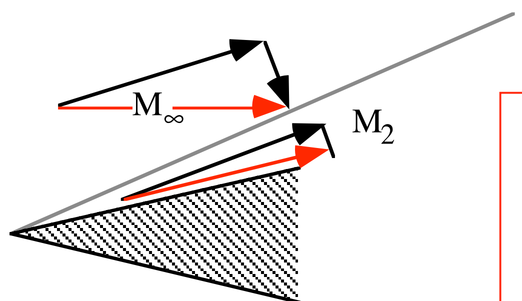


- Mechanical Energy is Dissipated into Heat
- Huge Loss in Momentum

Ideal Ramjet: *Inlet and Diffuser with Oblique shock*

- So … we put a spike in front of the inlet

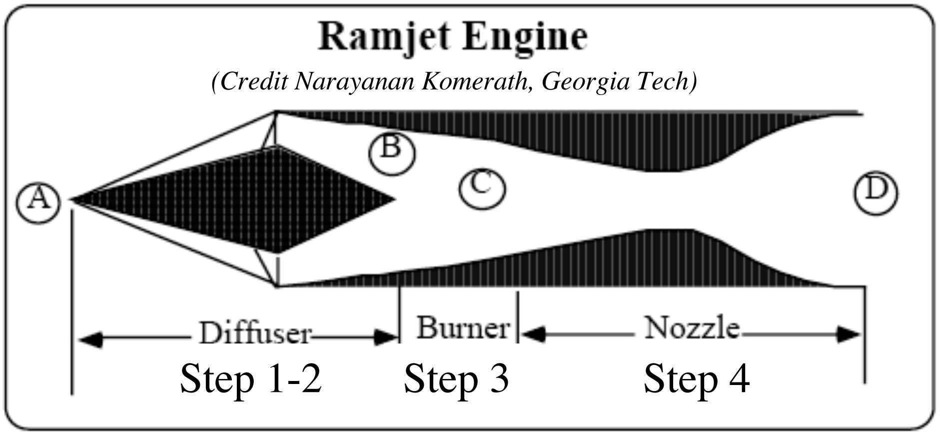




- How does this spike Help?
- By forming an Oblique Shock wave ahead of the inlet

Thermodynamic Efficiency of Ideal Ramjet, revisited

$$\eta = 1 - \left(\frac{P_A}{P_B}\right)^{\frac{\gamma-1}{\gamma}} \frac{\left(T_C - \left(\frac{P_{0_B}}{P_{0_A}}\right)^{\frac{\gamma-1}{\gamma}} T_B\right)}{\left(T_C - T_B\right)}$$



i) As engine pressure ratio, P_B/P_A, goes up … *η goes up*

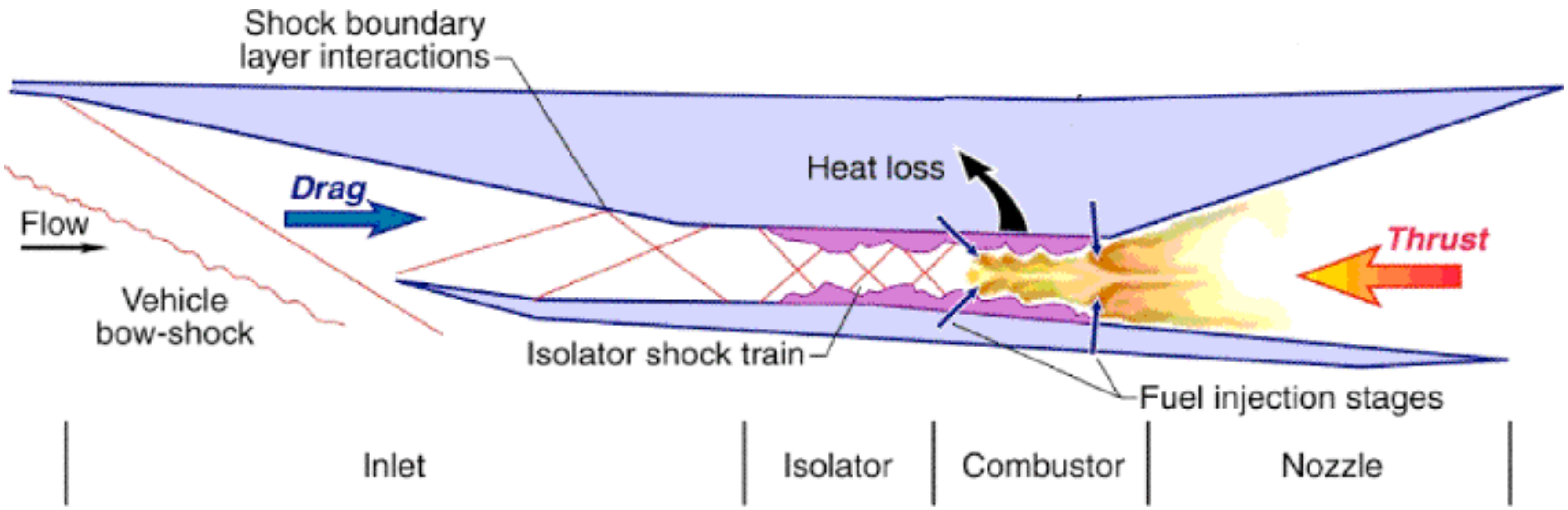
ii) As combustor temperature difference T_C-T_B goes up … *η goes up*

iii) As inlet total pressure ratio (P_{0_B}/P_{0_A}) goes down … (stagnation pressure loss goes up) … *η goes down*

ScrRamjet design Issues, I (cont'd)

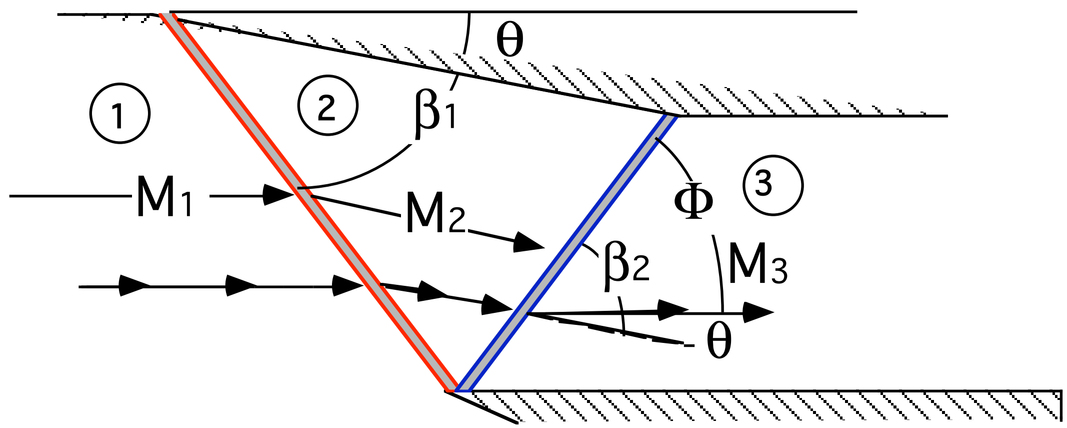
• What if we keep engine flow path supersonic to minimize stagnation pressure loss?

• How do we keep the Inflow supersonic?



• Series of very weak (highly oblique) shockwaves and expansion shocks keep the flow supersonic throughout the engine

SCRAMJet Inlet Design Example



- Find β_2, Φ, M_3

- Example Calculation

$$M_1 = 3.6$$

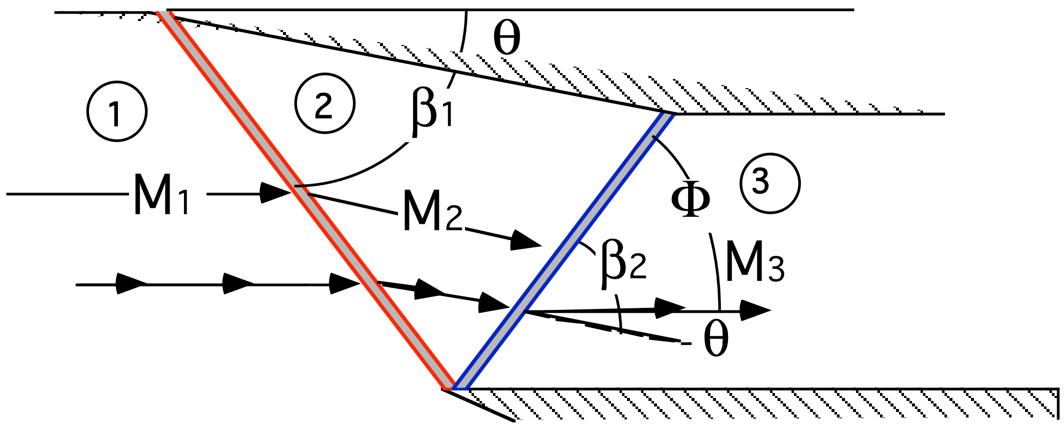
$$\tan(\theta) = \frac{2\left\{M_1^2 \sin^2(\beta) - 1\right\}}{\tan(\beta)\left[2 + M_1^2\left[\gamma + \cos(2\beta)\right]\right]} \rightarrow$$

$$\theta = 20^o$$

$$\gamma = 1.4$$

$$\frac{180}{\pi}\operatorname{atan}\left(\frac{2\left(3.6^2 \sin^2\left(\frac{\pi}{180}34.1102\right) - 1\right)}{\left(\tan\left(\frac{\pi}{180}34.1102\right)\right)\left(2 + 3.6^2\left(1.4 + \cos\left(\frac{\pi}{180}2\cdot 34.1102\right)\right)\right)}\right) = 20°$$

SCRAMJet Inlet Design Example (cont'd)



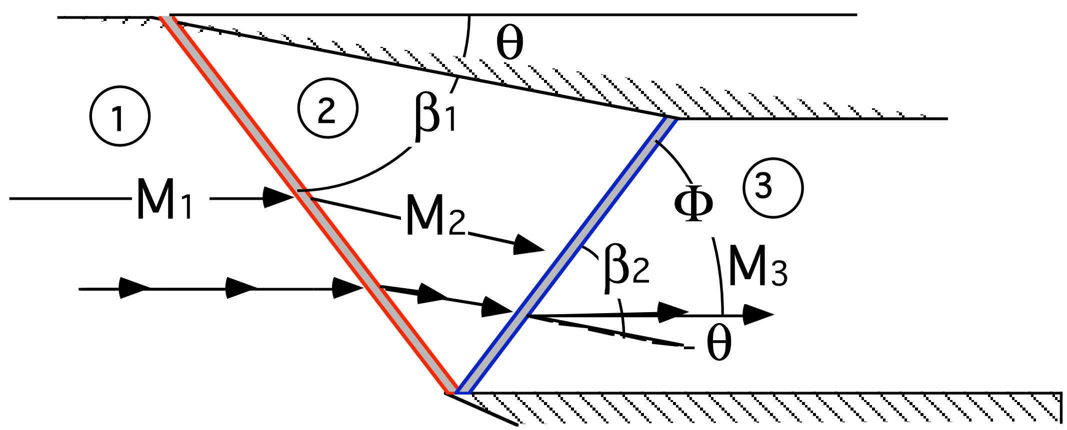
- Solve for β_1

$$\tan(\theta) = \frac{2\left\{M_1^{\,2}\sin^2(\beta)-1\right\}}{\tan(\beta)\left[2+M_1^{\,2}\left[\gamma+\cos(2\beta)\right]\right]} \rightarrow$$

$$\frac{180}{\pi}\,\text{atan}\left(\frac{2\left(3.6^2\sin^2\left(\frac{\pi}{180}34.1102\right)-1\right)}{\left(\tan\left(\frac{\pi}{180}34.1102\right)\right)\left(2+3.6^2\left(1.4+\cos\left(\frac{\pi}{180}2\cdot 34.1102\right)\right)\right)}\right) = 20^\circ$$

$$\beta_1 = 34.1102^\circ$$

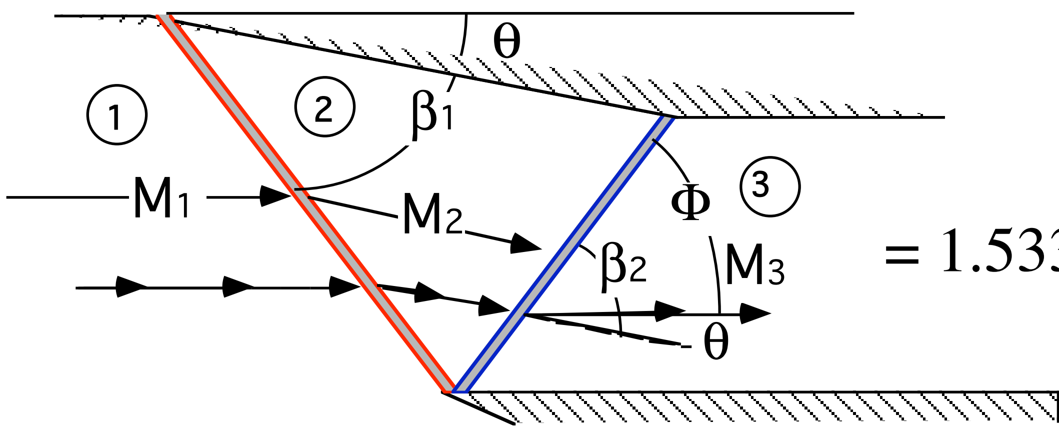
SCRAMJet Inlet Design Example (cont'd)



- $M_{1n} = M_1 \sin\beta_1 = 3.6 \sin\left(\frac{\pi}{180} 34.1102\right) = 2.0188$
- Normal Shock Solver-->

$$M_2 n = 0.574168 \rightarrow M_2 = \frac{M_2 n}{\sin(\beta_1 - \theta)} = \frac{0.574168}{\sin\left(\frac{\pi}{180}(34.1102 - 20)\right)} = 2.3552$$

SCRAMJet Inlet Design Example (cont'd)



= 1.5333

θ-β-M solver, for $M_2 = 2.3552$ and $\theta_2 = 20°$,

---> $\beta_2 = 45.0534° \text{---->} \Phi = 45.0534° - 20° = 25.0534°$

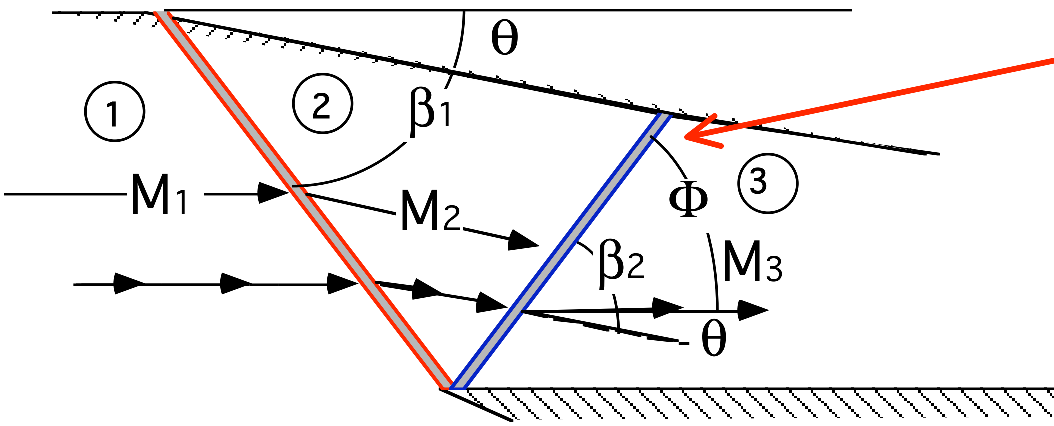
$$\left(M_2 n\right)_{\beta_2} = 2.3552 \sin(45.0534) = 0.649303$$

$$\rightarrow M_3 = \frac{\left(M_2 n\right)_{\beta_2}}{\sin(\beta_2 - \theta)} = \frac{0.649303}{\sin\left(\frac{\pi}{180}(45.0534 - 20)\right)} = 1.5333$$

So we have Gotten inside The duct and Still are supersonic!

Off Design Operation

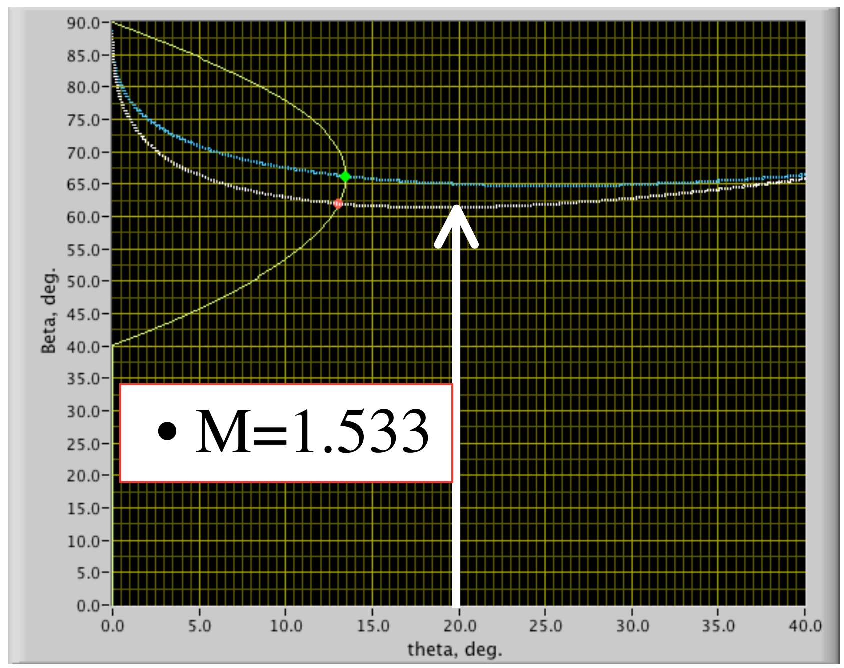
- What if we do our ramp geometry incorrectly for inlet mach?



- 20° $>\theta_{max}$

Detached Shockwave!

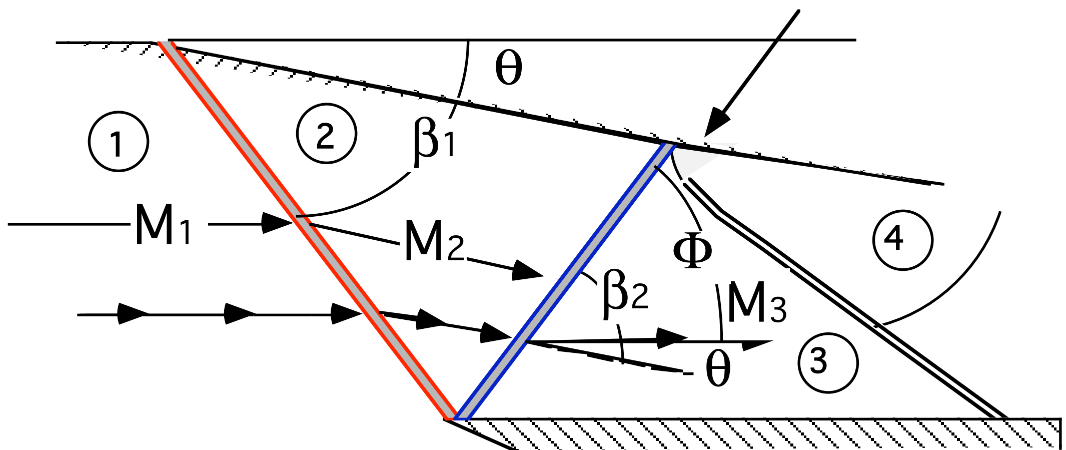
θ-β-M solver, for
$M_2 = 2.3552$ and $\theta_2 = 20°$,

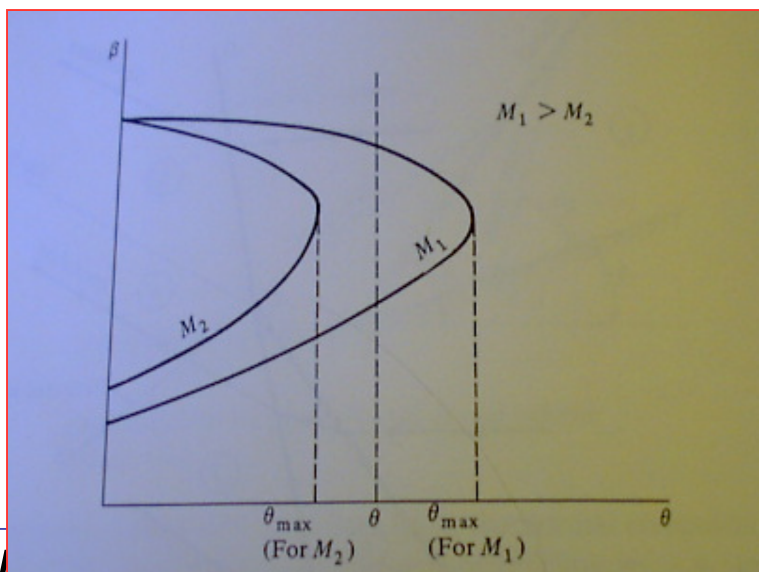


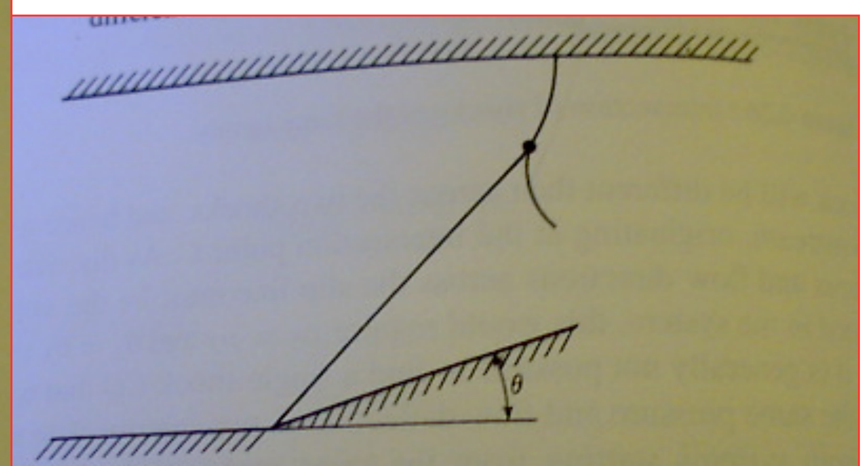
Off Design Operation

(cont'd)

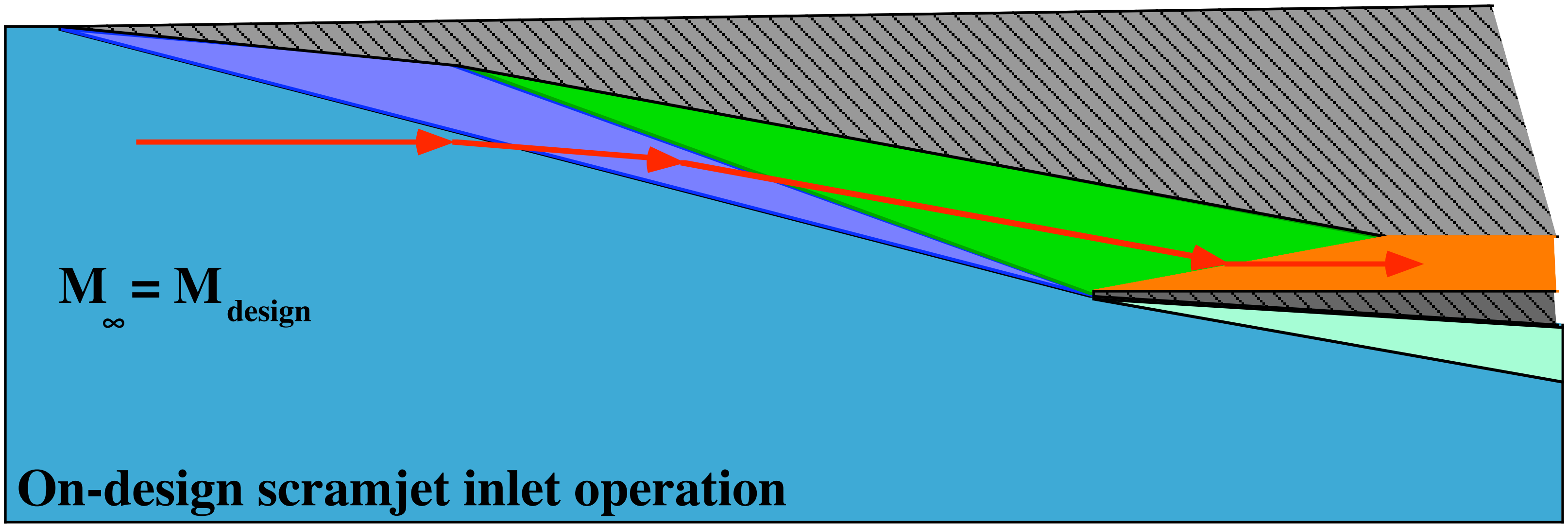
Mach reflection ... localized strong shockwave ... starts bad train of events leading to flow separation and possible unstart





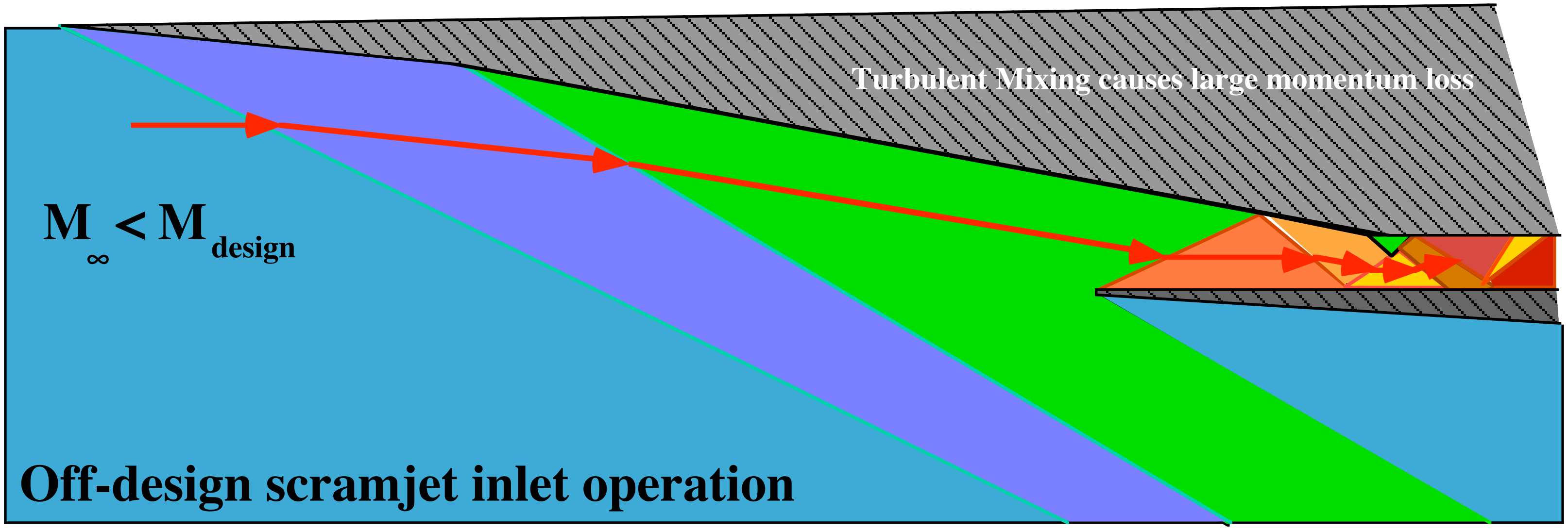


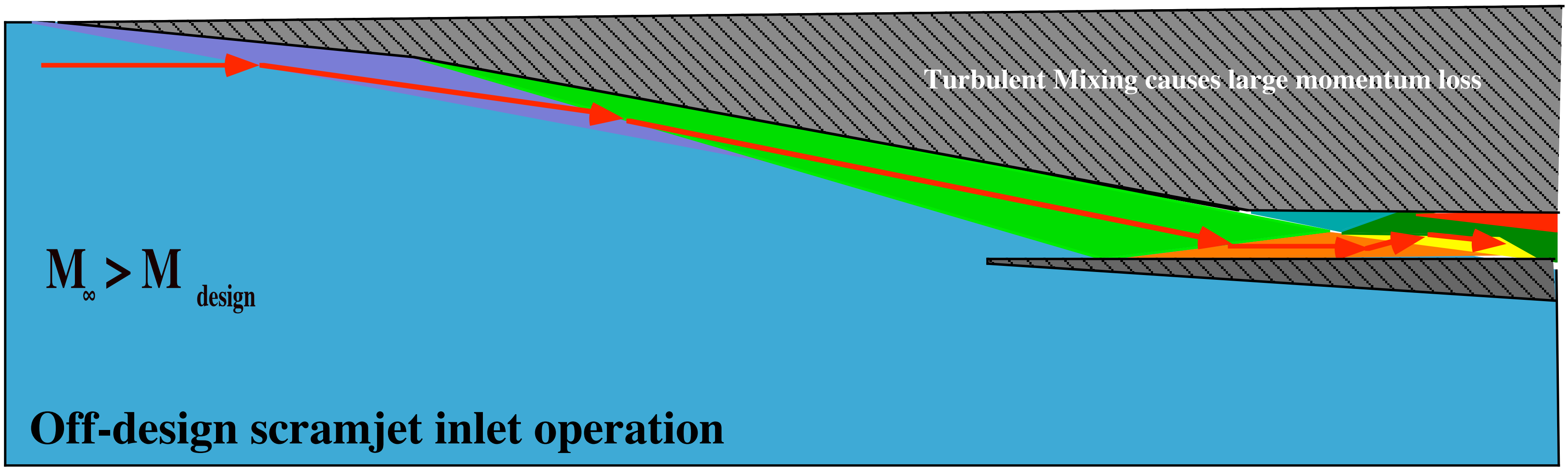
Inlet “Point Design”



- SCRAMjets are *VERY* …
  Sensitive to inlet mach number

Inlet "Point Design"(cont'd)





X-43A Side by Side Comparison

- Subtle but important shape differences Mach 10 Inlet likely would not start at Mach 7

Mach 7 Vehicle

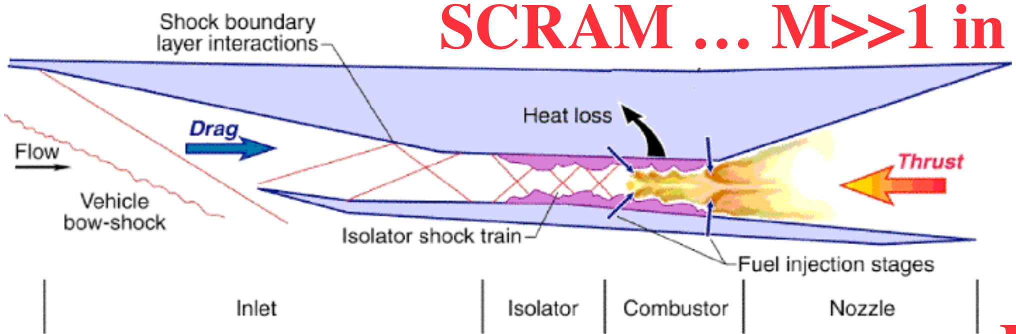
Mach 10 Vehicle

ScrRamjet design issues, II

• Supersonic flow makes flow control within the combustion chamber more difficult.

• Massflow entering combustion chamber must mix with fuel and have sufficient time for initiation and reaction, while traveling supersonically through combustion chamber, before the burned gas is expanded through the thrust nozzle.

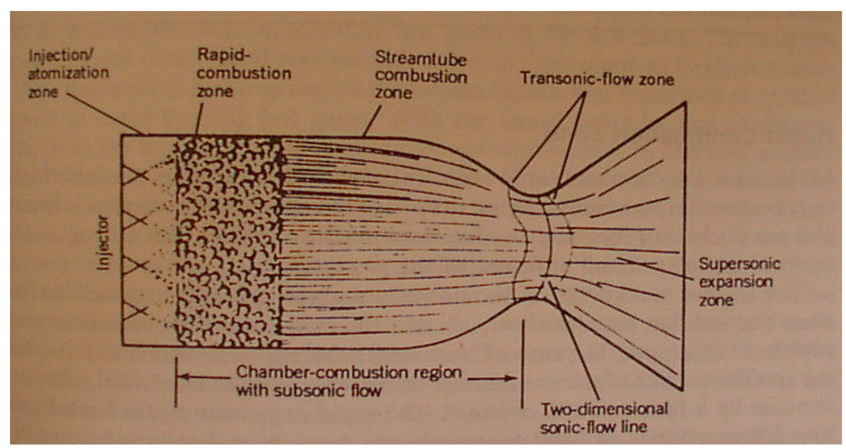
SCRAM … M>>1 in burner



$$aA + bB \underset{k_b}{\overset{k_f}{\rightleftharpoons}} cC + dD$$

Reaction times are Critically tuned to Flow path mach number

Rocket … M<<1 in burner



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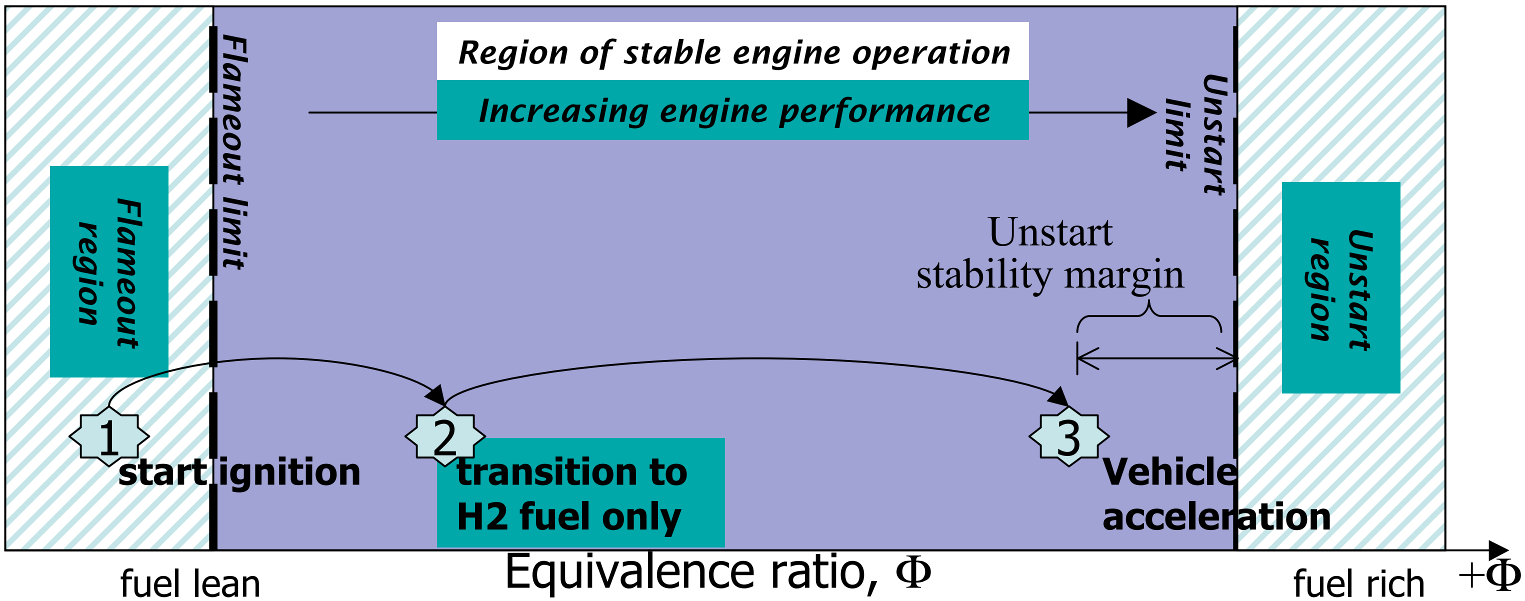
ScrRamjet design issues, II (cont'd)

• Supersonic flow places stringent requirements on the pressure and temperature of the flow, and requires that the fuel injection and mixing be extremely efficient.



•Propulsion controller designed to maintain stable operation while achieving necessary performance

-- Flameout - low fuel flow condition where hydrogen-only combustion is not sustained

-- Unstart - high fuel flow condition where shock train moves through isolator causing causing normal shock to Occur .. Choked Nozzle result … with flow spill out … likely that shockwave forced back up to inlet .. *Very bad*

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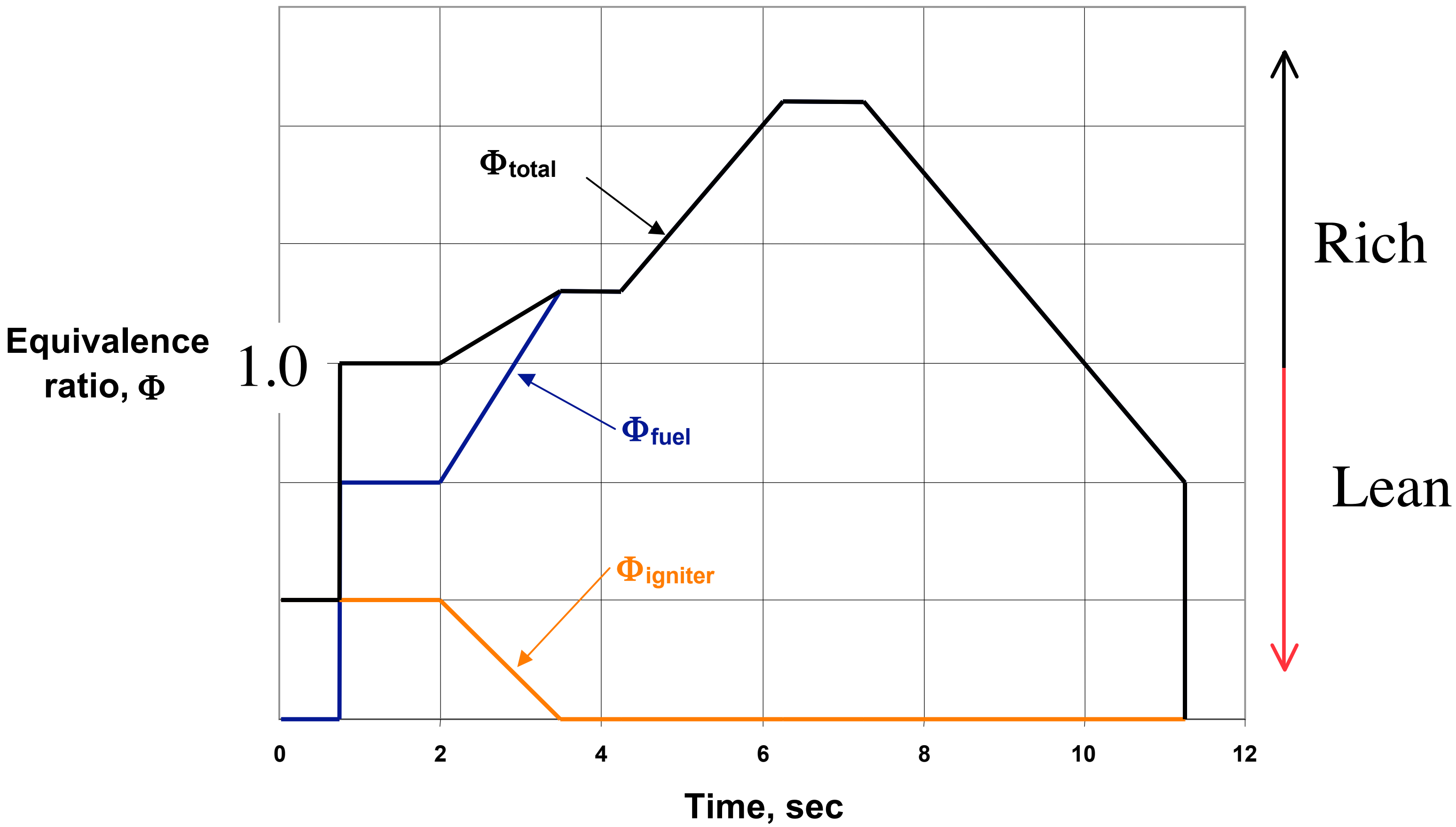
ScrRamjet design issues, II (cont'd)

- Typical Equivalence Ratio Schedule for Scramjet Burn



ScrRamjet design issues, II (cont'd)

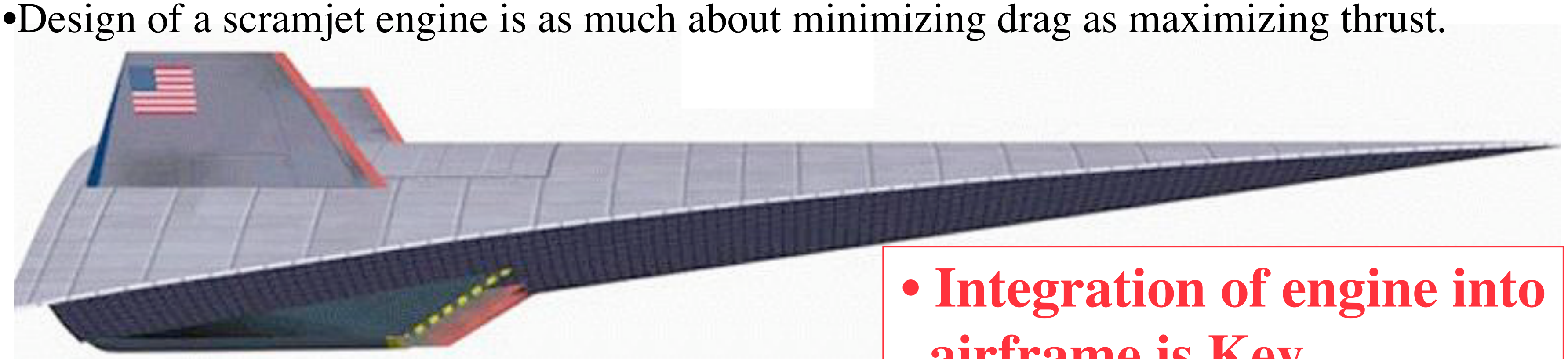
• In typical ramjet inflow is decelerated to subsonic speeds and then reaccelerated via nozzle to supersonic speeds to produce thrust. This deceleration, which is produced by a normal shock, creates a total enthalpy loss which limits the upper operating point of a ramjet engine.

• In supersonic combustion, enthalpy of freestream air entering the scramjet engine is large compared to the heat energy released by the combustion reaction

• Depending on fuel, combustion equivalence ratio, and freestream altitude,potential combustion heat release is equal to freestream flow enthalpy between Mach 8 and Mach 10.

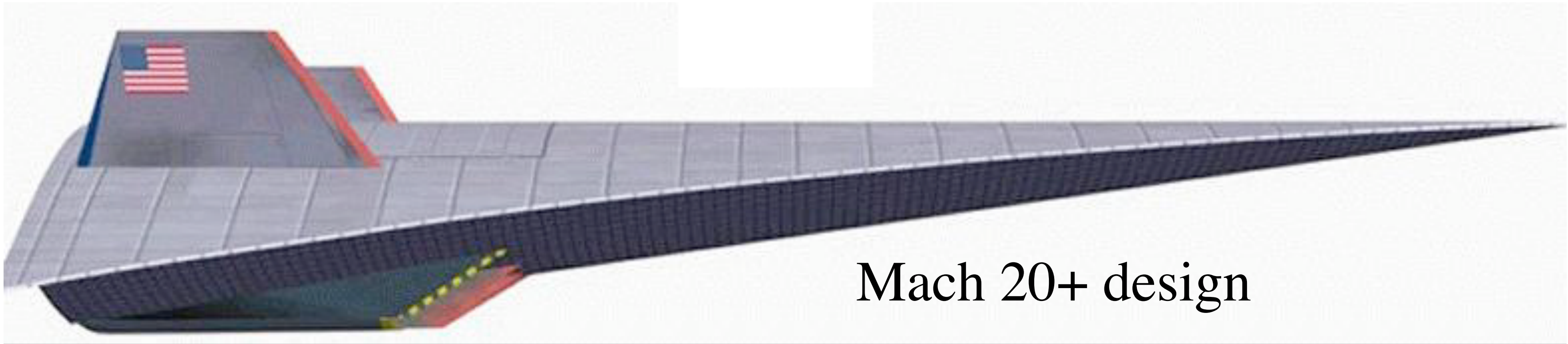
• Heat released from combustion at Mach 25 is only 10% of total enthalpy of working fluid.

•Design of a scramjet engine is as much about minimizing drag as maximizing thrust.

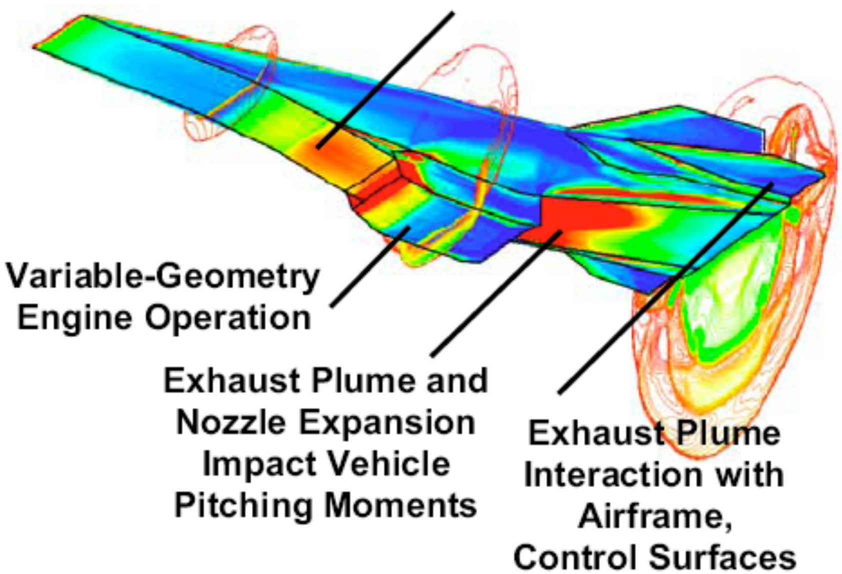


• Integration of engine into airframe is Key

ScrRamjet design issues, II (cont'd)



Mach 20+ design



Mach 7-10 design

- **Integration of engine into airframe is Key**

Example Enthalpy Calculation

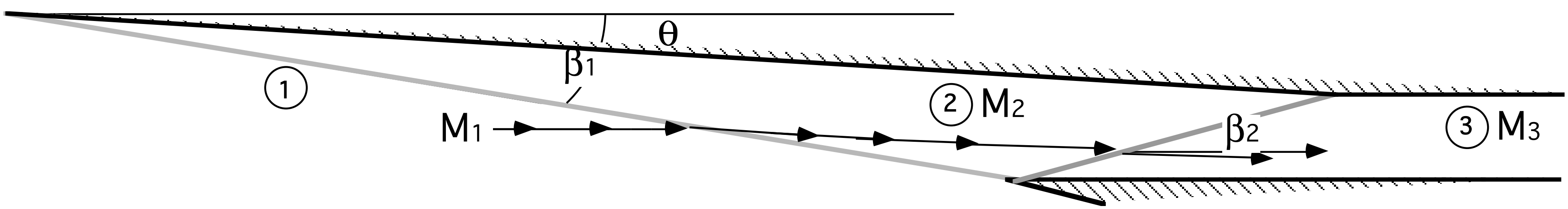
- Air enters Mach 10 SCRAM inlet at 30 km altitude

$$p_\infty = 1.17180\ kPa,\ 226.65\ °K,\ \theta_{ramp}=4°$$

Conditions at 2:

$$\tan(\theta) = \frac{2\left\{M_1^{\ 2}\sin^2(\beta)-1\right\}}{\tan(\beta)\left[2+M_1^{\ 2}\left[\gamma+\cos(2\beta)\right]\right]} \rightarrow$$

$\beta_1 = 8.6531°$
$M_2 = 8.622746$
$p_2/p_\infty = 2.474152$
$T_2/T_\infty = 1.323222$
$P0_2/P0_\infty = 0.928350$



Example Enthalpy Calculation (cont'd)

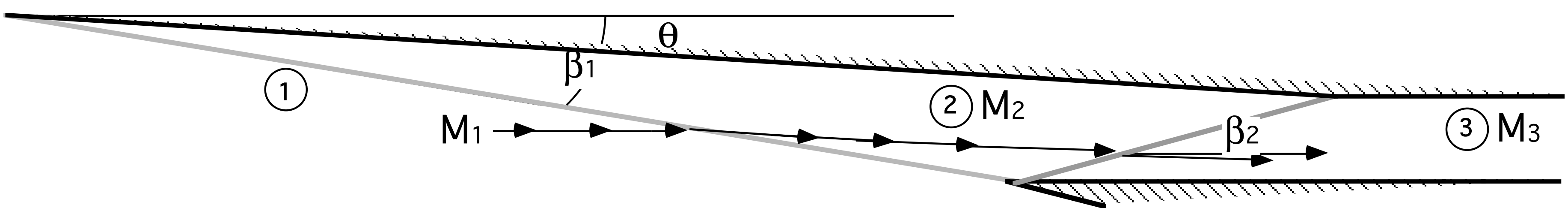
$\beta_1 = 8.6531°$
$M_2 = 8.622746$
$p_2/p_\infty = 2.474152$
$T_2/T_\infty = 1.323222$
$P0_2/P0_\infty = 0.928350$

$\beta_2 = 9.521°$
$M_3 = 7.576$
$p_3/p_2 = 2.20665$
$T_3/T_2 = 1.271723$
$P0_3/P0_2 = 0.951393$

$p_3/p_\infty = 5.4960$
$T_3/T_\infty = 1.6831$
$P0_3/P0_\infty = 0.8832$

$$P_3 = 5.496 \cdot 1.1718 = 6.550 \text{ kPa}$$

$$T_3 = 1.6831 \cdot 226.65 = 381.47 \text{ °K}$$



Example Enthalpy Calculation (cont'd)

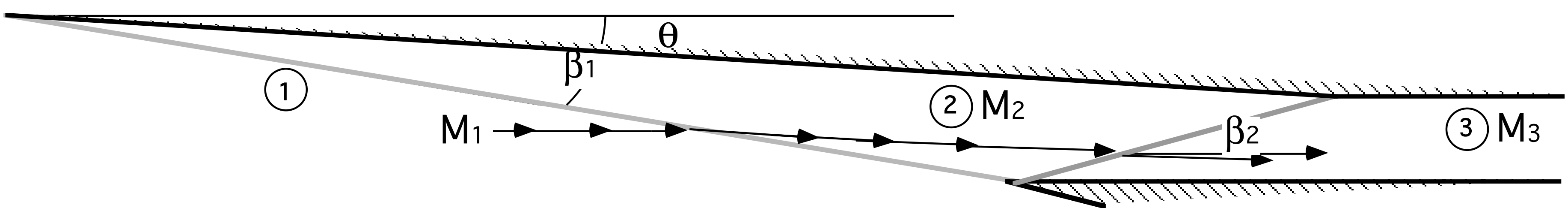
- Specific Enthalpy of flow entering combustor:

$$h_3 = C_p T_3 + \frac{\left[\sqrt{\gamma R_g T_3} M_3\right]^2}{2} = \frac{\left(\left(1.4 \cdot 287.056 \cdot 381.47\right)^{0.5} 7.576\right)^2}{2} + 1004.7 \cdot 381.47$$

$$= 4.7828 \text{ MJ/kg}$$

$$p_3 = 5.496 \cdot 1.1718 = 6.550 \text{ kPa}$$

$$T_3 = 1.6831 \cdot 226.65 = 381.47 \text{ °K}$$



Example Enthalpy Calculation (cont'd)

- CEA Calculation: GH_2 fuel, $\Phi=1$

$p_3 = 6.550$ kPa

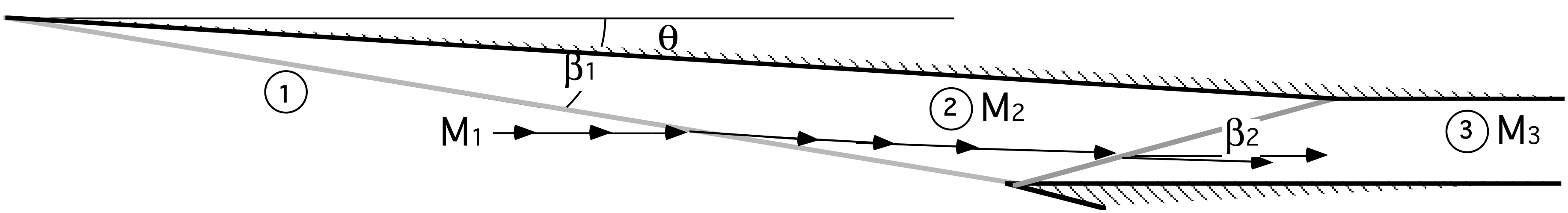
$T_3 = 381.47$ °K

T, K	**2238.92**
MW, (1/n)	**24.519**
GAMMA	**1.1565**

Combustion Enthalpy is Less than Freestream Enthalpy! 98.5%

$$\Delta h_{combustion} = C_p\left[T_{combustion} - T_3\right] = \frac{R_u}{M_w}\frac{\gamma}{\gamma-1}\left[T_{combustion} - T_3\right] =$$

$$\left(\frac{8314.4126}{24.519}\right)\left(\frac{1.1565}{1.1565-1}\right)(2238.92 - 381.47) = 4.655 \text{ MJ/kg}$$



Example Enthalpy Calculation (cont'd)

- Calculate thermodynamic efficiency of engine

T_B=381.47 °K
Tc= **2238.92**°K
p_3/ p_∞ = 5.4960
T_3 / T_∞ = 1.6831
$P0_3/ P0_\infty$ = 0.8832
γ ~ **(1.1565+1.4)/2=1.27825**

$$\eta = 1 - \left(\frac{p_\infty}{p_3}\right)^{\frac{\gamma-1}{\gamma}} \frac{\left(T_C - \left(\frac{P_{0_3}}{P_{0_\infty}}\right)^{\frac{\gamma-1}{\gamma}} T_3\right)}{\left(T_C - T_3\right)} =$$

$$1 - \left(\frac{1}{5.4960}\right)^{\frac{1.27825-1}{1.27825}} \frac{\left(2239.92 - \left(\left((0.8832)^{\frac{1.27825-1}{1.27825}}\right)\right)381.47\right)}{(2239.92 - 381.47)} = 0.3061$$

About 50% as efficient as out previous ramjet design (section 9.1) Operating at Mach 4 and 10km altitude ***(η=0.6)***

ScrRamjet Design Issues, III

- look at Mach 4 Ramjet problem (Section 9.1) …
  let $P_{0_B}/P_{0_A} = 1$

$$\eta = 1 - \left(\frac{P_A}{P_B}\right)^{\frac{\gamma-1}{\gamma}} \frac{\left(T_C - \left(\frac{P_{0_B}}{P_{0_A}}\right)^{\frac{\gamma-1}{\gamma}} T_B\right)}{\left(T_C - T_B\right)} =$$

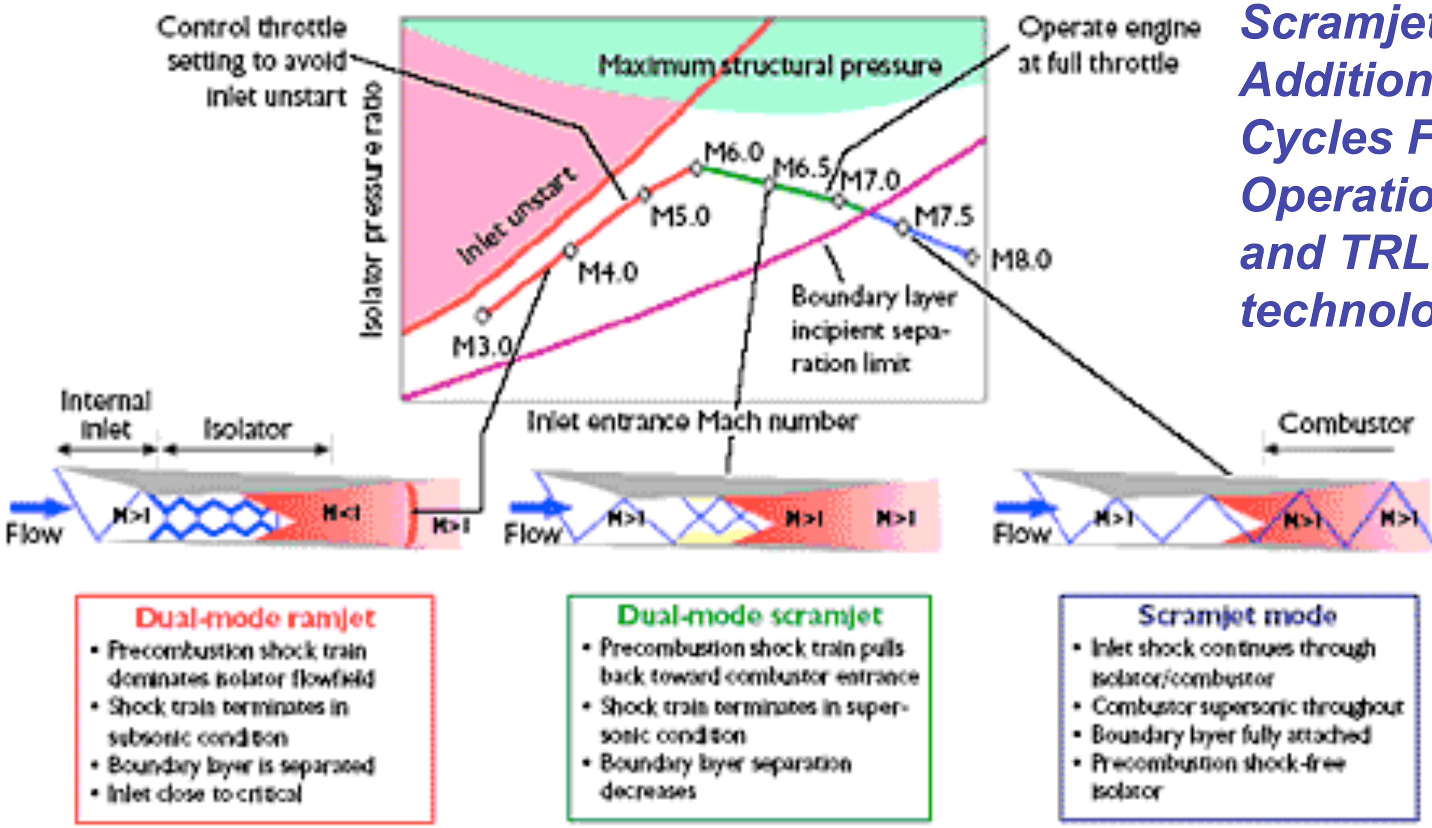
8% increase in Efficiency …
Compared to Ramjet
… but can we
Do this? … no!

$$1 - \frac{38.422^{\frac{-(1.4-1)}{1.4}}\,(2662.82 - 1 \cdot 856.61)}{(2662.82 - 856.61)} = 0.6475$$

ScrRamjet design issues, III (cont'd)

- Supersonic flow cannot maintain stable combustion below ~ Mach 6

- Scramjets are feasible only for sustaining hypersonic speeds, not for achieving them from zero velocity



Scramjets Require Additional Cycles For An Operational Vehicle … and TRL for these technologies are low

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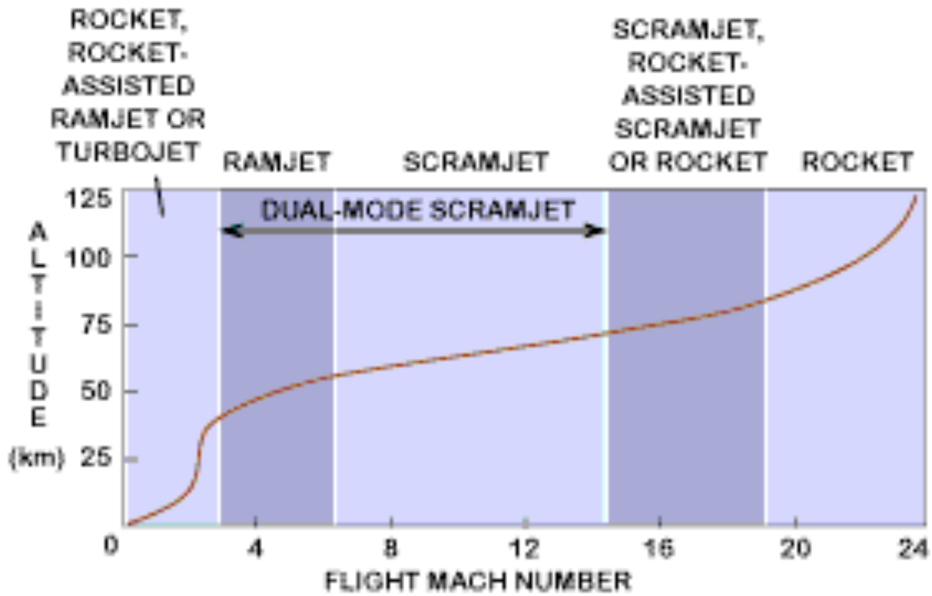
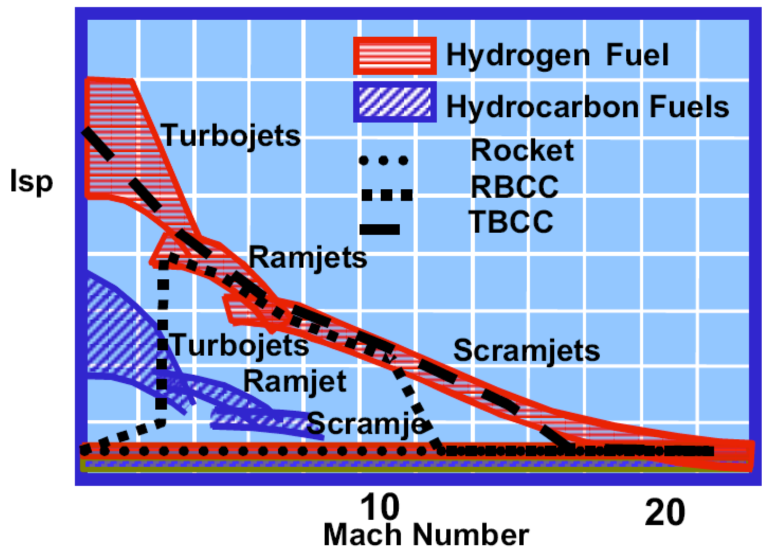
ScrRamjet design issues, III (cont'd)





Combined cycle rocket engines

… Engines that are part jet engine And part rocket motor!

… or part turbojet and part SCRAMjet

Rocket + Scramjet =

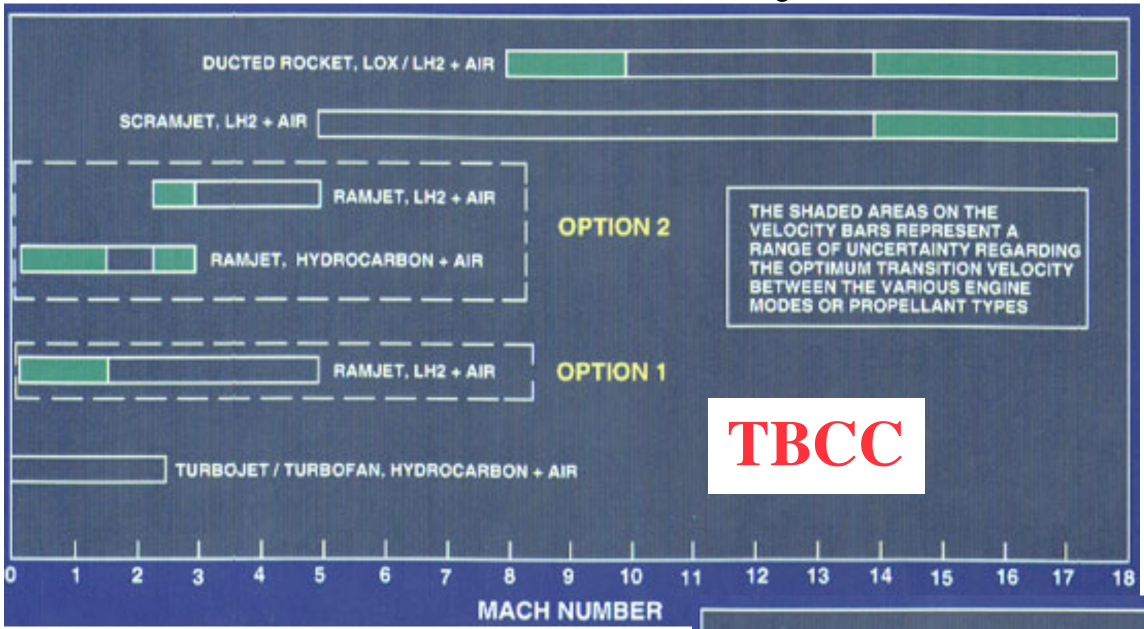
Rocket Based Combined Cycle (RBCC)

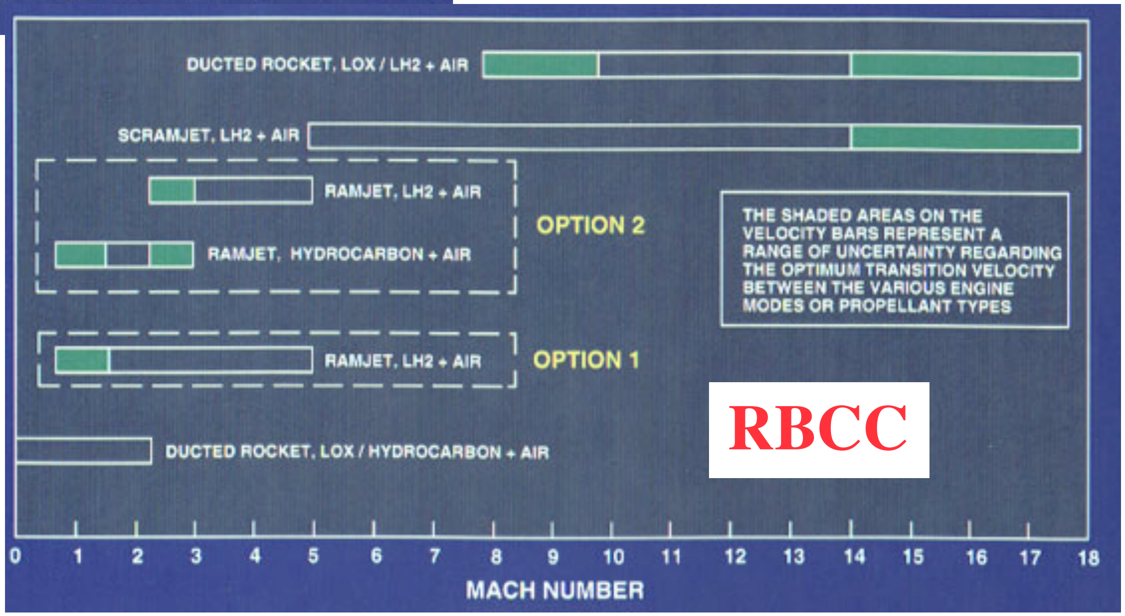
OR

Turbine + Scramjet =

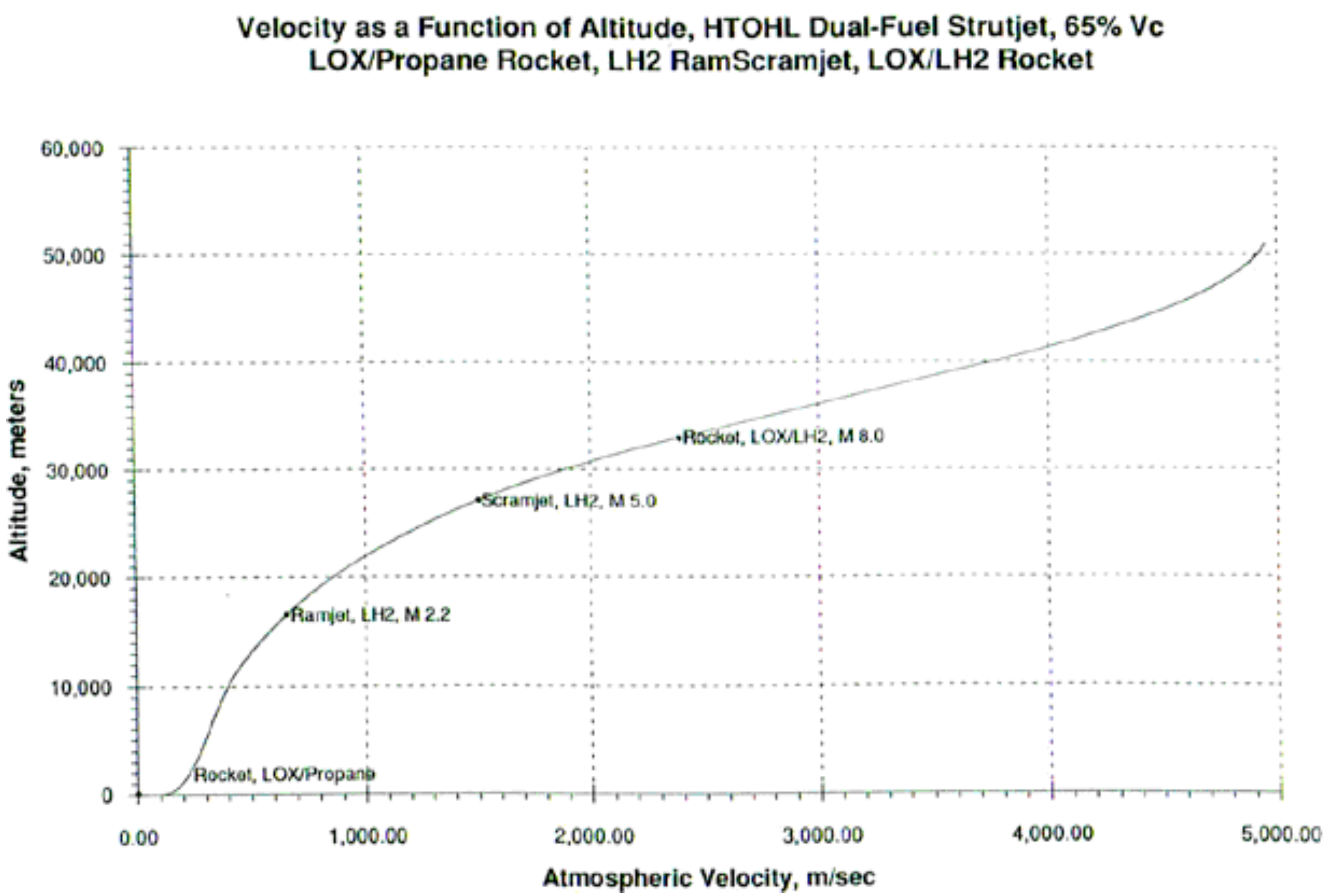
***Turbine Based Combined Cycle* (TBCC)**

Combined Cycle Mission Profile

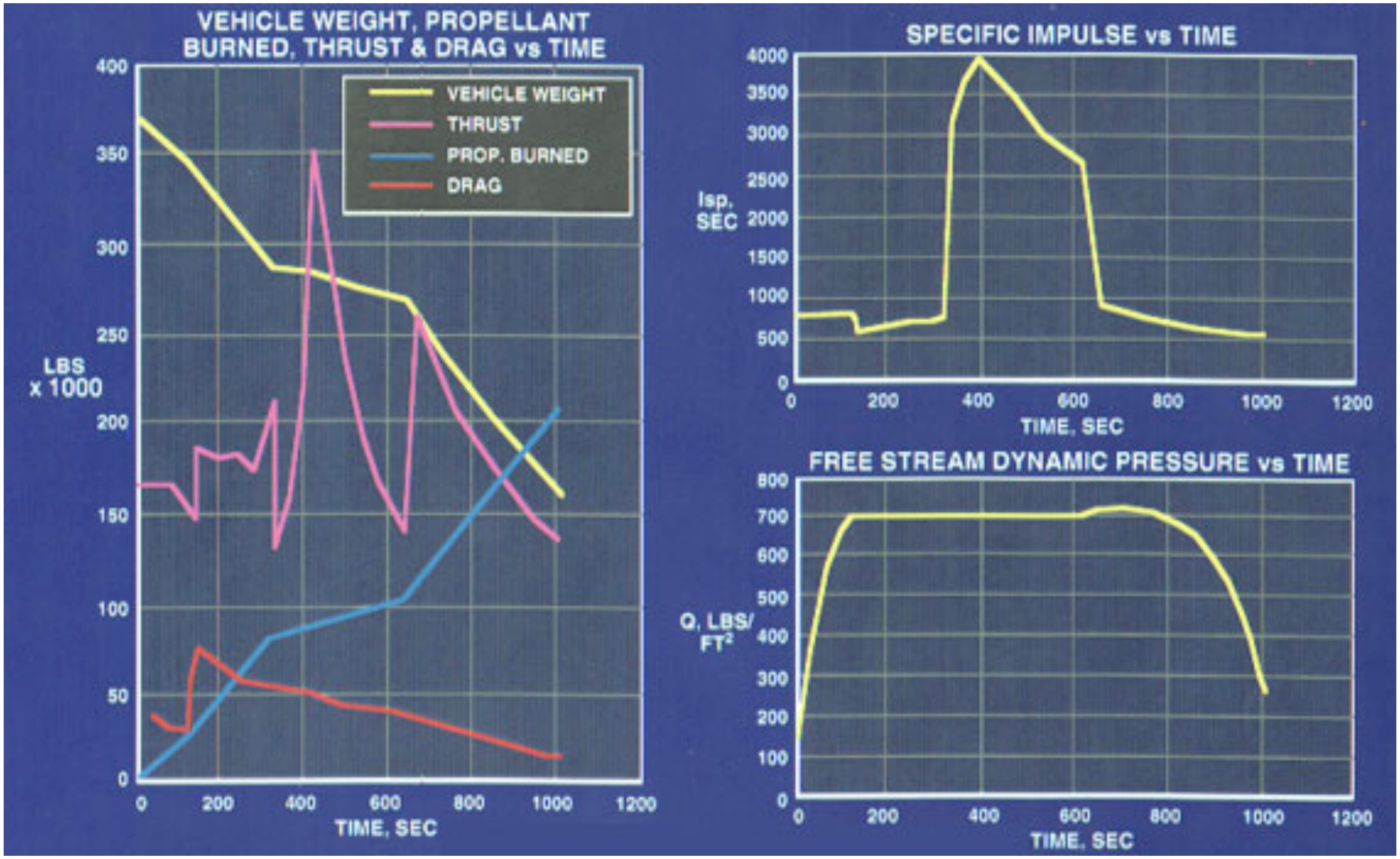




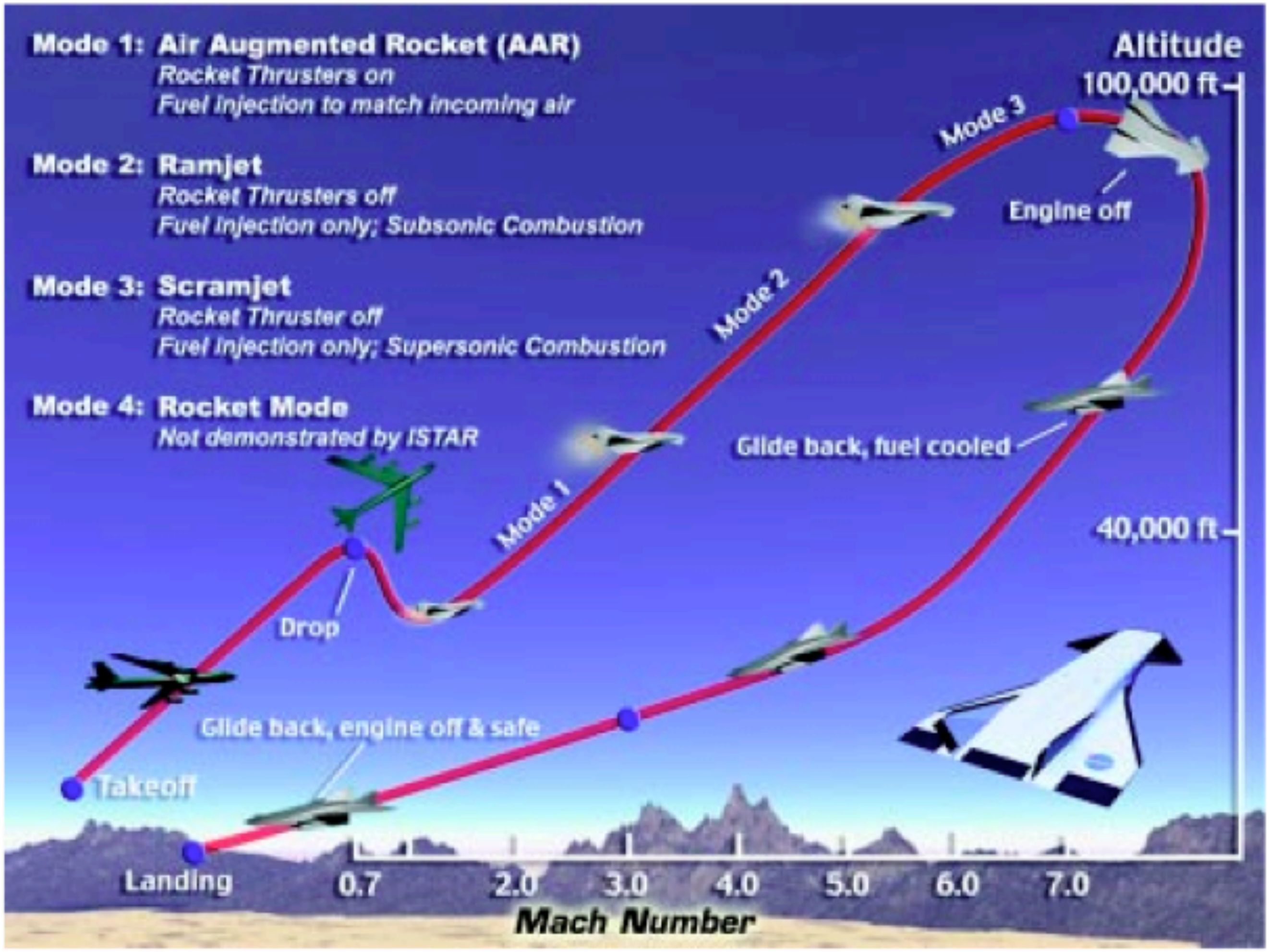
Rocket-Based Combined Cycle Mission Profile (cont'd)



RBCC Mission Profile (cont'd)



Proposed RBCC Demo Program)



Integrated System Test of an Air-breathing Rocket (ISTAR)

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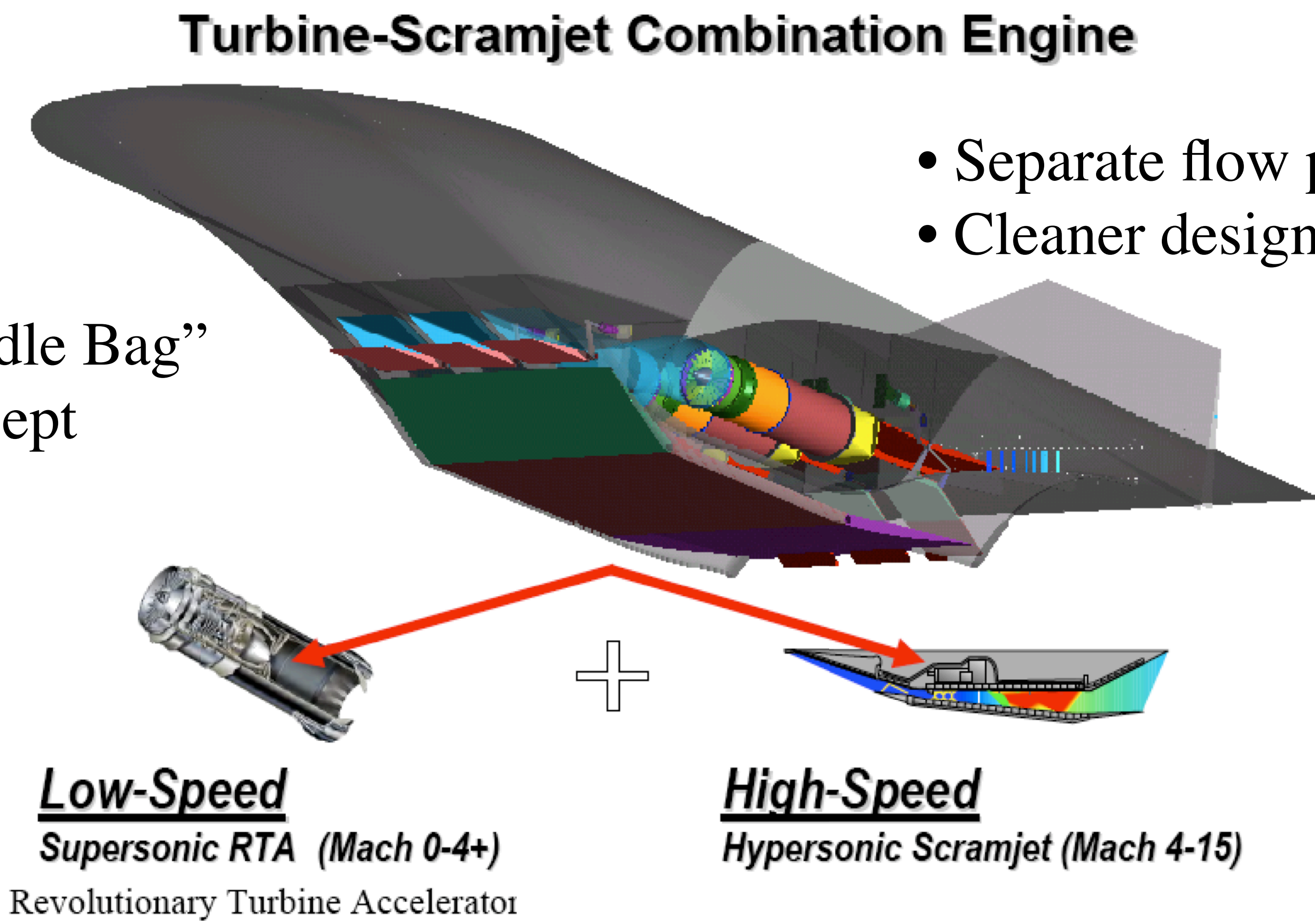
Turbine Based Combined Cycle (TBCC), I



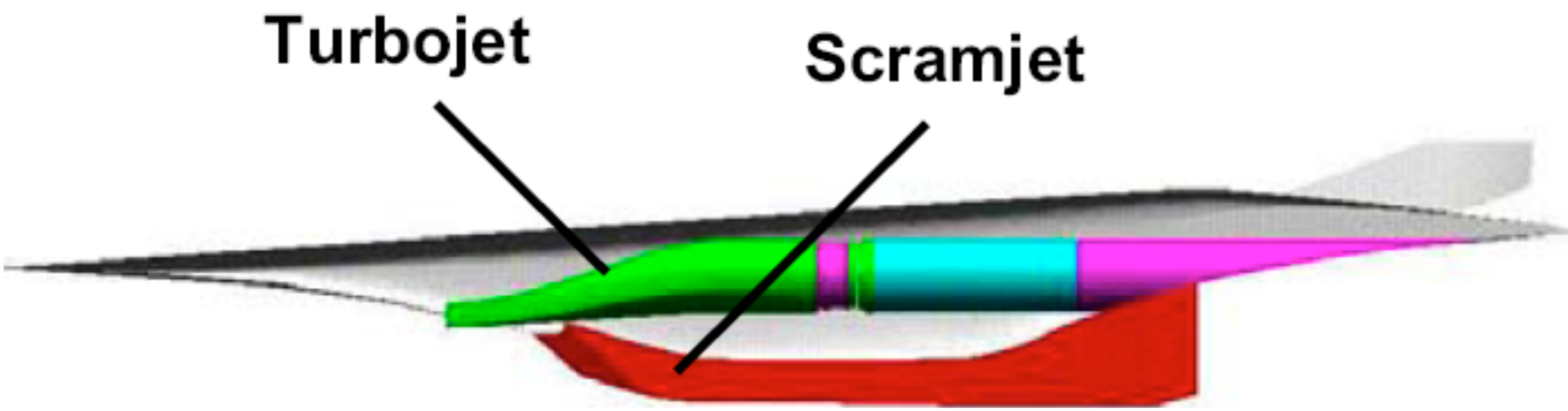
- Separate flow paths
- Cleaner design

"Saddle Bag" Concept

Credit: Chuck McClinton NASA

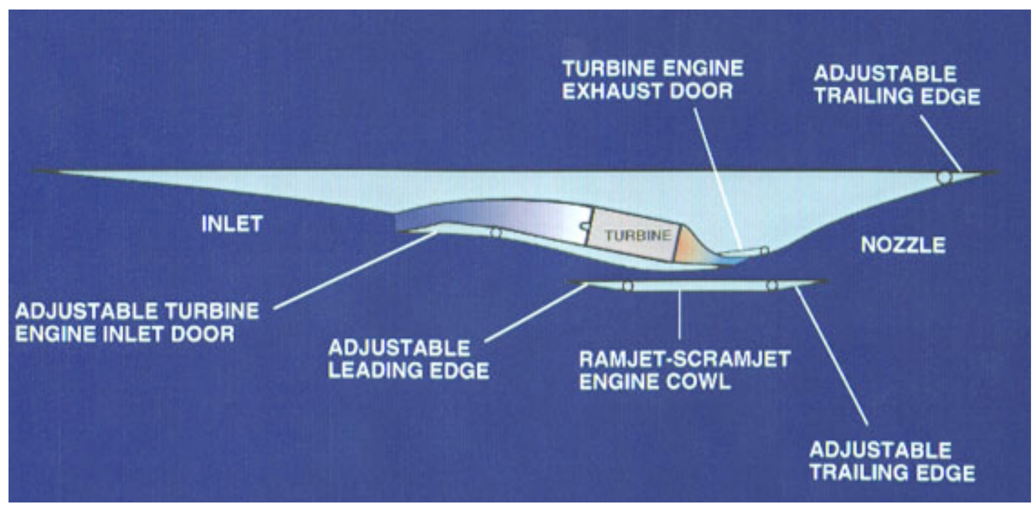
Turbine Based Combined Cycle (TBCC), II

(cont'd)



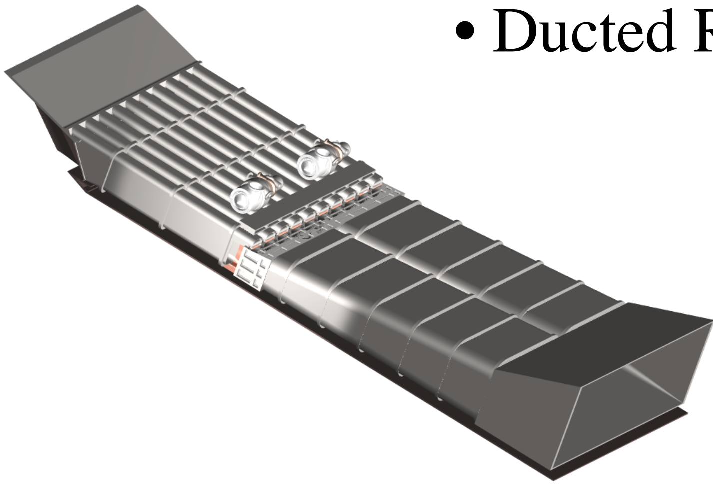
Over/Under Combination Cycle Concept.

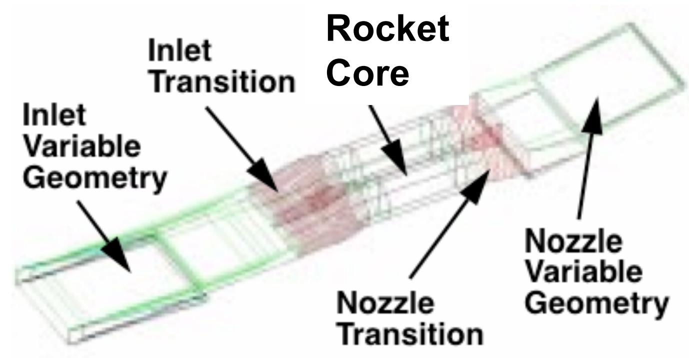
- Share parts of same flow path
- Weight savings

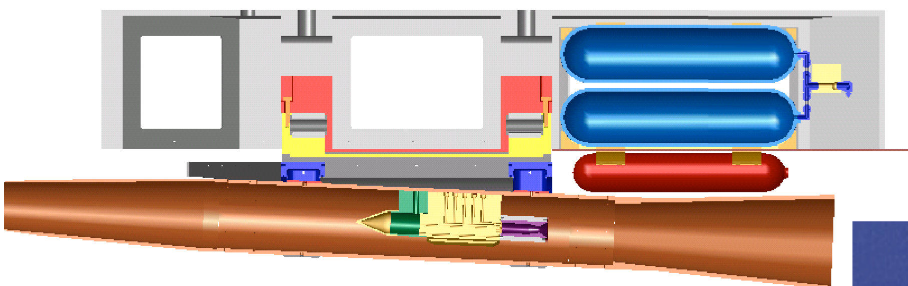


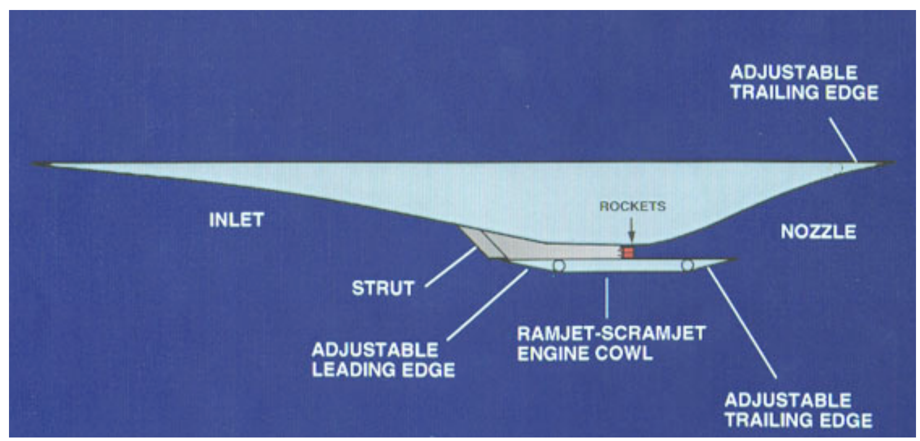
Rocket Based Combined Cycle (RBCC), I

- Ducted Rocket Approach



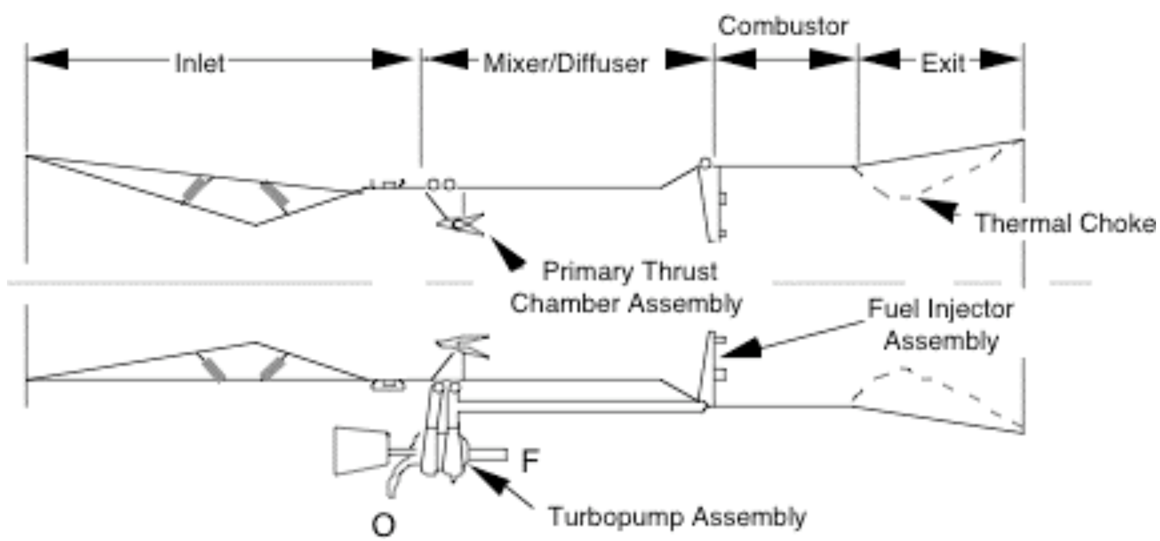






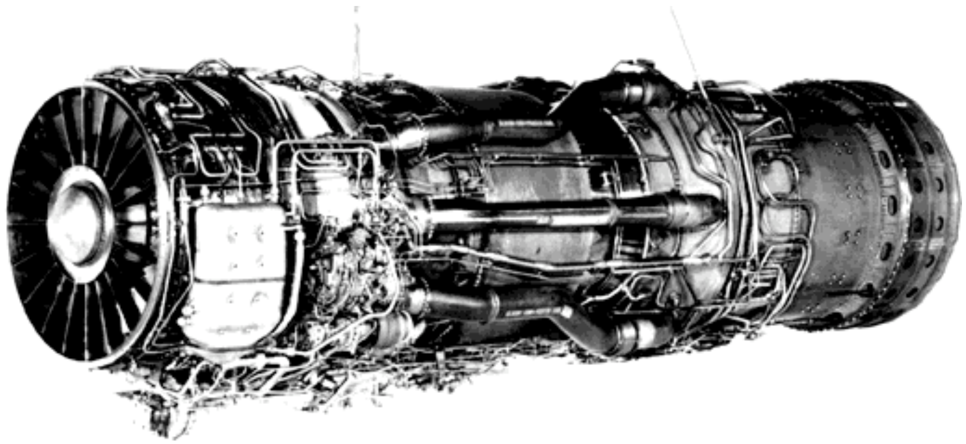
Rocket Based Combined Cycle (RBCC), II

- Dual Combustor Approach



- There is a precedent for this design

Pratt and Whitney J58 Turbojet/Ramjet Combined Cycle Engine



Part Turbo-jet

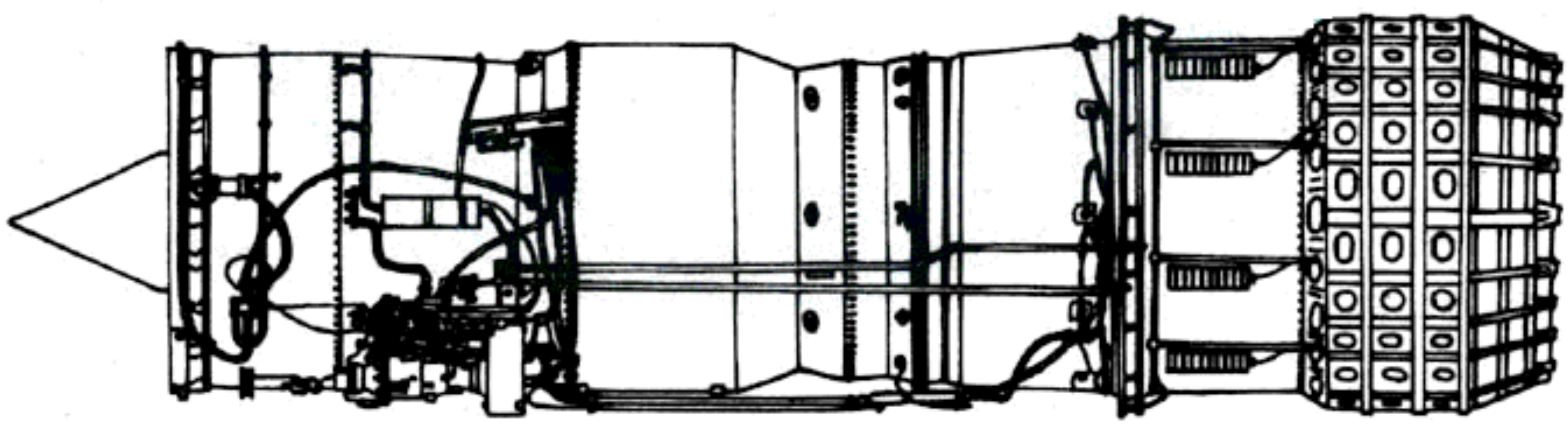
Part Ram-jet

Dual Burner … Same flow path

Pratt and Whitney J58 Turbojet/Ramjet Combined Cycle Engine (cont'd)

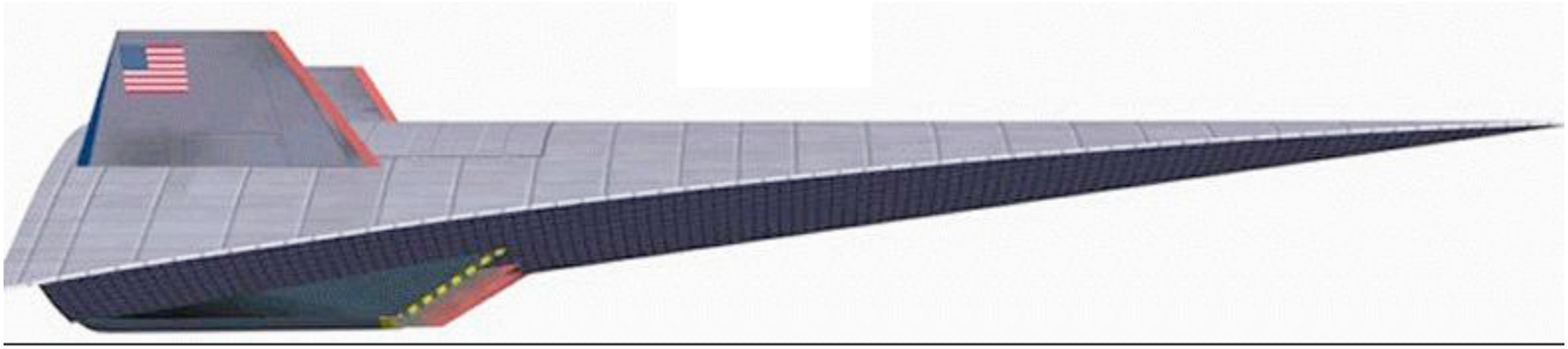
• Above mach 3 a portion of the flow bypasses the turbine and burns Directly in afterburner providing about 80% or thrust …

• At lower speeds the engine operates as a normal supersonic Turbojet … same nozzle used by both operational modes



SCRAMJET DESIGN ISSUES, IV

Thermal

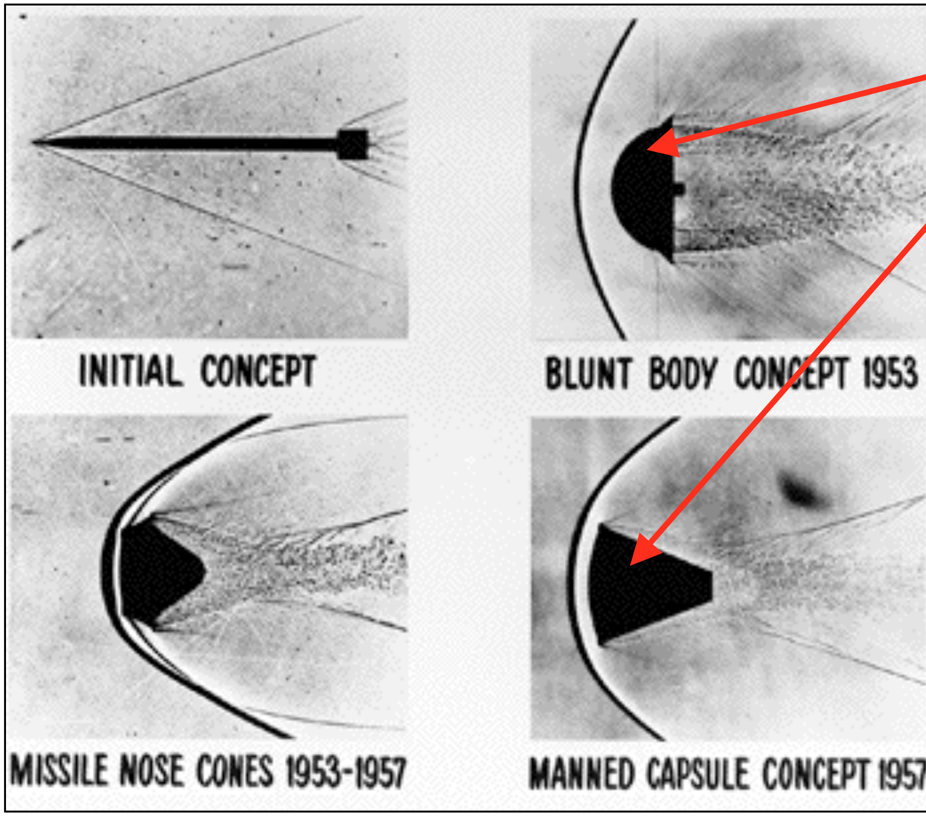


- The nature of the inlet design and need to minimize wave drag
Mandate very sharp leading edges

- Leading edges generate extreme hypersonic heating rates
In excess of 100 watts/cm^2

SCRAMJET DESIGN ISSUES, IV (cont'd)

Heating is Minimized by Blunt Body

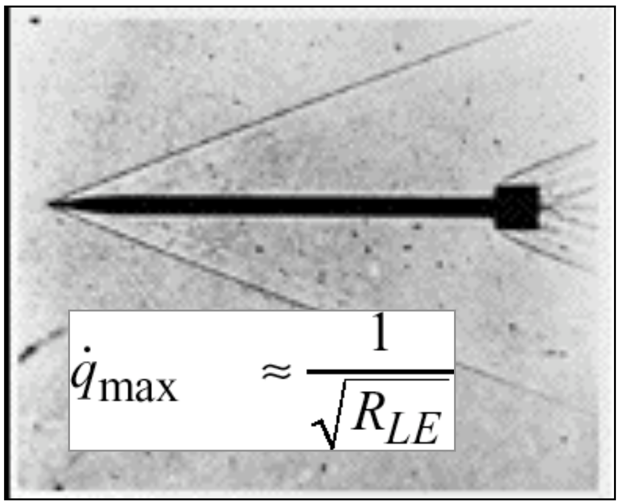


- Detached Normal Shockwave On Blunt Leading Edge Produces High level of Drag and Dissipates significant Portion of heat into flow

- **High Drag Profiles Have Lower Levels of Total Hypersonic Heating**

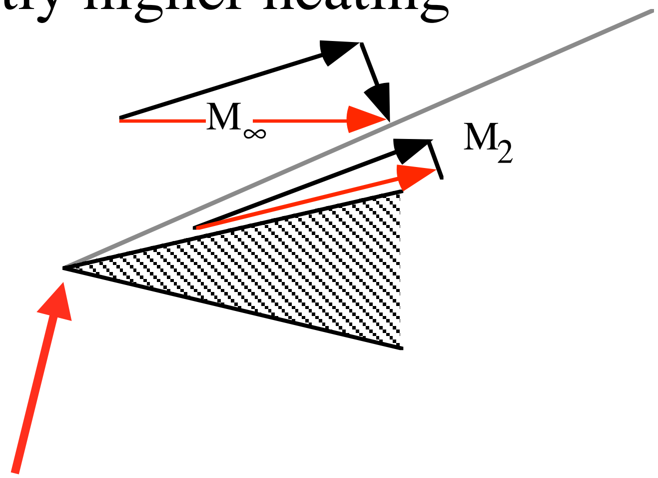
SCRAMJET DESIGN ISSUES, IV (cont'd)

- Sharp Leading Edge …Much Higher Hypersonic Lift-to-Drag, but also significantly higher heating



$$\dot{q}_{max} \approx \frac{1}{\sqrt{R_{LE}}}$$

Oblique Shockwave

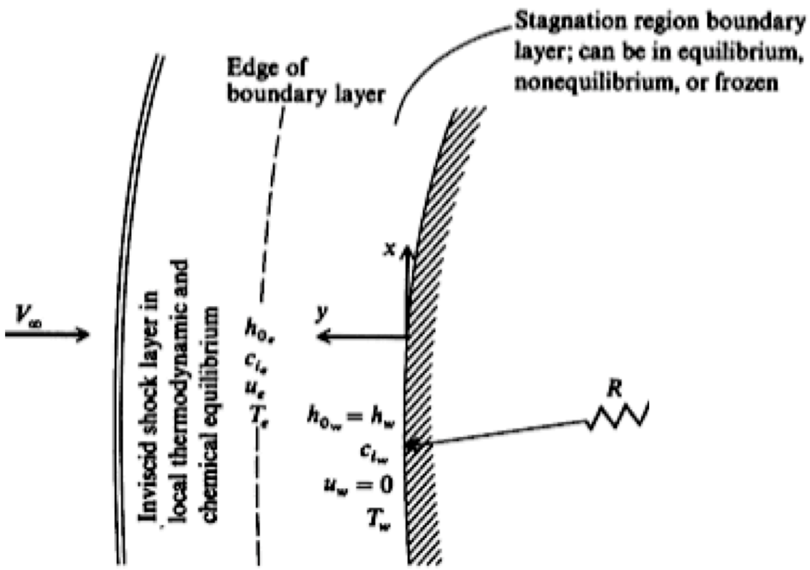


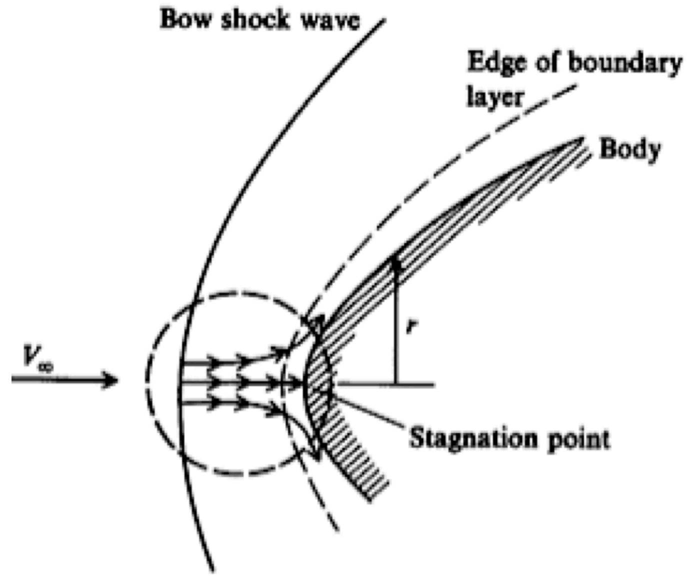
- Flow attached at leading edge Heating impinges directly

- More Exotic Thermal Protection Systems Required

SCRAMJET DESIGN ISSUES, IV (cont'd)

- Sharp leading Edge has very high heating because of small radius
- Mach number and flow density are also Key players





$$\dot{q}_{LE} = H_{tf}\left[h_0 - h_{wall}\right]\left[\frac{1}{R_{LE}}\sqrt{2\frac{\left(P_{0_2} - p_\infty\right)}{\rho_{0_2}}}\right]^{\frac{1}{2}}\left[C_{p\infty}T_\infty + \frac{V_\infty^{\ 2}}{2} - C_{p_{wall}}T_{wall}\right]$$

Stagnation heating Rate

SCRAMJET DESIGN ISSUES, IV (cont'd)

- Small LE radius also has lower thermal capacity and the problem is compounded

Equilibrium temperature is a function of heat in
And heat out

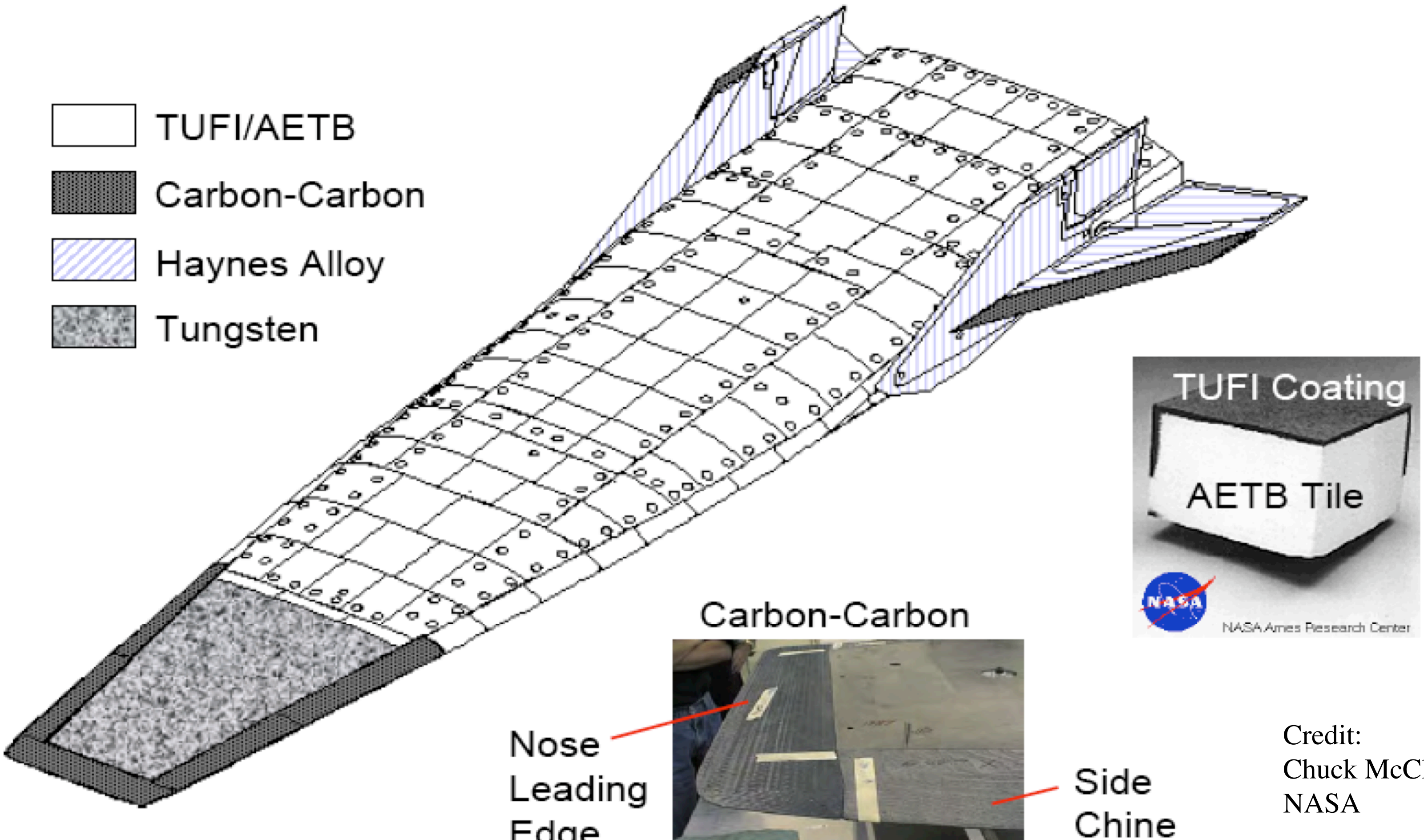
$$\dot{T}_{wall} = \frac{\left(\Phi(\theta) H_{tf}\right)\left[C_p T_\infty + \frac{V_\infty^{\ 2}}{2} - C_{p_{wall}} T_{wall}\right] + \left[\frac{\alpha}{2}\sigma T_2^{\ 4} - \varepsilon\sigma T_{wall}^{\ \ 4}\right]}{\left[\rho_{LE} C_{p\,LE} \tau_{LE}\right]}$$

- Shuttle tile manages heat by having high emissivity and very high heat capacity .. But it limited to < 2000°K

SCRAMJET DESIGN ISSUES, IV (cont'd)

X-43 Thermal Protection

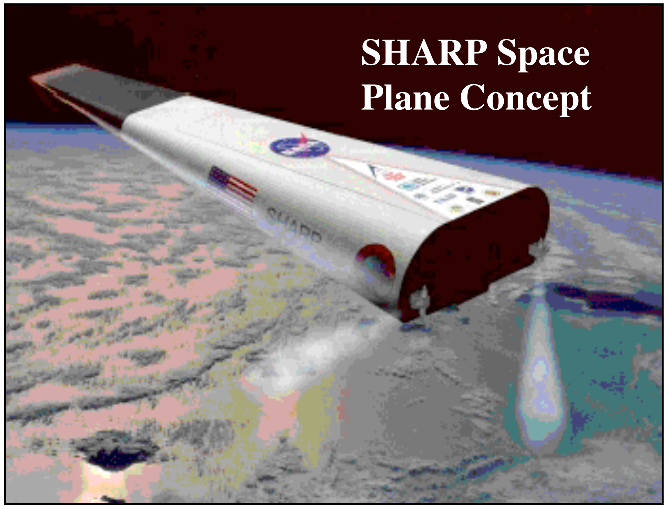
Mach 7 Vehicles (M 10 Vehicle has C-C Vertical Tail LE)



Credit:
Chuck McClinton
NASA

TUFI =Toughened Uni-piece Fibrous Insulation
AETB=Alumina Enhanced Thermal Barrier

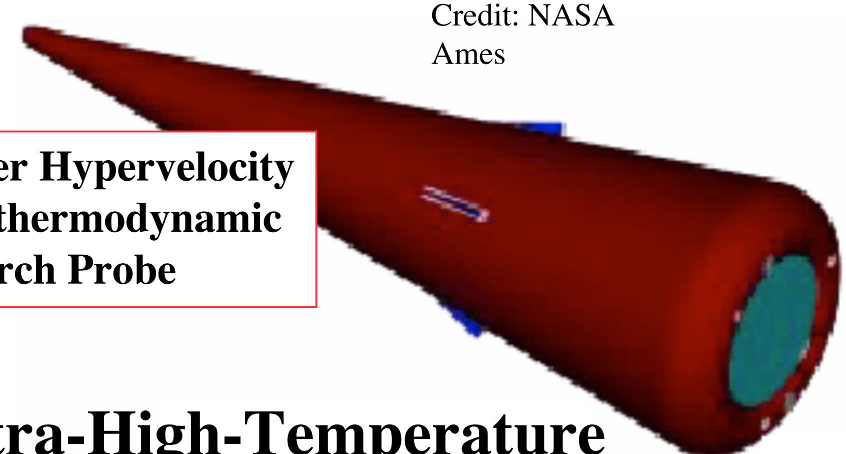
SCRAMJET DESIGN ISSUES, IV (cont'd)



- Technology readiness level (TRL) for UTHC TPS systems very low < 3/10

Mach 12+ TPS for sharp leading edge

Credit: NASA Ames

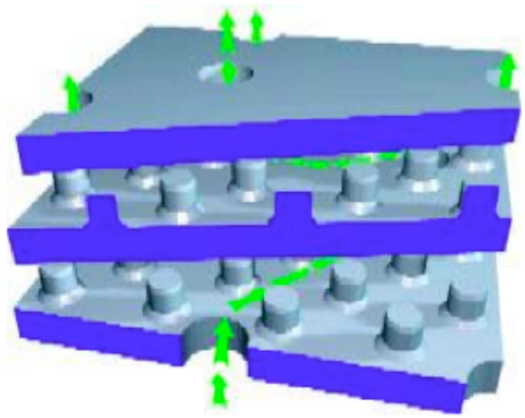


Slender Hypervelocity Aero-thermodynamic Research Probe

"Ultra-High-Temperature Ceramics" (UHTC)

SCRAMJET DESIGN ISSUES, IV (cont'd)

- Even with matured UTHC TPS heating will have to be actively managed for long duration hypersonic flight …

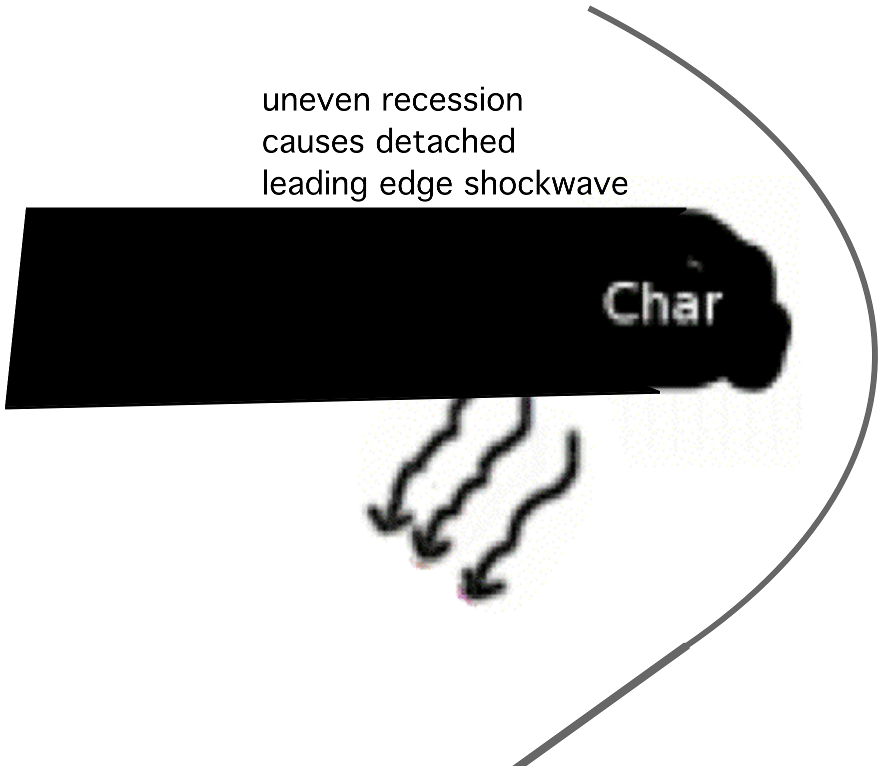


$$\dot{T}_{wall} = \frac{\left(\Phi(\theta) H_{tf}\right)\left[C_p T_\infty + \frac{V_\infty^2}{2} - C_{p_{wall}} T_{wall}\right] + \left[\frac{\alpha}{2}\sigma T_2^4 - \varepsilon\sigma T_{wall}^4\right] - \left(\dot{q}\right)_{removed}}{\left[\rho_{LE} C_{p\,LE} \tau_{LE}\right]}$$

Where do you put the heat you remove?

SCRAMJET DESIGN ISSUES, IV (cont'd)

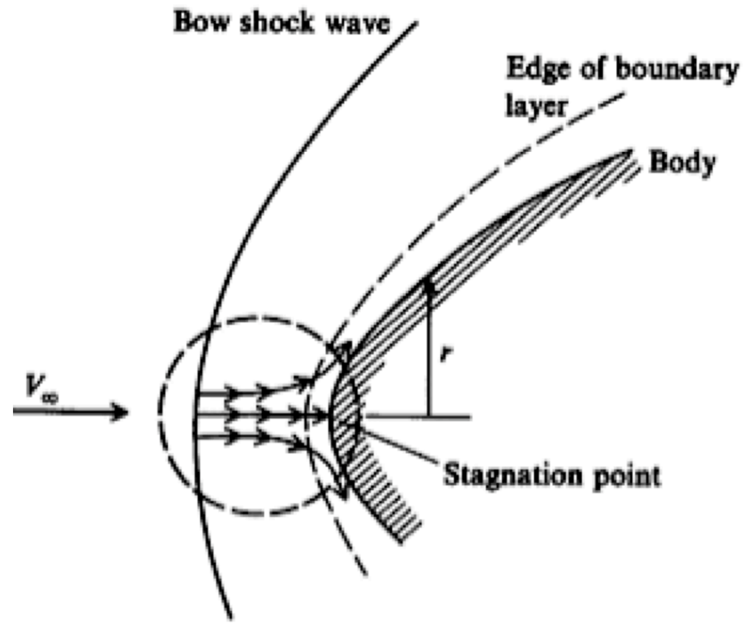
- How About Ablative leading edges



- Non-receding charring ablative (NRCA)

- **Detached shockwave effects inlet flow path increases drag**

- **Emitted gases can effect mixture ratio of engine**



SCRAMjet flight tests

• The high cost of flight testing and the unavailability of full enthalpy ground facilities have hindered scramjet development.

• A large amount of the experimental work on scramjets has been undertaken in cryogenic facilities, direct-connect tests, or burners, each of which simulates one aspect of the engine operation.

• Further, vitiated facilities, storage heated facilities, arc facilities and the various types of shock tunnels each have limitations which have prevented perfect simulation of scramjet operation.

• Full Enthalpy, full dynamic pressure data is a *REAL RARITY*

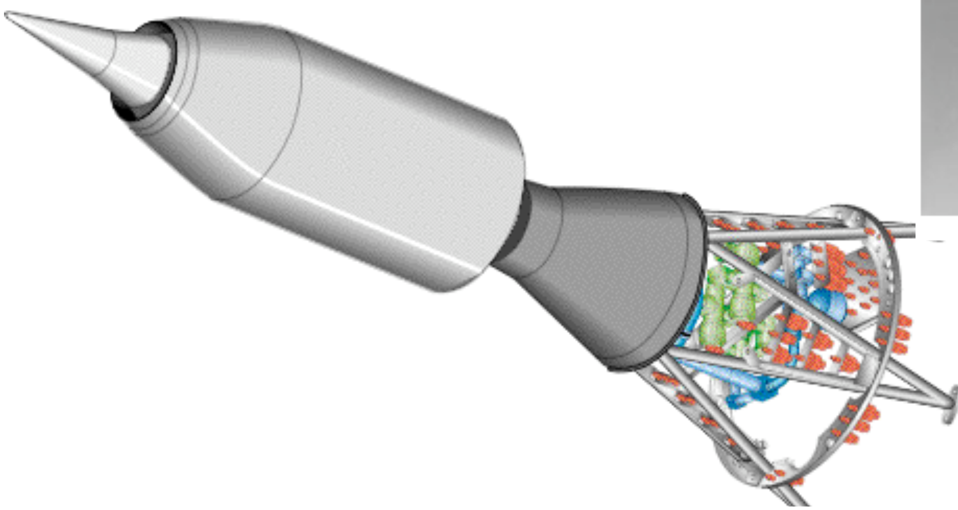
SCRAMjet flight tests (cont'd)

WHY FLIGHT TESTS?

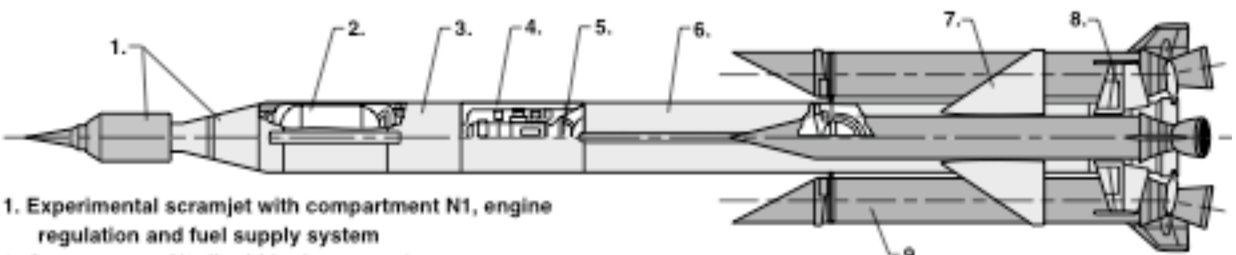
"...to separate the real from the imagined and to make known the overlooked and the unexpected problems..." Hugh L. Dryden

SCRAMjet flight tests, CIAM

• Russian CIAM … mid 1990's



• Supersonic Combustion Never verified by peer review … debate rages



1. Experimental scramjet with compartment N1, engine regulation and fuel supply system
2. Compartment N2, liquid hydrogen tank
3. Compartment N3A, nitrogen/helium pressure supply system
4. Compartment N3B, flight control system and power supply
5. Propellant tank control system
6. SA-5 rocket motor
7. Fin
8. Roll control surface
9. Solid booster rocket

Central Institute for Aviation Motors (CIAM)

SCRAMjet flight tests, HyShot

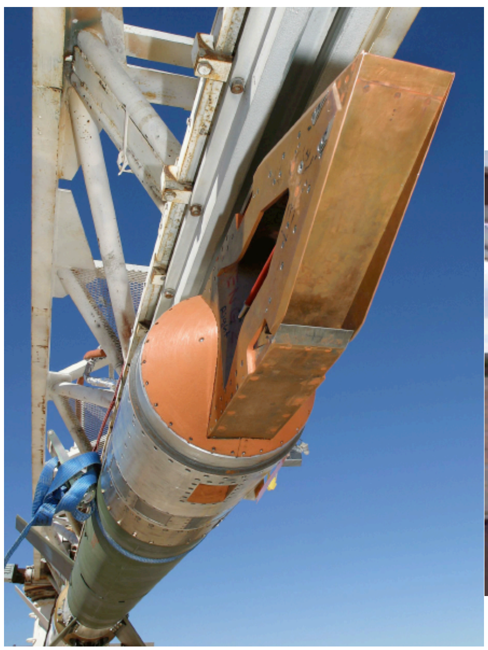
- U. Queensland (Australian) Hyshot Flight tests

HyShot I Launch 30 October 2001	HyShot II launch 30 July 2002	HyShot III launch 25 March 2006	HyShot IV launch 30 March 2006

- Flight 1 failed, Flights 2-4 successful

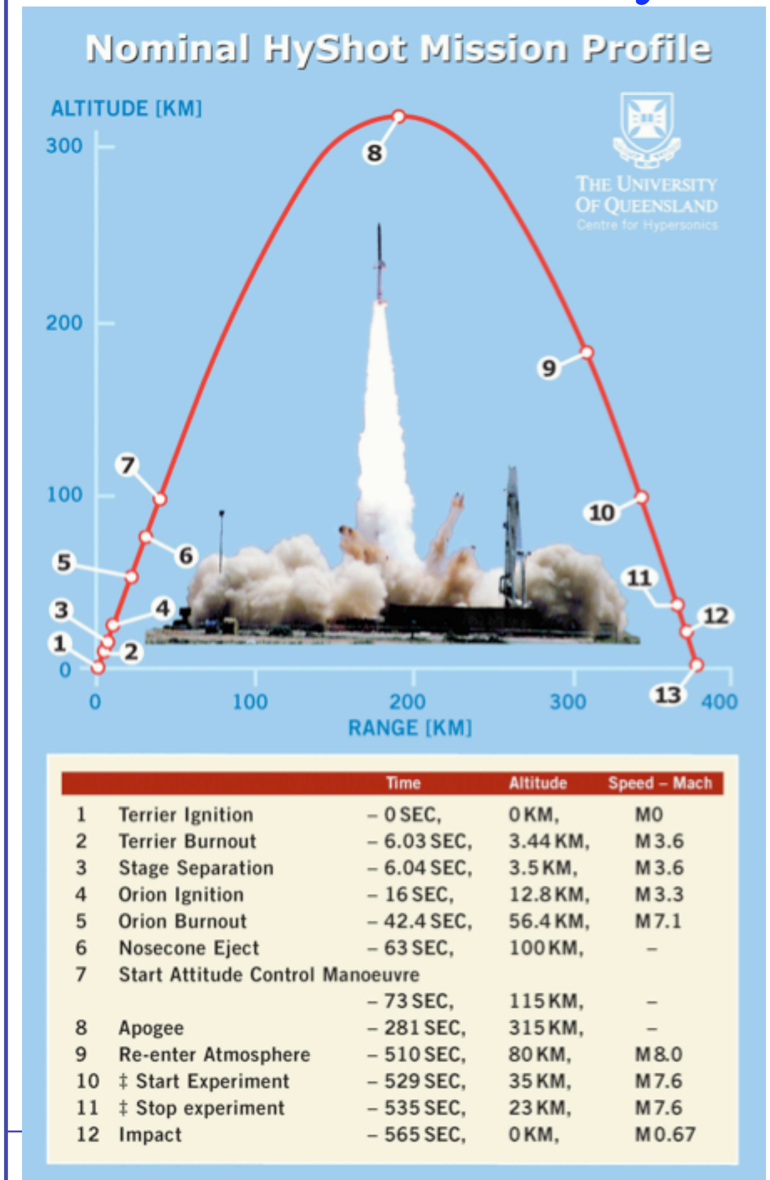
SCRAMjet flight tests, HyShot (cont'd)

- U. Queensland (Australian) Hyshot Flight tests
- Hyshot II First verified SCRAM flight operation July 30, 2002
- Engine only tests, not an integrated vehicle .. Hyshot I, II Flowpath tests …Never intended to produce more thrust than drag



Terrier-Orion sounding rocket

HyShot II Mission Profile

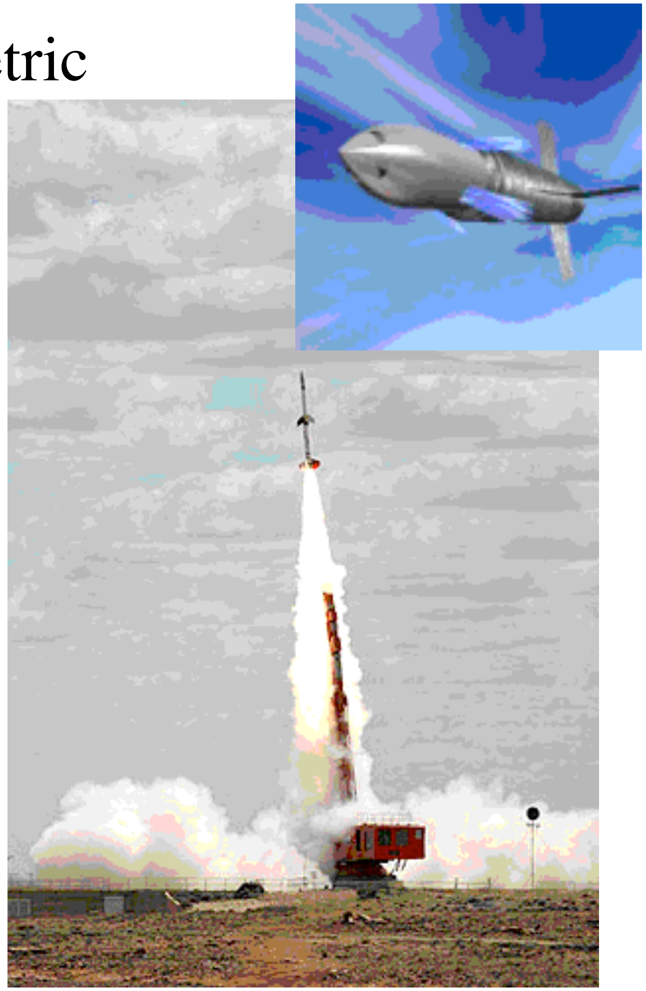


		Time	Altitude	Speed – Mach
1	Terrier Ignition	– 0 SEC,	0 KM,	M0
2	Terrier Burnout	– 6.03 SEC,	3.44 KM,	M 3.6
3	Stage Separation	– 6.04 SEC,	3.5 KM,	M 3.6
4	Orion Ignition	– 16 SEC,	12.8 KM,	M 3.3
5	Orion Burnout	– 42.4 SEC,	56.4 KM,	M 7.1
6	Nosecone Eject	– 63 SEC,	100 KM,	–
7	Start Attitude Control Manoeuvre	– 73 SEC,	115 KM,	–
8	Apogee	– 281 SEC,	315 KM,	–
9	Re-enter Atmosphere	– 510 SEC,	80 KM,	M 8.0
10	‡ Start Experiment	– 529 SEC,	35 KM,	M 7.6
11	‡ Stop experiment	– 535 SEC,	23 KM,	M 7.6
12	Impact	– 565 SEC,	0 KM,	M 0.67

- Terrier-Orion Mk 70 rocket
- Max liftoff spd: Mach 8+
- Liftoff accl: 22 g (60 g for 0.5 s)
- Apogee: 330 km
  - Nose is pushed over, cone
  - ejected (Bang-Bang maneuver)
- Max descent spd: Mach 7.6
  - Scramjet stage
  - Hydrogen Fueled

SCRAMjet flight tests, HyShot (cont'd)

- HyShot III Flight, March 25, 2006
- More Sophisticated 4-chamber axi-symmetric inlet design
- Teaming with British company Qinetiq
- Positive thrust accelerated vehicle from Mach 6.8 to Mach 8.0
- Hyshot IV data still being analyzed

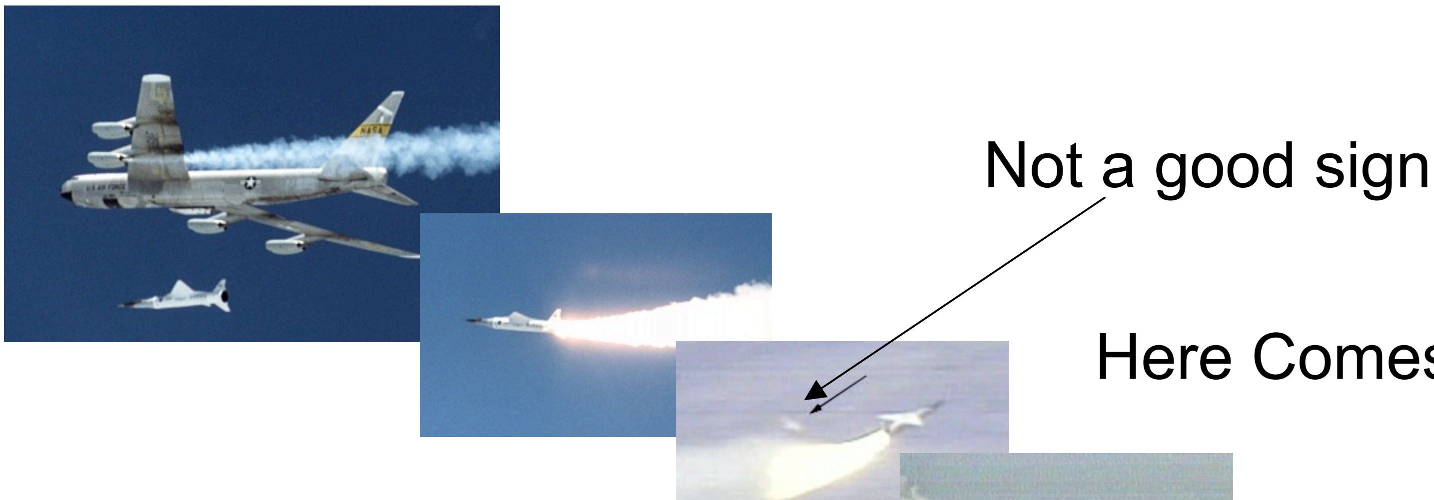


SCRAMjet flight tests, HyShot (cont'd)

SCRAMjet flight tests, X-43A

- NASA X-43A, three flights

Flight 1, June 2 2001 … booster failure, terminated flight

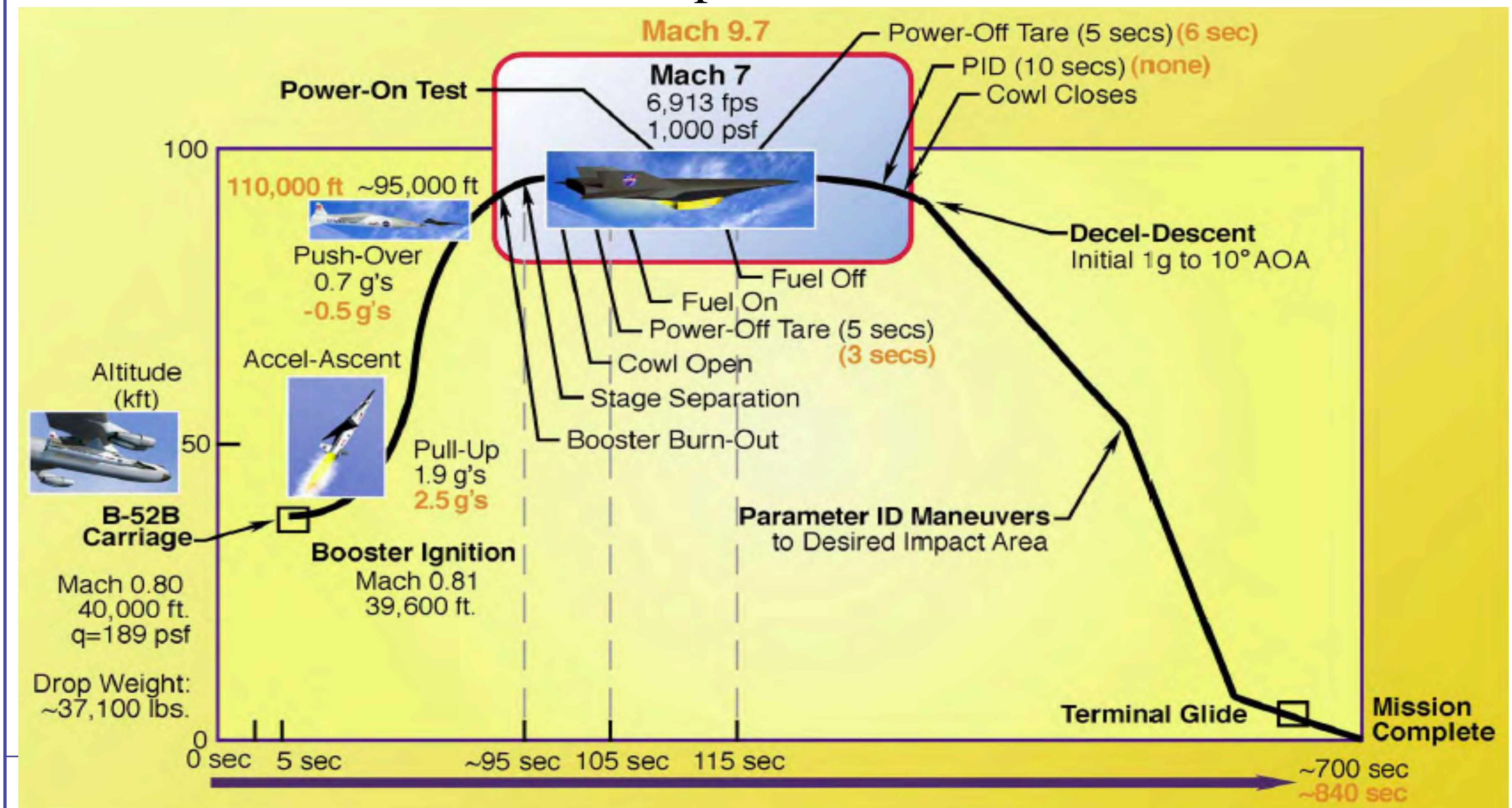


Not a good sign

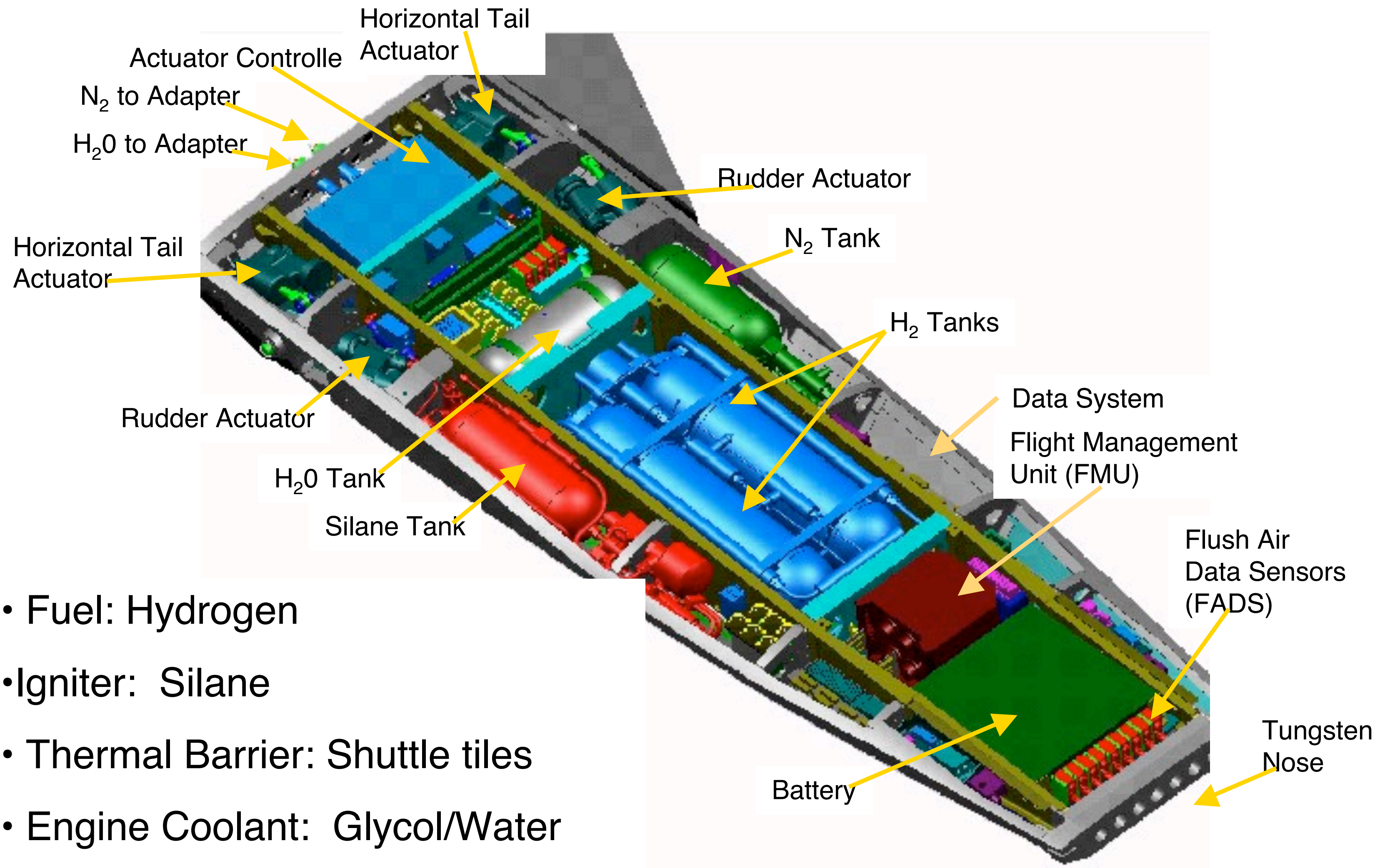
Here Comes the MIB.

SCRAMjet flight tests, X-43A (cont'd)

- Took three years to get Problem fixed … flight 2, *March 27, 2004* successful Mach 7 max engine operation, *Flight 3, November 16, 2004*, Mach 10 successful operation



X-43A Vehicle



- Fuel: Hydrogen
- Igniter: Silane
- Thermal Barrier: Shuttle tiles
- Engine Coolant: Glycol/Water
- Nitrogen Purge
- Electric Actuators

X-43A firsts (cont'd)

- Firsts
  - First flight of Integrated Scramjet Vehicle
  - Successful high dynamic pressure, high Mach, non-symmetrical stage separation (required for TSTO)
- Verified performance, operability and controllability
  - Airframe-integrated Scramjet
  - Integrated, powered, hypersonic airbreathing Vehicle
- Verified engineering application of NASA-Industry-University hypersonic vehicle design tools

Tools	Disciplines	Physics
- Experimental	- Propulsion	
- Analysis	- Aerodynamic	
CFD - Numerical	- Structural	
Analytical	- Thermal	
Empirical	- Boundary layer transition	
- MDOE for engine/vehicle design optimization	- Flight and engine controls	
	- Vehicle synthesis	

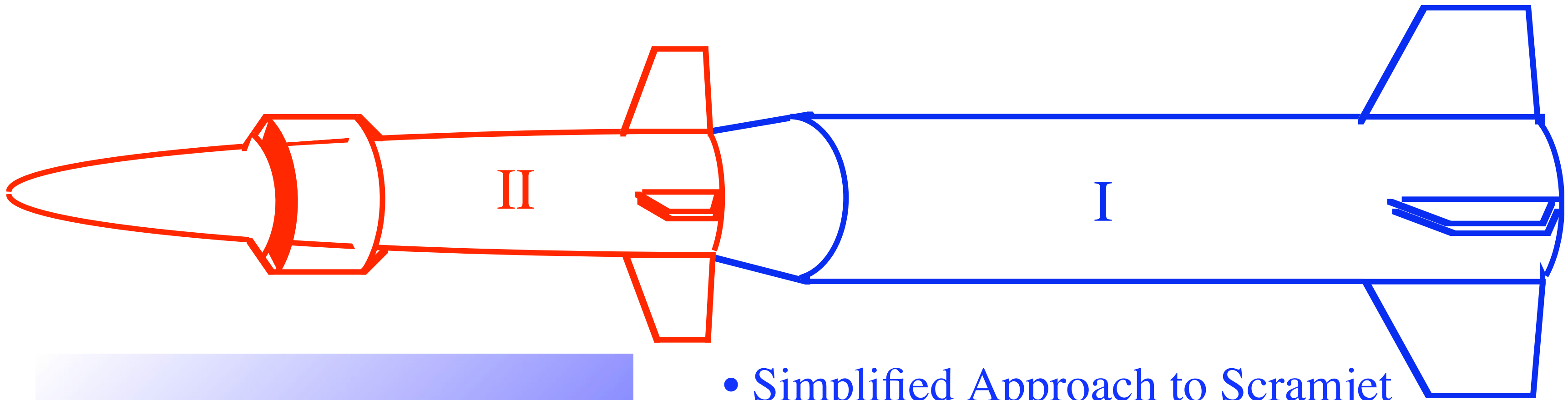
Credit: Chuck McClinton NASA

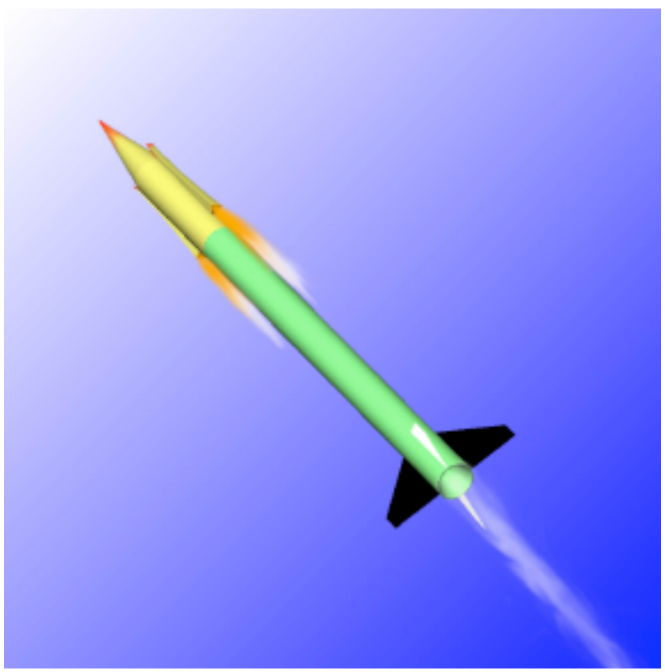
X-43A Lessons learned

- X-43 airframe drag (and lift) was slightly higher than nominal predicted, but within uncertainty prediction
- Scramjet engine performance was very close to preflight predictions (positive acceleration for M 7, Cruise for M 10)
- Control deflections to trim engine induced moments were very close to preflight predictions
- Other hypersonic vehicle technologies were as predicted
  - Aerodynamic stability and control
  - Natural and Tripped boundary layer transition
  - Airframe and wing structure
  - Thermal loads/Gap heating
  - TPS
  - Internal environment
  - Launch vehicle stiffness

Credit: Chuck McClinton NASA

Small Scale SCRAM experiments





- Simplified Approach to Scramjet Testing (SAST)
- Propulsion & Performance Branch (RP), NASA Dryden
- Small directionally-symmetric Mach 6 Scramjet design
- Configuration is aerodynamically stable

Small Scale SCRAM experiments

(cont'd)

SAST Design / Test Team

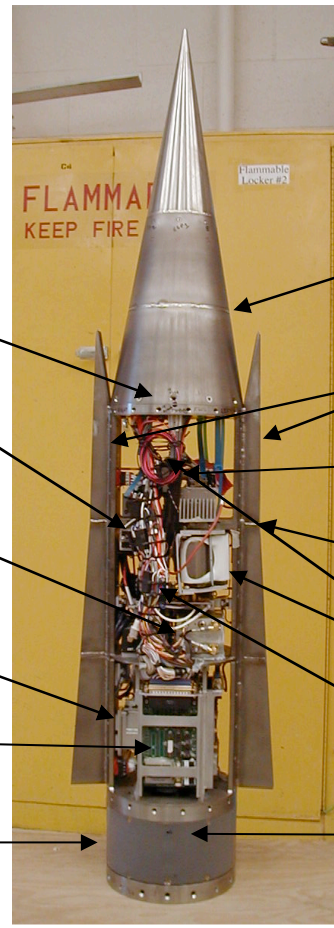
- ***NASA Dryden, Edwards, CA***
  - *Vehicle and experiment design, fabrication, and analysis.*
  - *Data acquisition / telemetry (Code FT).*
- ***NAWC-Weapons Division, Research Rockets Branch, White Sands Missile Range, NM***
  - *Ground, range, and flight operations and safety.*
- ***NAWC-Weapons Division, Pt. Mugu, CA***
  - *Flush mount antenna design, fabrication, and test.*
- ***NAWC, China Lake, CA***
  - *Payload welding.*
- ***Industrial Solid Propulsion (ISP), Las Vegas, NV***
  - *Rocket motors.*

SAST Objectives

- Build experience with hypersonic flight test techniques and instrumentation at NASA Dryden.
- Evaluate the feasibility and value of a simple, low cost hypersonic flight testbed.
- Obtain hypersonic propulsion flight data for a simplified scramjet engine.
- Get operational expertise through high flight rate

Simplified Approach to SCRAMjet Testing (SAST)

SAST Payload Internal Arrangement



Simplified Approach to SCRAMjet Testing (SAST)

Scramjet Engine Design

- ***Simple cone (9.5°) forebody***
  - *High dynamic pressure flight delivers high combustor entrance pressure using simple conical shock-on-lip, shock on shoulder configuration.*
- ***Self-starting scoop inlet***
  - *Swept sidewall, spilling design allows fixed geometry inlet to start at about Mach 3 and obtain full capture at design Mach of 6.*
- ***Diverging isolator (1°)***
  - *Diverging isolator prevents combustor-inlet interactions.*
- ***Single orifice, normal fuel injection***
  - *Fuel injection scheme chosen for simplicity but is easily changed to more optimum designs.*
- ***High pressure, gaseous hydrogen-silane fuel***
  - *Proven hydrogen-silane pyrophoric fuel used for auto-ignition.*
- ***Diverging combustor / nozzle (4°)***
  - *Conservative expansion ratio provides measurable engine thrust with low external aerodynamic drag.*

Simplified Approach to SCRAMjet Testing (SAST)

SAST Trajectory

- ***Launch at elevation angle, Q_E, of 79 deg.***
- ***Ballistic trajectory to impact. As directed by WSMR, no destruct system will be used.***
- ***Test point (at rocket motor burnout) of Mach 5.2, 17,000 ft. approx. 6 seconds after launch.***
- ***Maximum altitude of approx. 150,000 ft.***
- ***Impact point approx. 18 nmi. downrange.***
- ***Total flight time of approx. 220 seconds.***
- ***Dispersion footprint within WSMR range.***

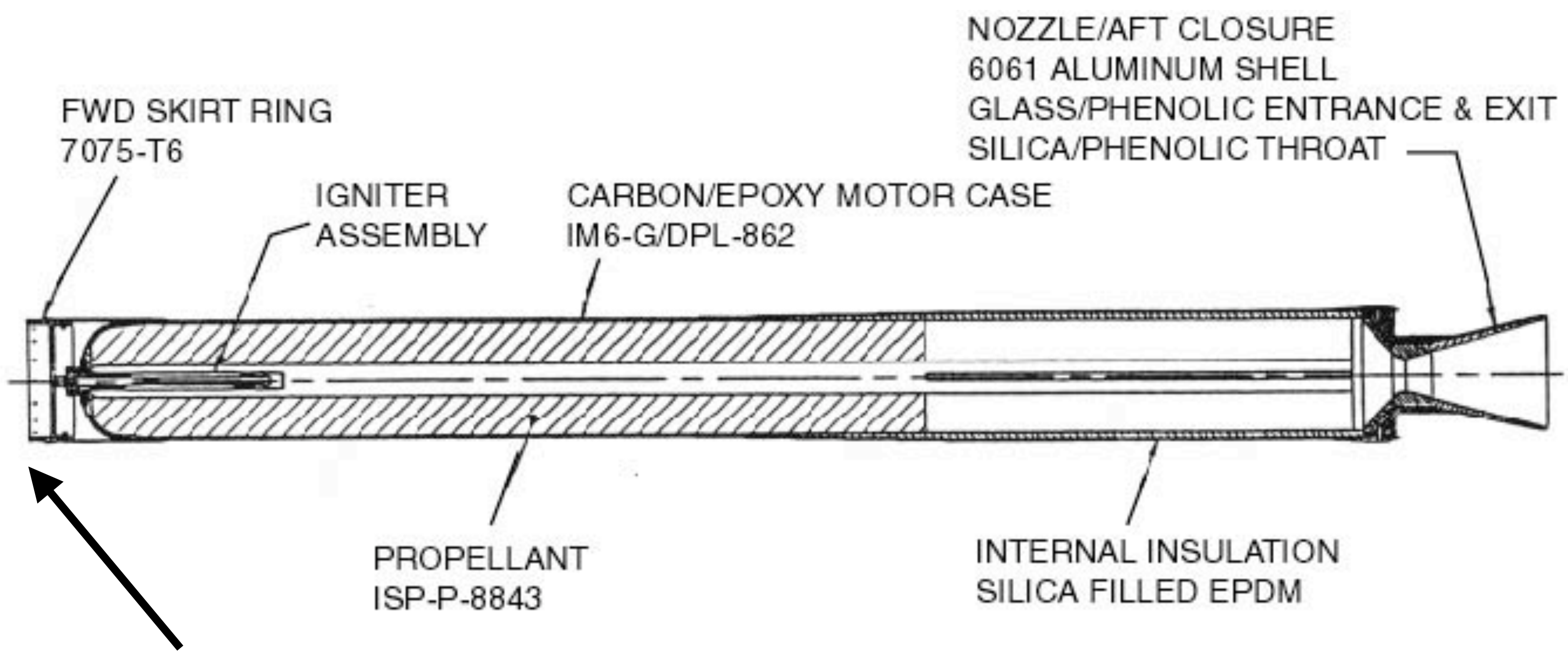
Rocket Motor Description

- Viper-V Block-II solid rocket motor
- Manufacturer -- Industrial Solid Propulsion, Inc.
- Propellant -- 87% solids HTPB/AP/AL
- Dimensions -- 131 in. length and 7 in. dia.
- Weight -- 225 lbs.
- Thrust -- approx. 6,000 lbs for 5.5 seconds
- Motor case -- carbon/epoxy composite
- Launch lugs -- fixed T-rail aft lug, ejectable T-rail forward lug

Scramjet Fuel System

- High pressure, gaseous blow down system.
- Gaseous hydrogen-silane fuel stored in fuel tank at 1800 psi.
- Pyrotechnic valve used to release fuel to fuel injectors.
- Pressure switch sensing booster burn-out opens pyrotechnic valve.
- Fuel injectors sized for initial ER=0.2.
- Scramjet burn time of about 2 sec. (with decreasing ER).
- Predicted peak combustion pressure of about 300 psi and change in force of about 150 lbs.

Viper V Block II Motor Cross Section



Booster Burn through

INDUSTRIAL SOLID PROPULSION Inc.

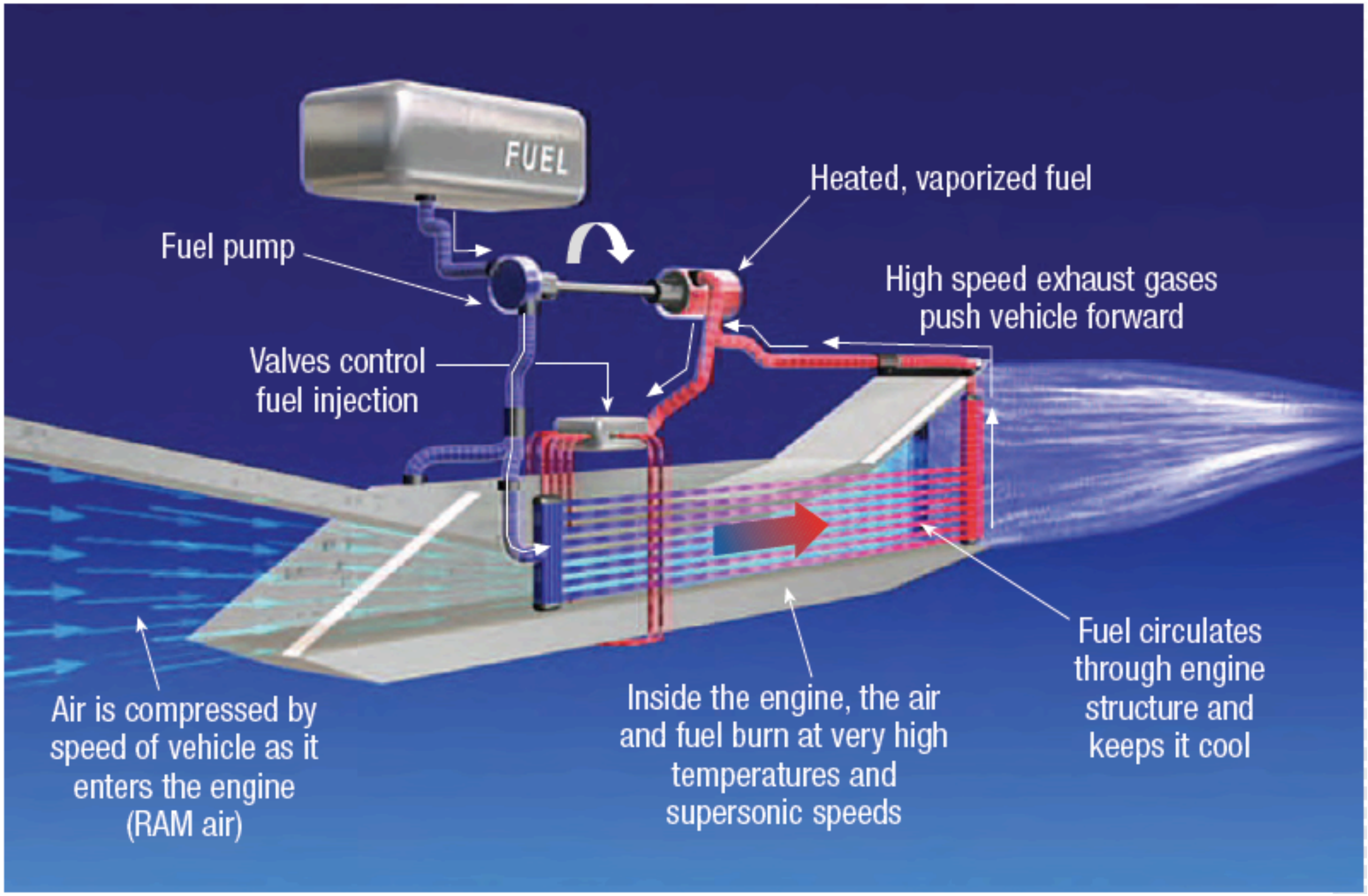
First Flight March 2000

- Guess What? Booster Failure

- Dust yourself off, try it again!!!

USAF X-51A (2)

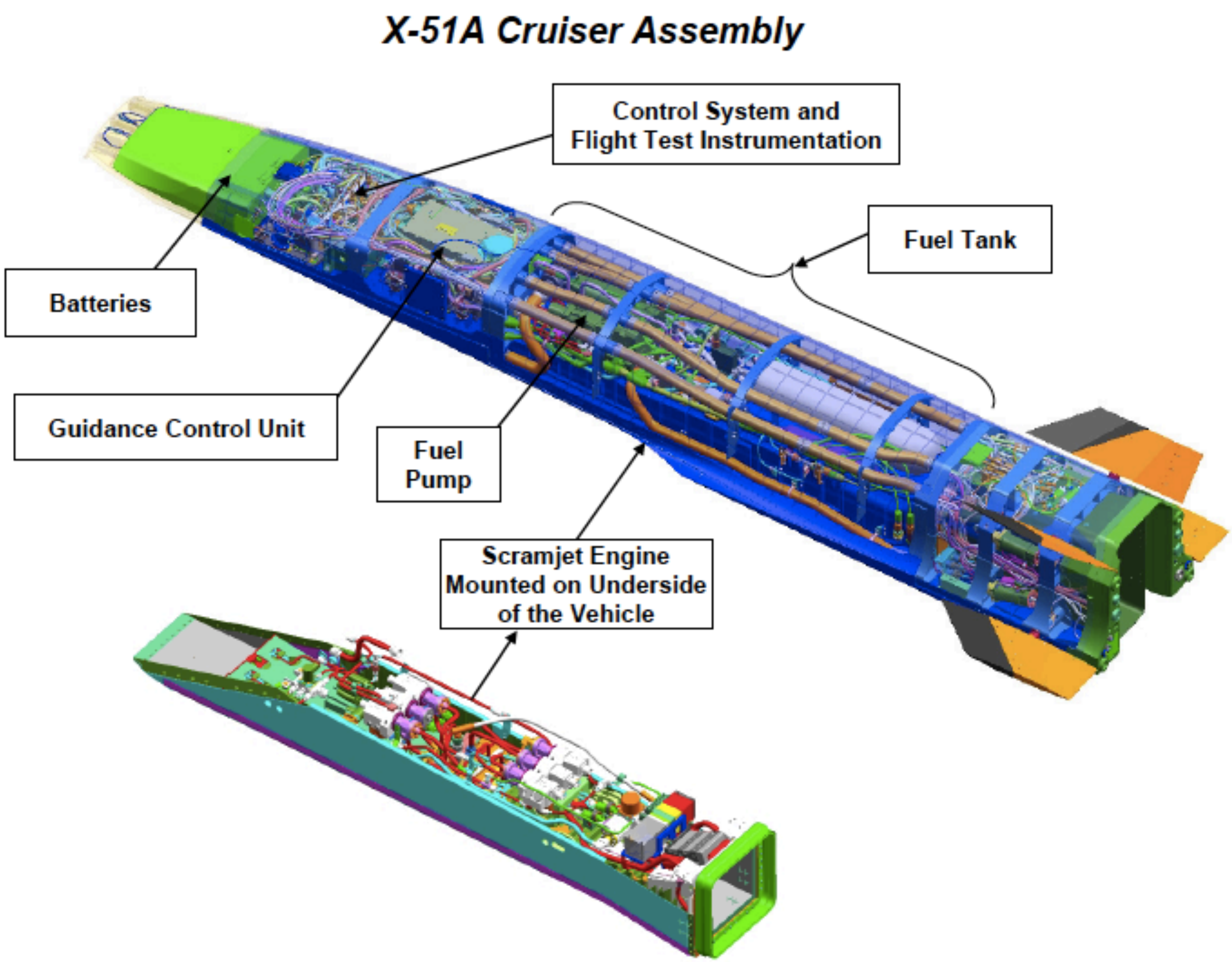
- First Hydrocarbon Fueled ScramJet



UtahState UNIVERSITY

Mechanical & Aerospace Engineering

USAF X-51A (3)



Hypersonic Physics - Propulsion

- Natural and forced boundary layer transition
- Turbulence
- Separation caused by shock-boundary layer interaction
- Shock-shock interaction heating (Type 3 and 4)
- Isolator shock trains
- Cold-wall heat transfer
- Fuel injection, penetration and mixing
- Finite rate chemical kinetics
- Turbulence-chemistry interaction
- Boundary layer relaminarization
- Recombination chemistry
- Catalytic wall effects

- Lot of Promise but Long way to go

- Most of these phenomena were modeled in the design tools. Some were avoided by application of a uncertainty factors.

- X-43 success demonstrates an engineering level understanding of "the physics". A better understanding of these issues will be beneficial for optimization of vehicle performance, but not "enabling"

- All designs share the same physics

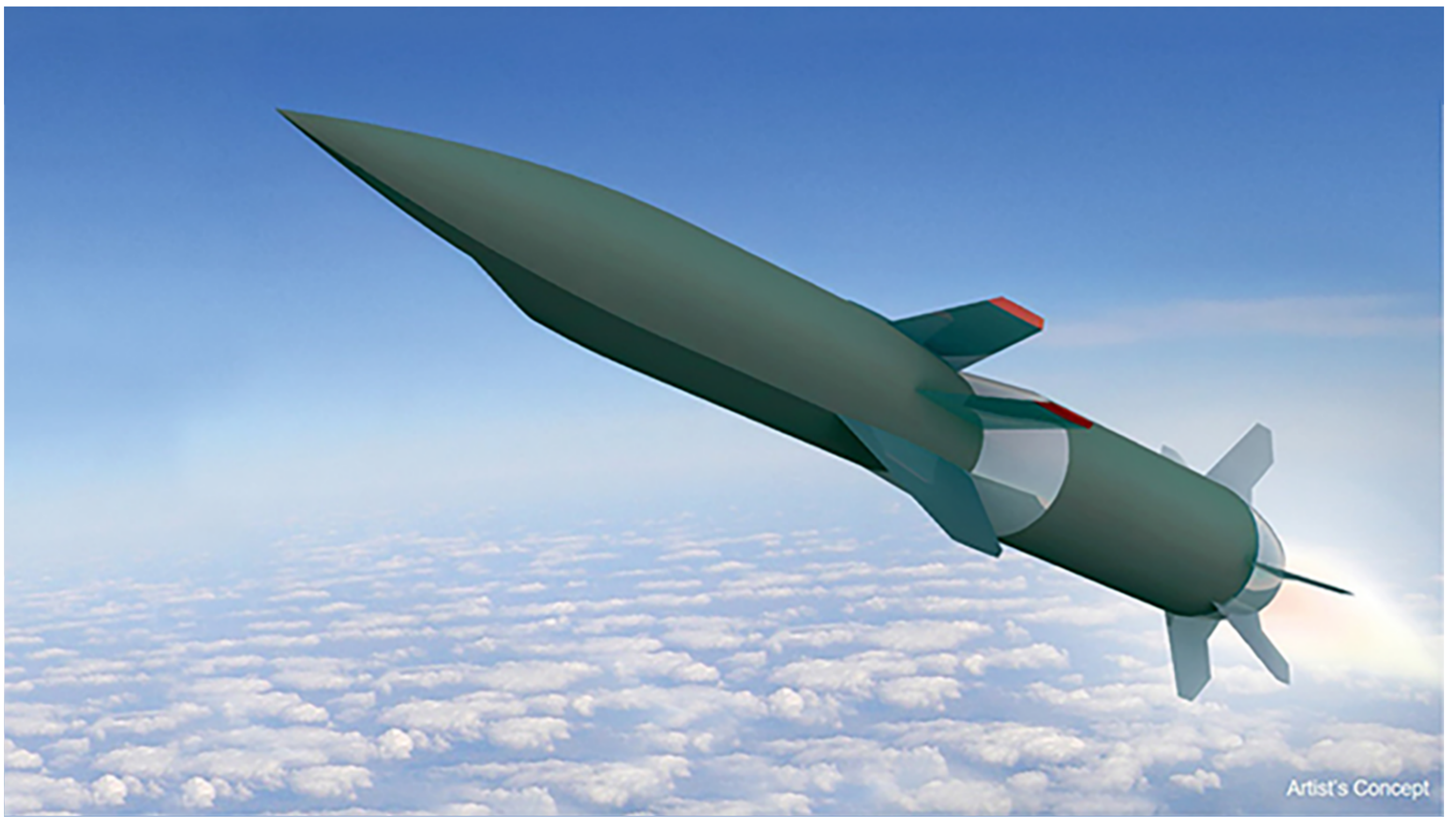
Credit: Chuck McClinton NASA

AIR WARFARE, GLOBAL

US hypersonic missile successful in flight test, DARPA says

The US reportedly kept the test a secret for weeks for fear of spooking Moscow, following Russia's own hypersonic use.

By LEE FERRAN on April 05, 2022 at 1:29 PM



Artist's concept of Hypersonic Air-breathing Weapons Concept (HAWC) vehicle. (Credit: DARPA)

WASHINGTON: The US recently completed a successful "free flight" test of a hypersonic missile, according to the Pentagon, but reportedly kept the test quiet in an effort to avoid escalation with Russia over Ukraine.

The Defense Advanced Research Projects Agency (DARPA) announced the test today, calling it the "second successful flight in DARPA's HAWC [Hypersonic Air-breathing Weapon Concept] program."

"This Lockheed Martin HAWC flight test successfully demonstrated a second design that will allow our warfighters to competitively select the right capabilities to dominate the battlefield," Andrew "Tippy" Knoedler, HAWC program manager in DARPA's Tactical Technology Office, said in a DARPA release. DARPA is partnered with the Air Force on the HAWC program. "These achievements increase the level of technical maturity for transitioning HAWC to a service program of record."

Lockheed's free flight test was supposed to happen in late 2020, but was delayed due to technical issues. Raytheon's competing version of the HAWC system was successfully tested in September 2021.

RELATED: 'Hundreds' of China hypersonic tests vs. 9 US; Hyten says US moves too slowly

According to DARPA, in the new test the missile was released from a "carrier aircraft," was boosted by a scramjet engine and then "quickly accelerated to and maintained cruise faster than Mach 5 (five times the speed of sound) for an extended period of time. The vehicle reached altitudes greater than 65,000 feet and flew for more than 300 nautical miles."

The DARPA announcement came hours after CNN reported the successful test, saying it took place in mid-March but that the Biden administration kept it quiet to avoid sending an escalatory signal to Russia.

Last month Russia claimed the first battlefield use of a hypersonic missile in combat operations in Ukraine, which US President Joe Biden later confirmed.

"We do understand that at least in one instance, they used a hypersonic missile," Pentagon Press Secretary John Kirby told reporters on March 22, while questioning exactly why the Russians would use it to reportedly take out a storage facility. "That's a pretty significant sledgehammer to take to a target like that. So, it's not exactly clear what their intentions were."

Kirby said the US did not consider the Russian use of a hypersonic missile a "game changer" in the Ukraine conflict.

Last fall the defense world was set abuzz by reports that the Chinese had tested its own hypersonic weapons system, one the US later said was part of a fractional orbital bombardment system (FOBS).

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"We can actually then change the mission systems and allow various vendors to compete, as long as they meet, form fit and function," Air Force Gen. CQ Brown said. "And because it drives competition, you get a better end product, and ideally, it brings the price down as well."

By VALERIE INSINNA

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Of its own hypersonic missile, DARPA's Knoedler said, "We are still analyzing flight test data, but are confident that we will provide the U.S. Air Force and Navy with excellent options to diversify the technology available for their future missions."

Scramjets take in oxygen from the atmosphere, rather carrying bulky oxygen tanks — as boost-glide rocket boosters do. Thus, air-breathing hypersonic missiles can be made smaller, to be carried by fighter jets rather than big, heavy bombers.

But flying at greater than Mach 5 (scramjet powered cruise missiles are estimated to be able to fly at about Mach 7) through the atmosphere also creates friction, heating up an air-breathing hypersonic weapon in ways a boost-glide design, which spends most of its time in a near-vacuum, does not. Scramjets remain experimental, as do many of the materials designed to keep temperatures on the missile down so that avionics and other subsystems can function.

https://www.youtube.com/watch?v=fuTwQ7KAwxw

Topics: darpa, HAWC, hypersonic, Russia

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