AFRL

Hypersonic Systems Analysis & Design

DR. JOSÉ CAMBEROS

Lead for Design of Aerospace Systems for Hypersonics
AIR FORCE RESEARCH LABORATORY
AFRL/RQHV

DASH DESIGN of AEROSPACE SYSTEMS for HYPERSONICS

University of Colorado, Boulder

21 June 2021

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Mission

Leading the discovery, development and integration of affordable warfighting technologies for our air, space and cyberspace forces

WHO WE ARE
We are experts in a wide range of technical fields.
LEAD
We lead the Air Force in science and technology.

WHAT WE DO
We explore, research and push the boundaries of technology.
DISCOVER
We are at the forefront of innovation.

WHY OUR WORK MATTERS
We provide the Air Force with the technology it needs to defend America.
DEVELOP
We bridge the gap between research and application.

WHEN WE DELIVER
We identify future needs and advance technologies to support these capabilities.
DELIVER
We provide superior technology to warfighters in a continuous manner.

Vision

We defend America by unleashing the power of innovative air and space technology.

Core Technical Competencies (CTC)

MATERIALS & MANUFACTURING

Structural Materials, Functional Materials, Manufacturing Technology, Support of Operations

HUMAN PERFORMANCE

Training, Adaptive Warfighter Interfaces, Bioeffects, Aerospace & Operational Medicine, and Bioengineering; Aerospace & Operational Medicine education, training, and consultation; Human Systems Integration analysis and implementation

SPACE VEHICLES

Space Environment, Advanced Space Resilience Technologies, Space Communication & Navigation Technologies, Space Awareness and Command & Control

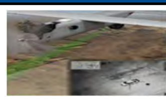
INFORMATION

Processing & Exploitation, Connectivity & Dissemination Autonomy, Command & Control and Decision Support, Cyber Science and Technology

BASIC RESEARCH

Engineering & Information Sciences, Physical & Biological Sciences

SENSORS

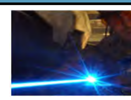


Radio Frequency (RF) Sensing, Electro Optical (EO) Sensing Spectrum Warfare, Trusted & Resilient Mission Systems, Multi-domain Sensing Autonomy, Enabling Sensor Devices & Components

AEROSPACE SYSTEMS

Aerospace Vehicles, Control, Power & Thermal Management, High Speed Systems, Rocket Propulsion, Turbine Engines

DIRECTED ENERGY



Laser Systems, Weapons Modeling, Simulation & Analysis, High Power Electromagnetics (HPEM), Directed Energy and Electro Optics for Space Superiority

MUNITIONS

Munitions Airframe, Guidance, Navigation & Control, Terminal Seeker Sciences, Modeling & Simulation Evaluation Sciences Ordnance Sciences

EXPERIMENTATION

Capability & Technology Prototyping

Investment Categories

6.1

Basic Research

Science Knowledge

Greater knowledge or understanding fundamental aspects

Observable facts

Without specific applications toward processes or products

New Science $319 M

6.2

Applied Research

Technologies

Applying knowledge or understanding to determine the means by which a recognized and specific need may be met

$1,411 M

Science to Application

6.3

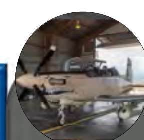
Advanced Technology Development

Capability Concepts

The development and integration of hardware for field experiments and tests

$862 M

From Application to Capability



Non S&T

Other AF Funds Executed

Operational Development / Experimentation

- **Research, Development, Test and Evaluation**
- **Strategic Development Planning Experimentation**
- **Small Business Innovation Research Program**
- **Air Force Surgeon General**

Experimentation $1,377 M

FY18 data S&T (6.1 - 6.3)

Non S&T (6.4 – 6.7, DHP, OM)

AFRL

Locations by State

AFRL

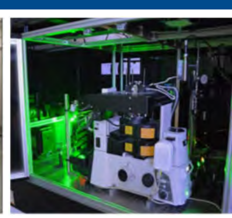
World-class Facilities and State-of-the-art Capabilities





Rocket Propulsion Test Facilities | AF Maui Optical & Supercomputing Site (AMOS) | Hypersonic Wind Tunnel | Radar Towers – Sensors Complex | Outdoor Antenna Test Ranges





Starfire Optical Range | Human-rated Centrifuge, USAF School of Aerospace Medicine | Autonomous Research Systems Robotic Testing | DoD Supercomputing Resource Centers (DSRC) | High Explosives R&D HERD Facility

Future Technologies - Big Bets

QUANTUM INFORMATION SCIENCE
Harnesses certain laws of particle physics to dramatically improve the acquisition, transmission and processing of information.

Applications include computing, communication and sensing. Quantum can be used to teleport information, create secure communication networks, gather location data in GPS-denied environments and enhance supercomputing capabilities.

ARTIFICIAL INTELLIGENCE / AUTONOMY
Facilitates the use of machine generated information by creating knowledge from observations gathered.

AI can provide expertly-planned courses of action, streamline business processes, enhance situational awareness and increase mission effectiveness.
It could save time, money, manpower and lives.

DIRECTED ENERGY WEAPONS
Strike critical targets at the speed of light and defeat attacks in an effective, affordable and expedient manner.

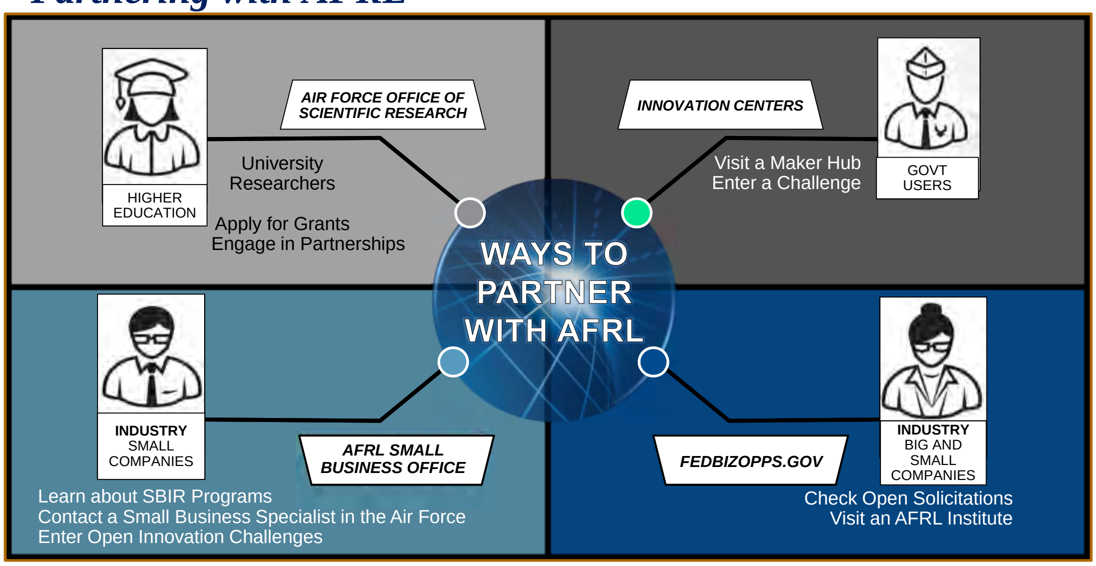
DEWs precisely engage targets with little to no collateral impacts or detectable disturbance. They can be integrated with aircraft, munitions or used on the ground.

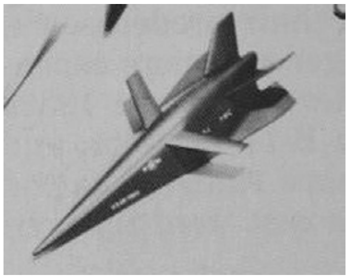
HYPERSONICS
Flying at five times the speed of sound, also known as Mach 5 or higher.

Hypersonic flight could enable the U.S. to conduct longer range military operations with shorter response times and enhanced effectiveness.

For more information, visit
AFRESEARCHLAB.COM

Partnering with AFRL





Major Developments

HYPERSONIC VEHICLE TECHNOLOGY

On Hypersonics

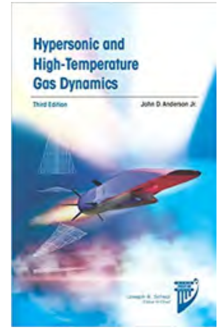
AFRL Initiative
"Game Changer"

- **Critical Flow Phenomena**
  - *Shock-shock and shock-boundary layer interactions*
  - *Non-equilibrium effects*
  - *Flow-structure interactions*
  - *Ablation*
  - *Flight controls*
  - *Atmospheric Noise*
- **Thermal Management, external and internal**
- **Multidisciplinary due to fully-coupled physics**
- **Coupling effects can be beneficial or adverse**
- **Systems Level Analysis and Design Optimization**

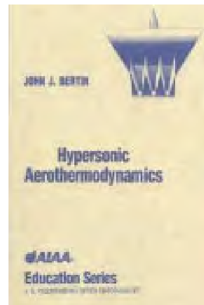
IT'S ALL ABOUT THE HEAT!!!

Facing the Heat Barrier: A History of Hypersonics by T. A. Heppenheimer

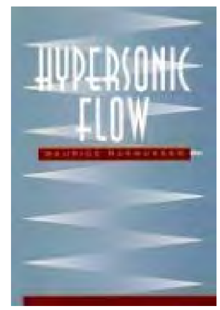
My Favorite Books on Hypersonics



- ★ ***Hypersonic and High Temperature Gas Dynamics***
  - ✧ *John D. Anderson, (AIAA 2006, 2001; McGraw-Hill, 1989)*



- ★ ***Hypersonic Aerothermodynamics***
  - ✧ *John J. Bertin, (AIAA, 1994)*



- ★ ***Hypersonic Flow***
  - ✧ *Maurice Rasmussen, (Wiley & Sons Inc., 1994)*

Other Useful/Interesting References

Basics of Aerothermodynamics

E. H. Hirschel, Springer-Verlag, jointly with AIAA, 2005

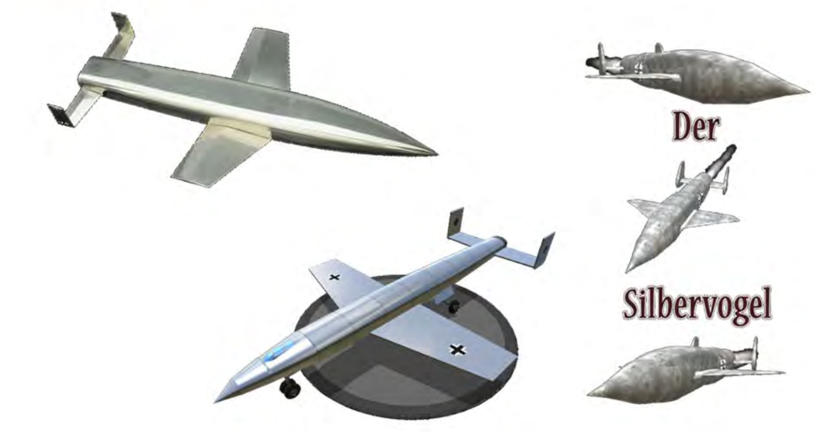
Selected Aerothermodynamic Design Problems of Hypersonic Flight Vehicles

E. H. Hirschel & C. Weiland, Springer-Verlag, jointly with AIAA, 2009

Historical, Misc. Other

- ✧ *Heppenheimer, T.A. Facing the Heat Barrier: A History of Hypersonics. NASA SP-2007-4232*
  `https://history.nasa.gov/sp4232.pdf`
- ✧ Magazine articles, Technical papers, Technology & Design Studies, Popular literature, historical, etc.

Sanger Silbervogel ~ 1934

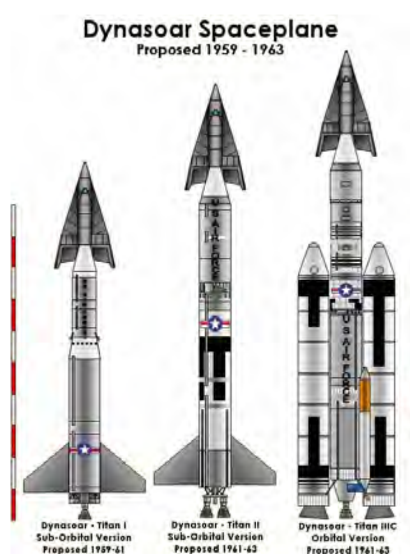


<u>Specs ca 1934</u>
Mass: 133,773 kg
Payload: 5,000 kg
L/D: 5.1
Mach at burn-out: 13
Cruise Mach: 3.3
Cruise altitude: 50 km

- ***Silbervogel*, German for Silver Bird, by Eugen Sänger & Irene Bredt ~ late 1930s**
- **Liquid-propellant rocket-powered sub-orbital bomber**
- **Sled launch, sub-orbital, atmospheric skip to extend range**

X-20 DynaSoar

- ★ **Piloted reusable space vehicle, 35.5 ft long & 20.4 ft wingspan**
- ★ **11 manned flights planned from Cape Canaveral starting Nov 1964 & 1st orbital flight ~ 1965**
- ★ **Program canceled Dec 1963:**
  - ✧ *X-20 had no viable military mission*
  - ✧ *Too expensive for a research vehicle*
  - ✧ *X-20 funding moved to the Manned Orbiting Laboratory which used Gemini capsules*

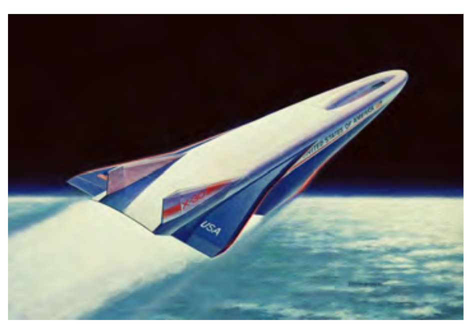


X-15

- ★ Joint NACA, USAF, Navy program; North American Aviation selected Sep 55
- ★ 3 flight vehicles produced; 199 flights; 1 fatality
- ★ Conventional aero controls plus reaction control system
- ★ Heat sink structure w/ Inconel X skin; ablative with sealant for high Mach
- ★ Initially 2 XLR-11 engines (16 Klb thrust); later XLR-99 engine (67 Klb thrust)
- ★ First application of hypersonic theory & wind tunnel work to actual flight
- ★ Max altitude: 354,200 feet on 22 Aug 1963
- ★ Max Mach: 6.72 on 3 Oct 1967
- ★ Type 4 SBLI w HRE

National Aero Space Plane (NASP)

- ★ Overly ambitious program for HTHL single stage to orbit, 1986 - 1995
- ★ Highly integrated air breathing propulsion system from SLS to Mach 25
- ★ High reliance on CFD; eliminate wind tunnel testing
- ★ No intermediate demonstrations for key components/subsystems



X-51 Flight Test Summary

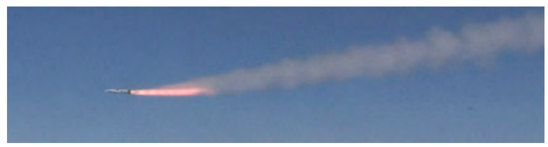
Four Powered Flights over Three Years (May ‘10 – May ‘13)

First Flight: May 26th, 2010
- 143 seconds of scramjet operation
- Peak Mach of 4.87; 150 nm travelled
- Seal / nozzle breach ended flight early

Second Flight: June 13th, 2011
- Engine “unstarted” nine seconds after scramjet ignition
- Post-flight investigation and ground testing yielded several scramjet operability lessons learned

Third Flight: August 14th, 2012
- Run-away control fin actuator and loss of control prior to engine light

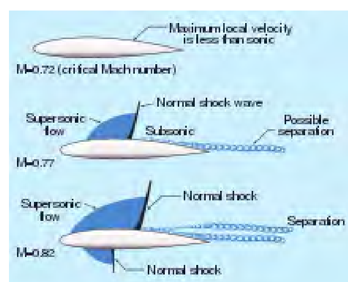
Fourth Flight: May 1st, 2013
- Full duration flight: ~209 seconds of scramjet operation and 377 seconds of controlled flight
- Peak Mach of 5.1; ~240 nm travelled in six minutes



Hypersonic Flow

★ **What is it?**

- ✧ *Subsonic Flow:* $M_\infty < 1$
  - ✫ *Incompressible* $M_\infty \leq 0.3$
  - ✫ *Compressible* $0.3 \leq M_\infty \leq 0.7$
- ✧ *Transonic:* $0.7 \leq M_\infty \leq 1.3$
- ✧ *Supersonic Flow:* $M_\infty > 1$
- ✧ *Hypersonic Flow:* $\boxed{M_\infty \gtrsim 5}$



https://en.wikipedia.org/wiki/Shock_wave

★ **Most experts agree: Hypersonic flow @ M ~ 4-6**

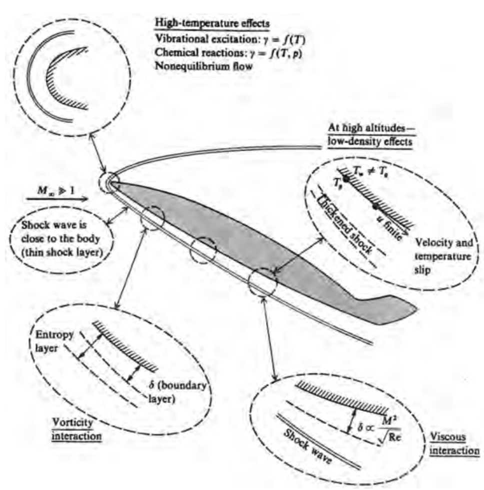
Working Assumptions & Approximations

- ★ **Basic Assumptions**
  - ✧ *High Mach number:* $M_\infty >> 1$
  - ✧ *Large density change across shock:* $\dfrac{1}{\varepsilon} = \dfrac{\rho_2}{\rho_\infty} >> 1$
  - ✧ *Thin shock-layer*
- ★ **Aerodynamic Forces**
  - ✧ *Local pressure coefficient follows the "Newtonian flow" model:* $C_p = 2\sin^2\theta_b$
  - ✧ *Mach Number Independence Principle: (relates to pressure drag of blunt bodies/wedges/cones)* $M_\infty \sin\theta_b >> 1$
- ★ **Aerodynamic Heating**
  - ✧ *Local aerodynamic heating can be approximated by hypersonic boundary layer analysis:*

$$\dot{q}_w = \rho_e u_e C_H (h_{aw} - h_w)$$

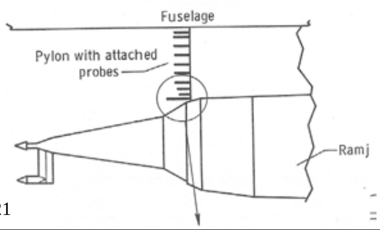
Hypersonics – Basic Features

- ★ **Basic:**
  - ✧ *High Mach number flight through atmospheric medium*
- ★ **Distinguishing Features:**
  - ✧ *Thin Shock Layer → region between shock wave and vehicle surface*
  - ✧ *Entropy Layer → strong entropy gradients leading to significant vorticity generation and propagation*
  - ✧ *Viscous Interaction → standard BLT analysis fails*
  - ✧ *High Temperature Effects*
    - ☆ *Thermal & chemical non-equilibrium*
  - ✧ *Possibly Low-Density Flow → Knudsen number*

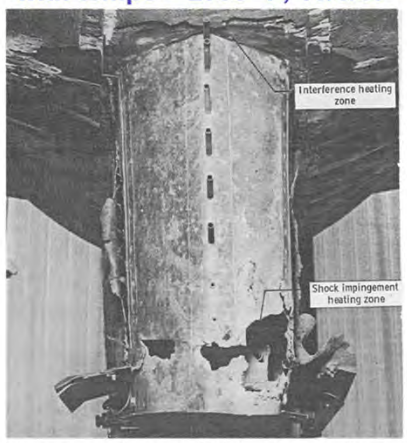


Surprise!

Dummy ramjet installed



The result melted the metal with temps > 2795° F, 10/3/67

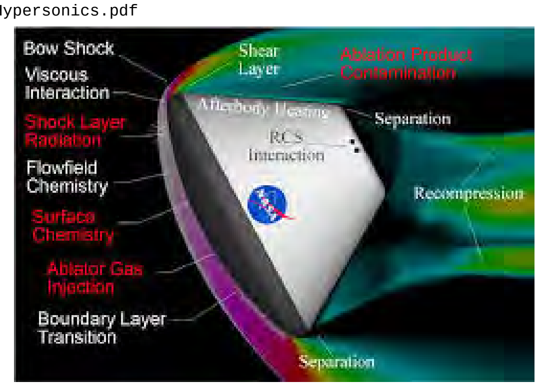


Structure: Inconel X (a nickel-chromium alloy) plus an ablative cover

From Iliff and Shafer, AIAA Paper 93-0311and NASA TM X-1669

http://www.dept.aoe.vt.edu/~mason/Mason_f/ConfigAeroHypersonics.pdf

https://en.wikipedia.org/wiki/Atmospheric_entry



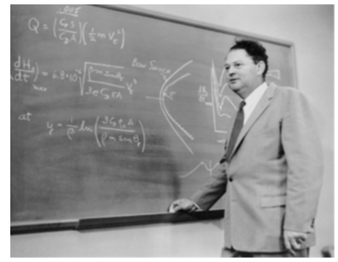
Viscous Boundary Layer Theory

AERODYNAMIC HEATING APPROXIMATIONS FOR HYPERSONICS

1950's Hypersonics Challenge

Ballistic Missile Atmospheric Entry

1st thought: a slender shape with pointed nose would be best



But! H. Julian Allen and A.J. Eggers, Jr.:

A blunt nose forces a detached shock and most of the heat goes off the surface and into the flowfield, not the vehicle, and enables practical re-entry "vehicles"

This was the major theoretical advance in the 1950s

-NACA R 1381, H. Julian Allen and A.J. Eggers, Jr., "A Study of the Motion and Aerodynamic Heating of Ballistic Missiles Entering the Earth's Atmosphere at High Supersonic Speeds," 1953

Allen showed:

$$\dot{q}_{\substack{\text{max}\\\text{laminar}}} \sim \frac{1}{\sqrt{R_{LE}}}$$

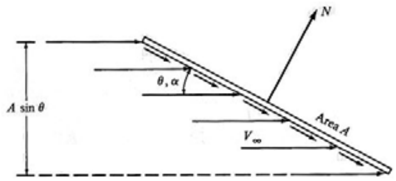
Heating in Hypersonic Flow

- **Approximate Heating Formula**
  - *Generic approximation resulting from boundary layer theory (similarity analysis)*

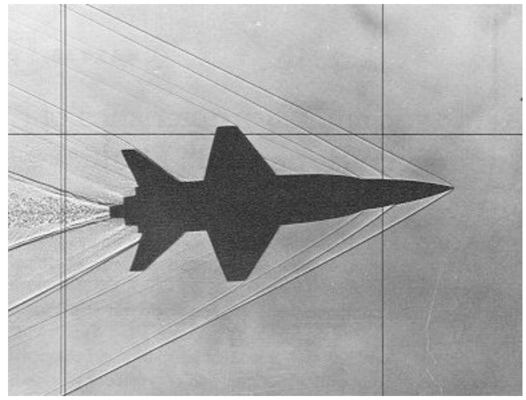
$$q_w = \rho_\infty^N V_\infty^M C$$

  - *Example: Inserting parameters for stagnation point*

$$q_w = \frac{1.83\times10^{-8}}{\sqrt{R}}\rho_\infty^{1/2} V_\infty^3 \left(1-\frac{h_w}{h_0}\right)\ \frac{\text{W}}{\text{cm}^2}$$



http://www.aerospaceweb.org/design/waverider/theory.shtml



https://history.nasa.gov/SP-60/ch-5.html

Surface Inclination Methods

AERODYNAMIC FORCE APPROXIMATIONS FOR HYPERSONICS

Supersonic vs Hypersonic

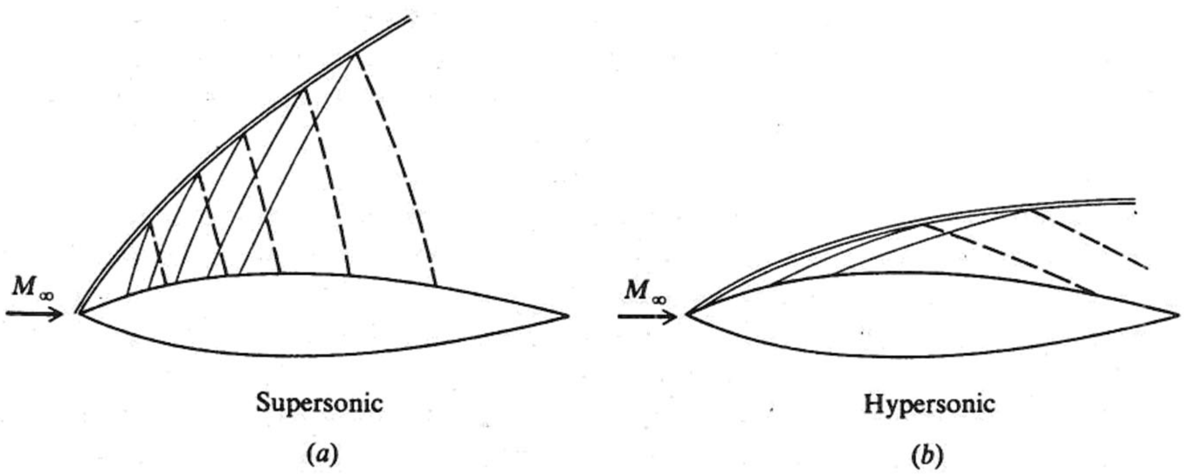


FIGURE 3.22
Schematic of shock wave and Mach wave patterns. (*a*) Supersonic; (*b*) hypersonic.

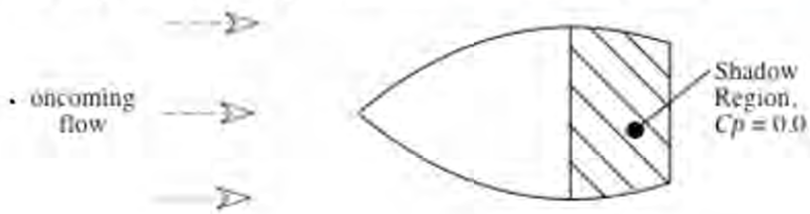
Surface Pressure

Local slope rules differ in supersonic and hypersonic flows

Linearized supersonic flow	Hypersonics: Newtonian flow rule
$C_p = \dfrac{2\theta}{\sqrt{M_\infty^2 - 1}}$	$C_p = 2\sin^2\theta$

No Mach number!
Nonlinear! ($M = \infty$, $\gamma = 1$)

Many other hypersonic "rules" available



$$C_p = C_{p_{\max}} \sin^2\theta$$

Cp_{max} is Cp behind a normal shock

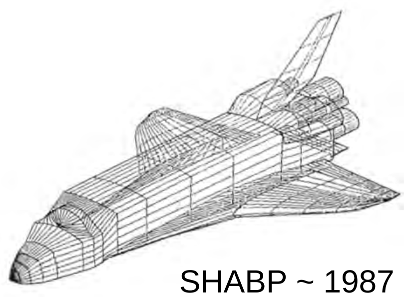
– For $\gamma = 1.4$, Cp_{max} at $M = \infty$ is 1.84, at $M = 4$, Cp_{max} 1.79

Newtonian/Modified Newtonian is typically good for blunt bodies with large inclination angles

Surface Inclination Methods Summary

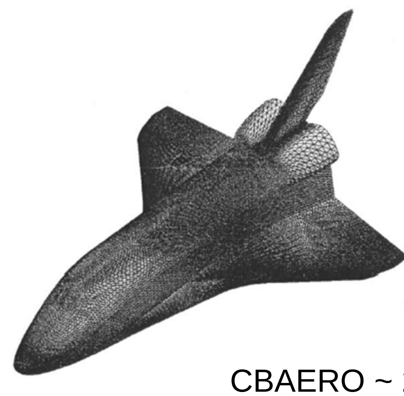
- **Newtonian method:** $\boxed{C_p = 2\sin^2\theta}$
- **Modified Newtonian:** $\boxed{C_p = C_{p,\max}\sin^2\theta}$
- **Newton-Buseman accounts for centrifugal effects**
- **Tangent Wedge/Cone Methods**
- **Shock-Expansion Method (considered the "exact" solution)**
- **Good exercise: Compare and contrast for various 2D and 3D bodies as applicable**
- **Automation: Computer program by A. E. Gentry**
  - *AFFDL-TR-73-159 (3 vols.) The MARK IV Supersonic-Hypersonic Arbitrary-Body Program*
  - *More recently, HEAT-TK (AFRL – Boeing) and CBAERO (NASA)*

Computational Models



SHABP ~ 1987

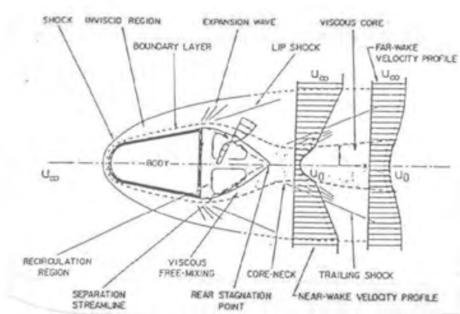
Fisher, Carren, M. E., "Experiences Using the Mark IV Supersonic Hypersonic Arbitrary Body Program," *Aerodynamics of Hypersonic Lifting Vehicles*, AGARD Conference Proceedings 428, 1987, pp. 31-1–31-18.



CBAERO ~ 2006

Kinney, David J., and Garcia, Joseph A., "Predicted Convective and Radiative Aerothermodynamic Environments for Various Reentry Vehicles Using CBAERO," AIAA Paper 2006-659, Jan. 2006.

https://www.semanticscholar.org/paper/FUNDAMENTALS-OF-HYPERSONIC-FLOW-AEROTHERMODYNAMICS-Fletcher/6b9df4dc0795326c33ba7a1b027e76e0af63c880



Hypersonic Vehicle Design

AEROTHERMODYNAMIC EFFECTS IN HYPERSONIC FLOW

Aero-thermodynamics

- **Atmospheric re-entry: energy conversion**
- **Kinetic energy → internal energy**
  - *Example: at 7 km/sec,* $e_k = 2.45 \times 10^7$ J/kg
  - *Perfect gas model (frozen chemical composition and constant specific heats) gives a temperature increase of 2.4 x* 10^4 *K*
- **In reality:**

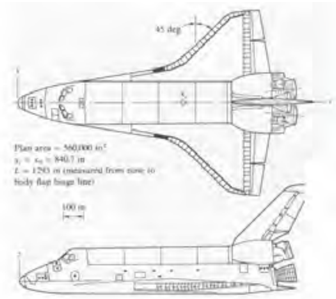
Kinetic Energy → Thermal energy
Kinetic Energy → Vibrational energy
Kinetic Energy → Dissociation/ionization

- **Most Cases: thermodynamic state between limits of frozen and equilibrium.**

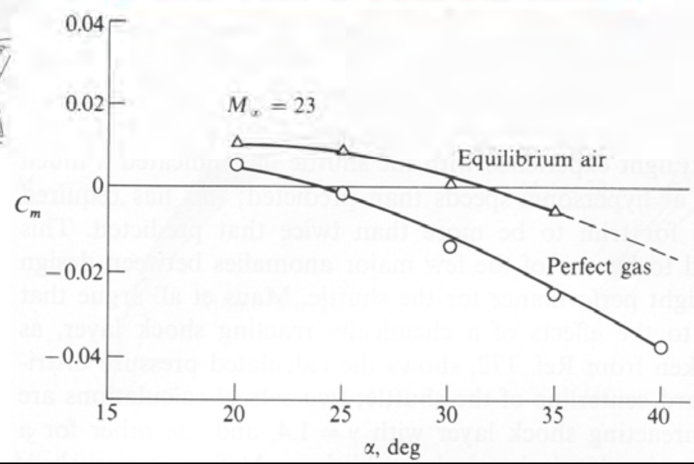
Thermo-chemical dynamics

- **Thermally perfect: Ideal gas law holds**
- **Calorically perfect: Constant Specific heats**
- **Real-gas model: use compressibility charts**
- **Equilibrium, chemical reacting gas: modified equations of state using either empirical data curve fits or tabulated data/charts**
- **High-Temperature Effects**
  - *Thermal non-equilibrium*
  - *Chemical non-equilibrium*

High Temperature Gas Effects



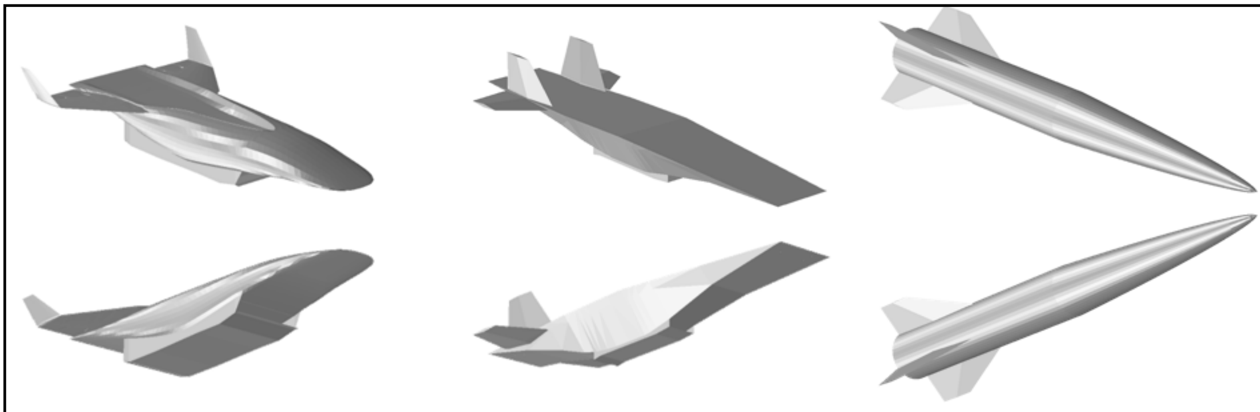
They almost ran out of deflection to trim - could have been a disaster!



From Anderson, *Hypersonic and High Temperature Gas Dynamics,* but originally from Maus, et al, *JSR* Mar-Apr 1984, pp 136-141

Things to Note

- ★ ***Understanding the physics of hypersonics is key*** **to technology development**
- ★ **Accurate modeling of relevant physics prevents disasters**
- ★ **Application/mission of a hypersonic system determines relevant physics**
- ★ ***Relevant physics in hypersonics strongly influence system design and performance*** **(not to mention cost, operability, …)**



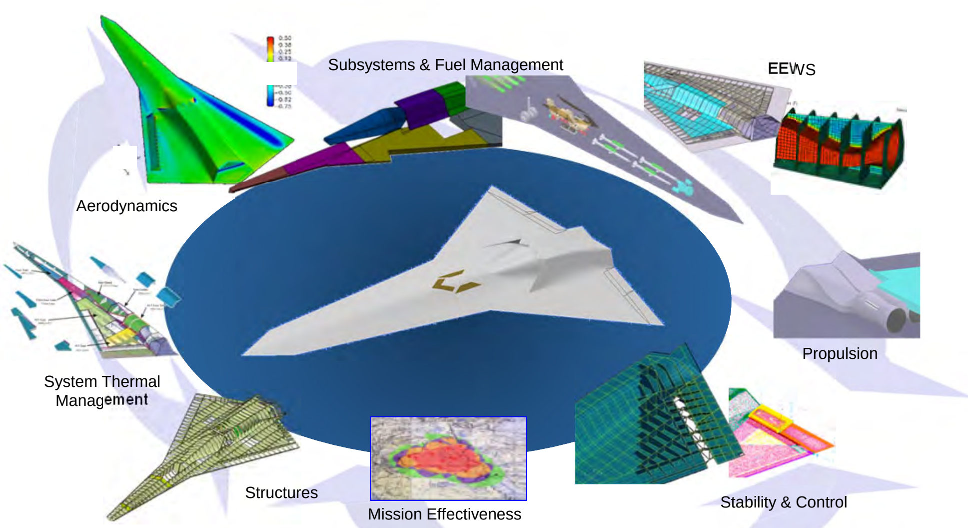
NASA Vision Vehicle AFRL ISR Hypersonic Cruiser AFRL IC3X High Speed Vehicle

https://a2srl.engin.umich.edu/research/maccs/hyper_flexible-2/

Systems Integration, Analysis, Design, and Optimization

HYPERSONIC VEHICLE DESIGN

Integrated Design Process - Systems Engineering



Add All Disciplines, Couplings, & Fidelity - Early

USSF

Conceptual Design

AFRL

Abstract Creation *Theoretical Drawing*

“Conceptual modelling is the abstraction of a simulation model from the part of the real world it is representing (‘the real system’). The real system may, or may not, currently exist. Abstraction implies the need for simplification of the real system and for assumptions about what is not known about the real system. In other words, all simulation models are simplifications of the real world. The *secret to good conceptual modelling is to get the level of simplification correct*, that is, *to abstract at the right level*.”

– **Robinson, “Conceptual Modeling for Simulation,” *Proc. of the 2013 Winter Simulation Conference***

- ☆ **Conceptual Design has a slightly different meaning from one organization to another. It depends on your purpose for the work**
- ☆ **Generally conceptual design is intended for *design space exploration*, that is testing out multiple options before down-selecting the *system concept*.**

USSF

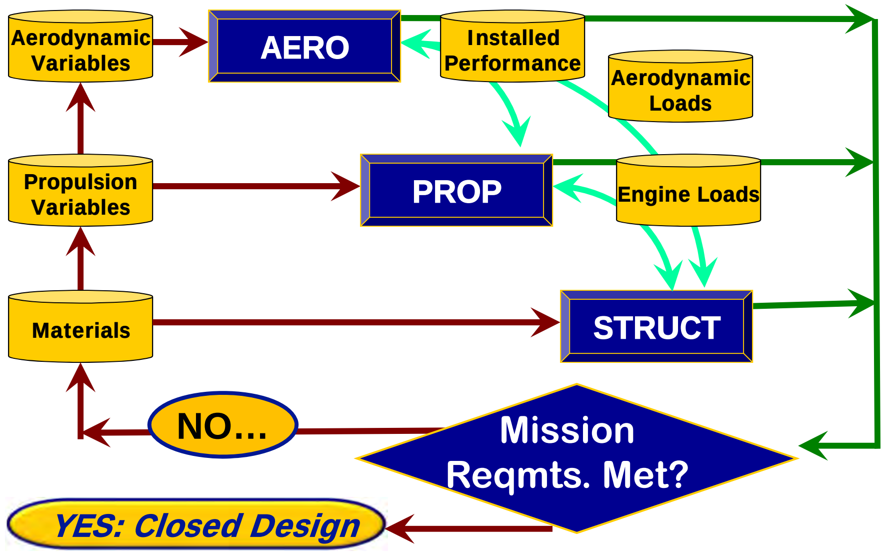
Fidelity Fairness

AFRL

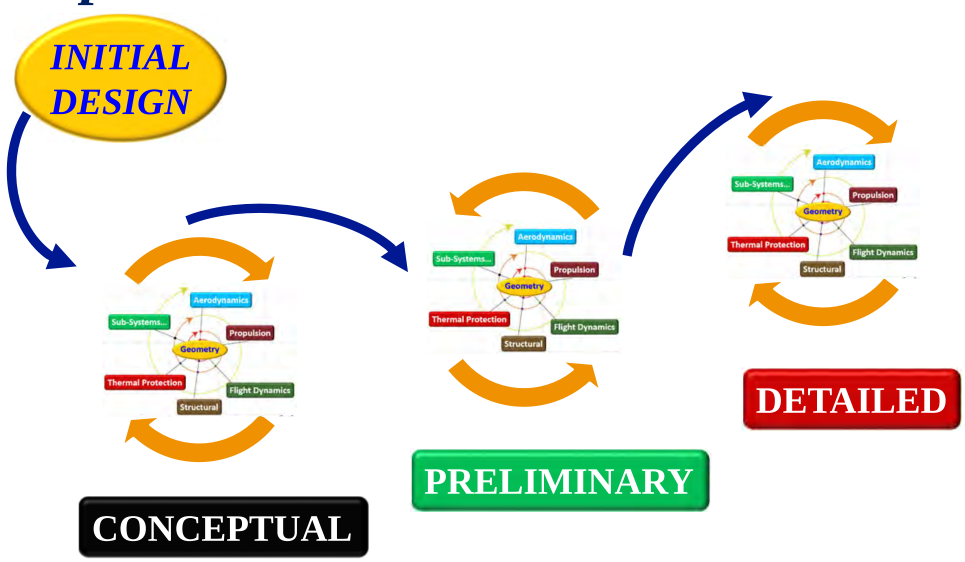
Fidelity Level	System Level	Review	Description	Timeframe
0	System	Initiation	rapid assessment of system architectures (generally no geometry).	Weeks (1-4)
1	Subsystem	Pre-Conceptual	initial assessment of as-drawn system design	Months (2-6)
2	Component	Conceptual (CoDR)	refined assessment of as-drawn system & subsystem design	Months (6-18)
3	Part	Preliminary (PDR)	preliminary assessment of as-drawn system, subsystem & component design	Years (1-5)
4	Part	Detailed (CDR)	detailed assessment of as-drawn system, subsystem, component & part design	Years (3-7)

“Conceptual Design”

System Synthesis



Design Spiral



Supersonic vs Hypersonic

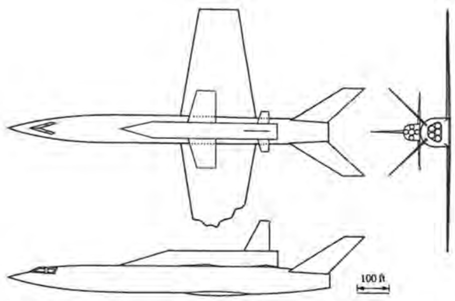


FIGURE 1.4
The Drake-Carman hypersonic aircraft/orbiter, proposed in 1953. (*From Hallion, Ref. 2.*)

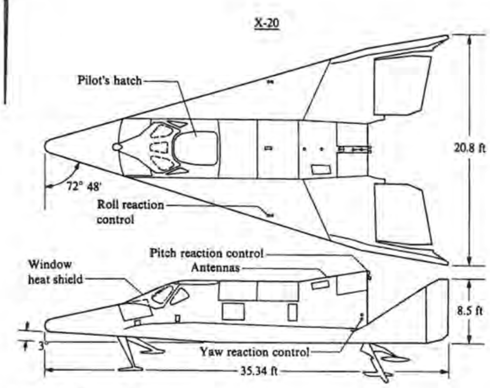
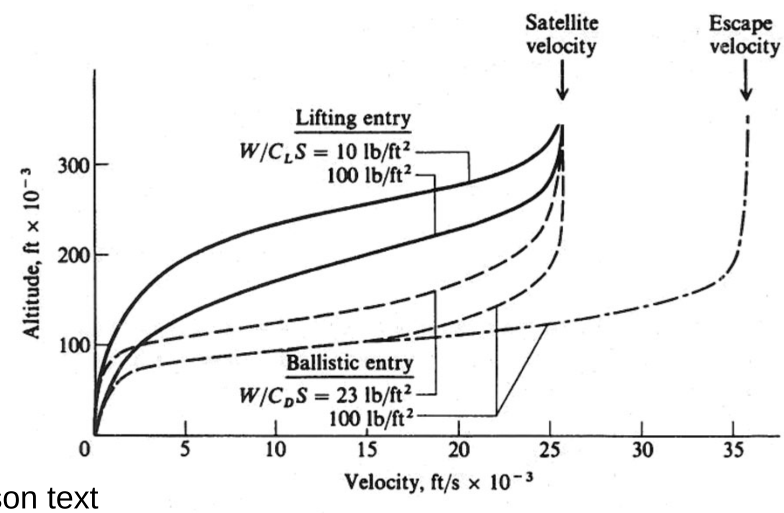


FIGURE 1.5
The Boeing X-20A Dynasoar orbital hypersonic aircraft, 1963. (*From Hallion, Ref. 2.*)

Vehicle Constraints

- **Hypersonic flow characterization:**
  - *Mission requirements*
  - *Vehicle shape/size constraints*
- **Blunt vehicles**
  - *Large drag coefficient, small flight-path angle → high-altitude deceleration*
- **Slender vehicles**
- **Low drag coefficient, large flight-path angle → deep penetration into atmosphere to decelerate**
- **See: Velocity vs Altitude Chart**

Velocity-Altitude Chart



Anderson text

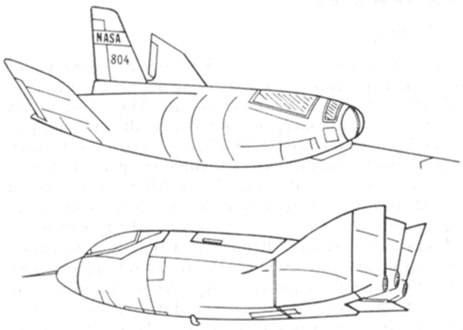
FIGURE 1.22
Atmospheric entry flight paths on a velocity-altitude map.

Design Considerations

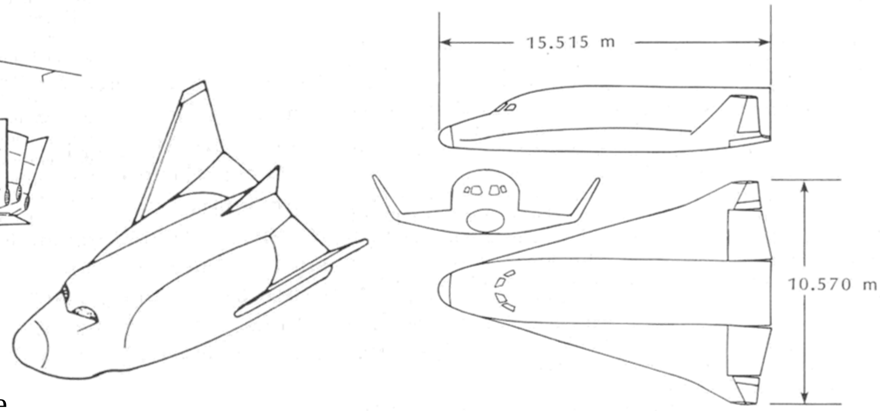
- **Consider two basic types:**
  - *Vehicle placed into orbit with rocket propulsion system, then returns as an unpowered glider.*
    - *Apollo Command Module.*
    - *Space Shuttle, Russian Buran, European Hermes.*
  - *Vehicle powered by air-breathing propulsion system.*
    - *NASP, some current TAV's.*
    - *Trajectory represents a compromise between propulsion requirements & heating.*

Design must consider relative importance of hypersonic flow parameters such as physical chemistry, viscous interactions, BL transition, etc.

Blunt Lifting Bodies



Some blunt, lifting bodies
from the 1960s and 1970s

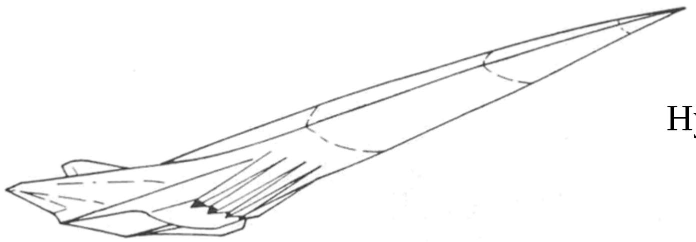


Assured Crew Return Vehicle

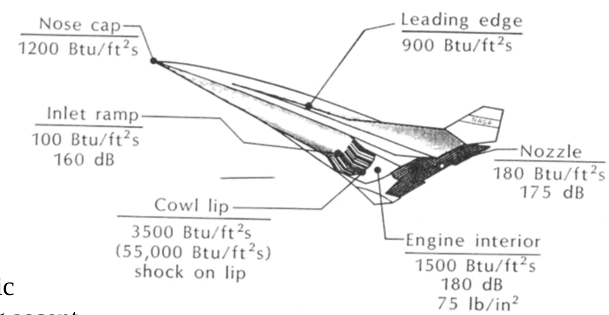
Air-breathing Vehicles

- **Vehicle powered by air-breathing propulsion system must consider:**
  - *Aerothermodynamic environment.*
  - *Propulsion system integration.*
  - *Structure and structural dynamics.*
  - *Flight control system integration.*
- **Technical problems are multi-disciplinary to first-order!**
- **Must integrate highly-coupled interacting elements to achieve desired performance.**

Hypersonic Air-Breathing Concepts



Hypersonic Vehicle Concept
ca.1970's

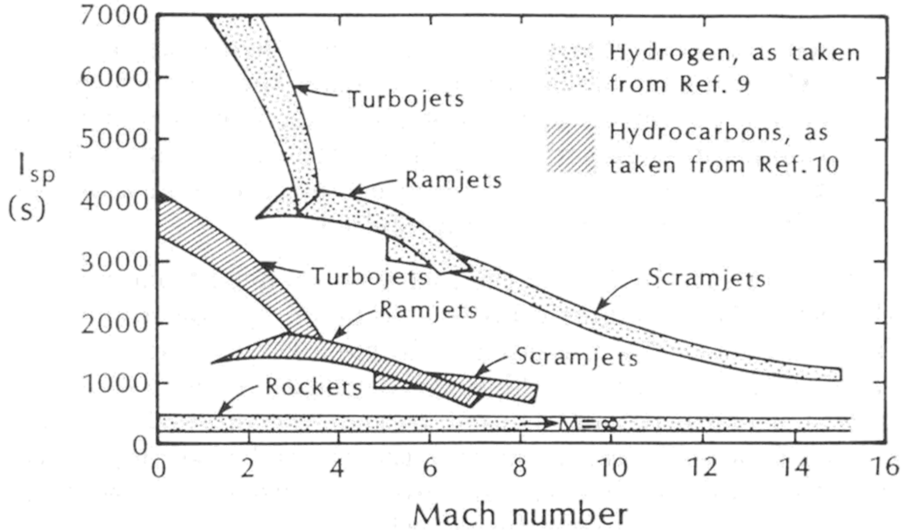


Typical aerothermo-dynamic constraints on NASP during ascent.

Design Considerations

- **Range → cruise efficiency (Breguet factor).**
- **Propulsion → specific impulse for various engine cycles, fuel characteristics, etc.**
  - *Practical, near term design will likely utilize more than one mode of propulsion to operate efficiently over a wide range of Mach number.*
- **Control & Stability**
  - *Leads to different shapes at hypersonic speeds*
- **Aerothermodynamics:**
  - *Temperature and heating become critical; blunt shapes common (required in some cases)*
  - *Climb, cruise, landing trajectories.*
  - *Fuel consumption, maximum dynamic-pressure*
  - *Fully coupled interactions between aerodynamic, structural, and propulsive systems – Engine-Airframe integration is key*
  - *Heating: Very severe on ascent and considerable on return (e.g. NASP).*

Specific Impulse



Design of New Hypersoinic Vehicles

- ★ Use existing complex technology when new one not mandatory.
- ★ Use existing design or extrapolate (conventional design preferred to optimized).
- ★ Select large margins covering uncertainties given by each complex physical phenomenon not well understood.
- ★ Use first vehicles as test benches for later ones.
- ★ Reduce flight envelope to remain inside small risk but efficient domain.

Design Tools & Process

- ★ **Theoretical Analyses.**
- ★ **Computational Fluid Physics.**
- ★ **Ground-Based Testing & Experimentation.**
- ★ **Flight Tests (scale models, full-scale).**
- ★ **Ultimately, only flight of full-scale vehicle at actual conditions provides true representation (expensive, time consuming, and high risk).**
- ★ **Optimum configuration will require fully integrated multi-disciplinary approach.**

Recognize the strengths and weaknesses of each tool and range of applicability!

Recent Success