Hypersonic Aerothermodynamics

ME 699 -- 2020 Fall Term

Lecture 1 - August 19th 2020

ME 699 – Hypersonics

Monday & Wednesday, 2:00 – 3:15 PM
https://uky.zoom.us/j/7344744383

Fall Semester 2020

Instructor

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Course description

Fluid dynamics and heat transfer applied to hypersonic flows. Flight dynamics, aerothermodynamics, surface phenomenon, boundary layers, propulsion and thermal protection systems.

Prerequisites

MA 530

Outcomes

Upon conclusion of the course, the student should be able to do the following:

1. Understand fluid dynamic applied to hypersonic systems
2. Understand heat transfer applied to hypersonic systems
3. Understand the various characteristic properties of hypersonic systems
4. Solve hypersonic problems

Concepts and topics

- Introduction (1 lecture)
- Flight dynamics (3 lectures)
- Fluid dynamics (4 lectures)
- Aerothermodynamics phenomena (4 lectures)
- Surface pressure (5 lectures)
- Boundary layers (3 lectures)
- Heat transfer and skin friction (3 lectures)
- Hypersonic propulsion (2 lectures)
- Thermal protection systems (5 lectures)

Materials

References

[1] J. D. Anderson Jr. *Hypersonic and High Temperature Gas Dynamics*. McGraw-Hill, 1989.

[2] J. D. Anderson Jr. *Modern Compressible Flows – With historical perspective*. McGraw-Hill, 3rd edition, 2002.

[3] J. J. Bertin. *Hypersonic Aerothermodynamics*. AIAA Education Series, 1994.

[4] W. L. Hankey. *Re-Entry Aerodynamics*. AIAA Education Series, 1988.

[5] W. H. Heiser and D. T. Pratt. *Hypersonic Airbreathing Propulsion*. AIAA Education Series, 1994.

[6] M. L. Rasmusen. *Hypersonic Flow*. John Wiley & Sons, 1994.

Course assignment

- Homework assignments and projects (6-7): 40%
- 1 mid-term exam: 25%
- 1 final exam: 35%

Description of course assignment

Homework assignments

Problem sets will be assigned approximately every two weeks.

Examinations

Although the content of the mid-term test will focus on specific sections of the course, all tests and exams will be considered comprehensive, in that you will be expected to be able to apply basic concepts form everything that has been covered up to that point. The final exam will be comprehensive and will cover material of the entire course. Emphasis will be placed on understanding the basic physics and mathematics associated with fluid mechanics and the ability got translate this understanding into conceptual problem solving. This will be strongly reflected in the nature of written examinations (and to a lesser extent, homework assignments). **Both exams will take place during regular class time.**

Grading

A curved grading scale might be used, although it generally is not.

Mid-term Grade

A Mid-term grade, based on the progress, will be posted in *myUK* by the deadline established in the Academic Calendar (http://www.uky.edu/Registrar/AcademicCalendar.htm)

Course Policies

Submission of Assignments

The late submission policy is 1 day = 75%, 2 day = 50%, more = 0%.

Excused Absences

Students need to notify the professor of absences prior to class when possible. S.R. 5.2.4.2 defines the following as acceptable reasons for excused absences: (a) serious illness, (b) illness or death of family member, (c) University-related trips, (d) major religious holidays, and (e) other circumstances found to fit "reasonable cause for nonattendance" by the professor.

Students anticipating an absence for a major religious holiday are responsible for notifying the instructor in writing of anticipated absences due to their observance of such holidays no later than the last day in the semester to add a class. Information regarding dates of major religious holidays may be obtained through the religious liaison, Mr. Jake Karnes (859-257-2754).

Students are expected to withdraw from the class if more than 20% of the classes scheduled for the semester are missed (excused or unexcused) per university policy.

Verification of Absences

Students may be asked to verify their absences in order for them to be considered excused. Senate Rule 5.2.4.2 states that faculty have the right to request "appropriate verification" when students claim an excused absence because of illness or death in the family. Appropriate notification of absences due to university-related trips is required prior to the absence.

Content

1. Introduction [1 lectures]

- Course outline
- Broad overview of hypersonics

2. Flight Dynamics [3 lectures]

- Trajectory equations outline
- Ballistic entry (missile)
- Equilibrium glide (space shuttle)
- Air-breating, powered flight

3. Aerothermodynamics phenomena [5 lectures]

- Review of compressible gas dynamics
- Real gas effects and air chemistry
- Fluid conservation equations
- Transport phenomena
- Review of aerodynamics

4. Surface Pressure [5 lectures]

- Stagnation point
- Newtonian models
- Aerodynamics
- Slender bodies

5. Boundary Layers [3 lectures]

- Self-similar equation
- Solution for flat plate
- Fay-Riddell stagnation point convective heat transfer

6. Heat Transfer and Skin Friction [3 lectures]

- Surface temperature
- Eckert's reference temperature method
- Laminar and turbulent boundary layers

7. Hypersonic propulsion [3 lectures]

- Rockets
- Air-breathing systems (turbo-jets, ramjets, scramjets)
- Air-breathing inlet
- Rocket based and turbine based combined cycles

8. Thermal Protection System [2 lectures]

- Design drivers
- Passive (space shuttle, X-43)
- Ablative (Stardust)

9. Other topics in hypersonics [1 lectures]

- Entry capsule
- Hypersonic experimental facilities

Schedule (tentative!)

	Tuesday	Topics	Homeworks and Talks	Thursday	Topics	Homeworks and Talks
Week 1				August 19	Introduction	
Week 2	August 24	Flight I		August 26	Flight II	
Week 2	August 31	Flight III	HW 1 out	September 1	Fluids I	
Week 3	September 7	Fluids II	HW 1 in	September 9	Fluids III	HW 2 out
Week 4	September 14	Fluids IV		September 16	Surface I	HW 2 in
Week 5	September 21	Surface II	HW 3 out	September 23	Surface III	
Week 6	September 28	Surface IV	HW 3 in	September 30	Surface V	
Week 7	October 5	**Mid-term**		October 7	B. Layer I	HW 4 out
Week 8	October 12	B. Layer II		October 14	B. Layer III	HW 4 in
Week 9	October 19	Heat Tr. I	HW 5 out	October 21	Heat Tr. II	
Week 10	October 26	Heat Tr. III	HW 5 in	October 28	Propulsion I	HW 6 out
Week 11	November 2	Propulsion II		November 4	TPS I	HW 6 in
Week 12	November 9	TPS II	HW 7 out	November 11	TPS III	
Week 13	November 16	TPS IV	HW 7 in	November 18	TPS V	
Week 14	November 23	**Final**				

Chapter 1: Introduction

1.1 Some basic ideas

- The course is loosely adapted from Prof. Boyd's notes (UMich)
- Some slides are taken from the *Advanced Hypersonic Aerothermodynamics* short courses given by Graham V. Candler (U. of Minnesota) and Iain D. Boyd (U. of Michigan) for the *National Institute of Aerospace* (NIA) as part of the *Hypersonic Education Initiative* (available online at http://www.nianet.org)
- Some other slides are taken from the *EDL* short courses given by Robert Braun (Georgia Tech) and Michael J. Wright (NASA Ames) for the *National Institute of Aerospace* (NIA)
- Comments are taken from official web sites, scientific papers and ... WikiPedia

What is Hypersonic Flow?

- Working definition of hypersonic flow:

$$M = (U / a) >> 1$$

- Hypersonic aerothermodynamic phenomena:
  - strong shock waves with high temperature
  - not calorifically perfect (variable γ)
  - chemical reactions
  - significant surface heat flux
  - several different types of vehicles:
    - missiles, space planes, capsules, air-breathers

Examples

Vehicle	Speed (mph)	M	Classification
Car on I-94	70	0.1	subsonic
Cessna 150	120	0.2	subsonic
Boeing 777	570	0.8	transonic
Concorde	1400	2	supersonic
X-15	4100	6	hypersonic
Shuttle, ICBM	17000	25	hypersonic
Apollo capsule	25000	36	hypersonic
Stardust	28900	40	hypersonic

Stardust re-entry

- NASA mission to collect samples of comet Wild-2 (2006)
- Fastest re-entry speed into Earth's atmosphere ever achieved by a man-made object: 12.6 km/s
- The re-entry is filmed on board of NASA’s DC-8 «Airborne Laboratory»

Aerothermodynamics

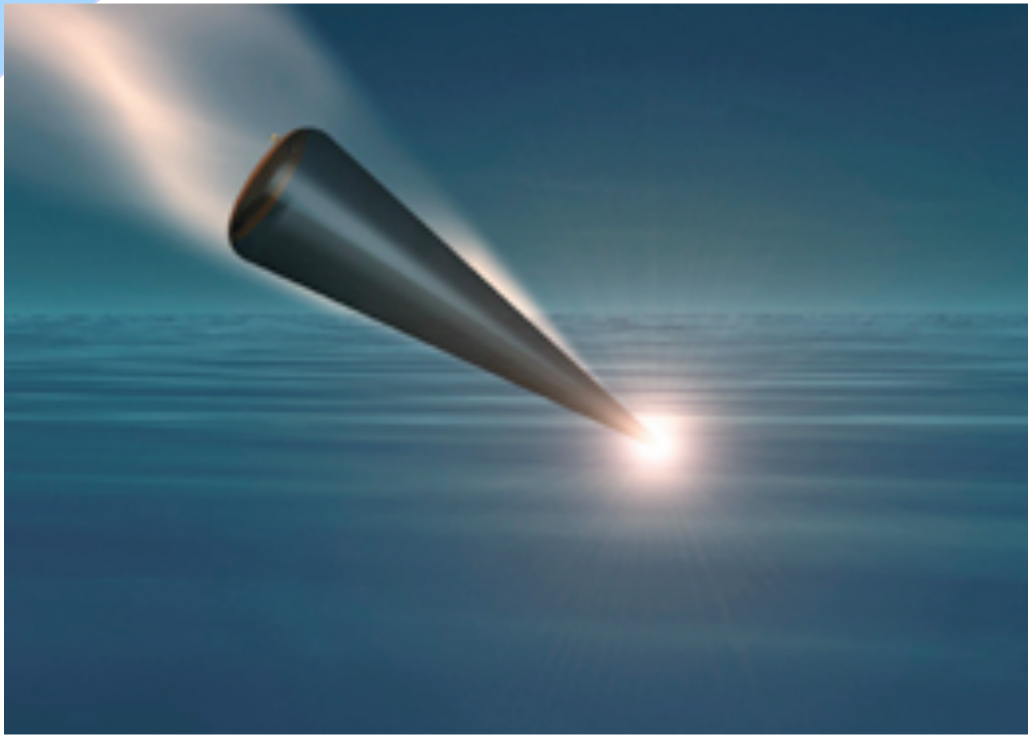
- This word is composed of:
  - aerodynamics: the study of the properties of moving air, and especially of the interaction between the air and solid bodies moving through it
  - thermodynamics: physical science that deals with the relations between heat and other forms of energy
- Thus, this course deals with the study of the aerodynamics and thermal management of very high speed flying vehicles

Hypersonic Vehicle Historical Overview

- Flight vehicles:
  - WAC Corporal missile (1949, M~8)
  - Vostok I (1961, M~25)
  - X-15 (1963-1967, M~7)
  - Space Shuttle (1981-???, M~25)
  - HyShot (2002, M~8)
  - X43 (2004, M>7)
  - Hy-CAUSE (2007)

- Recent programs without flight:
  - NASP, Hermes, AFE, AOTV (1990)
  - VentureStar-X33 (2000)

Hypersonic Examples: I. Missiles



- Mission: high-speed delivery of explosives
- Aerodynamics: slender body with blunt nose
- Propulsion: rockets, ramjets
- Examples: AMRV, SCUD, Patriot, Hy-Fly

Design drivers

- Rapid, accurate delivery of payload
- Very low drag
- Efficiency not really an issue

AMRV

- *Advanced Maneuvering Re-Entry Vehicle*
- Can change trajectory during re-entry, rendering interception more difficult
- Controlled by two flaps
- Used to deliver the LGM-30 Minuteman (MX)

SCUD

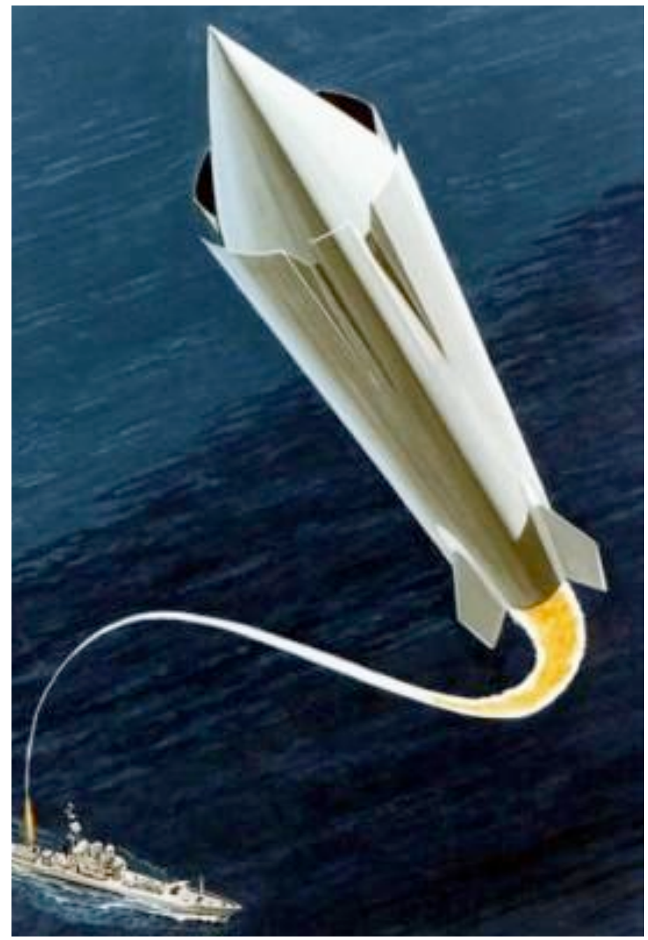
- Tactical ballistic missiles developed by the Soviet Union during the Cold War and exported widely to other countries
- Based on the german V-2
- The Russian names for the missile are R-11, R-17 and R-300 Elbrus
- Propelled by a single engine to ~1.7 km/s

MIM-104 Patriot

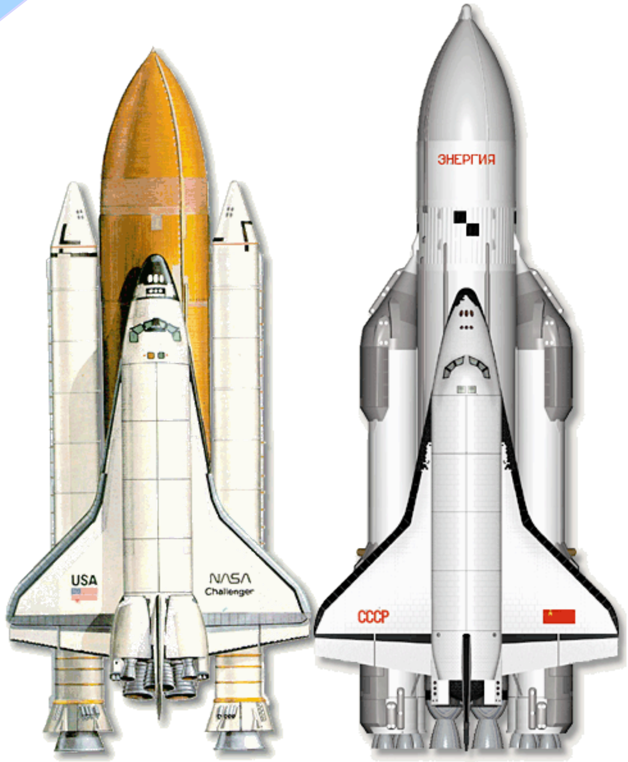
- Surface-to-air missile (SAM) system, the primary of its kind used by the United States Army
- Assumed the role as the U.S. Army's anti-ballistic missile (ABM) platform
- Speed in excess of Mach 3
- Used in the first Gulf war to intercept SCUD

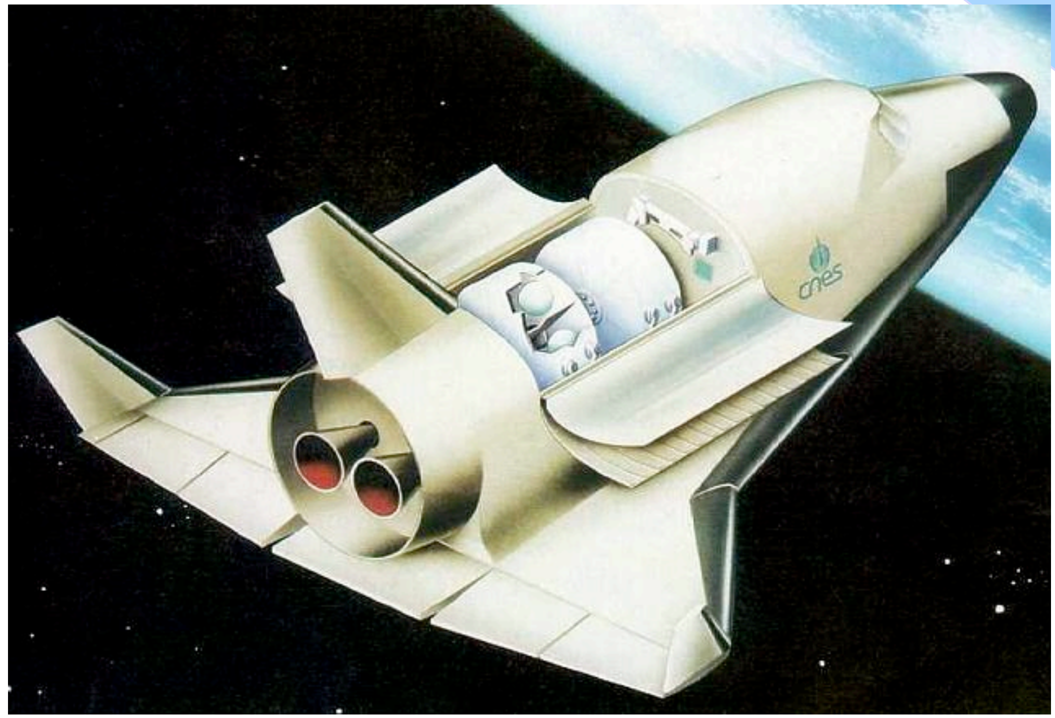
Boeing Hy-Fly

- Initiated in 2002 by DARPA and the Office of Naval Research, using concepts from the Applied Physics Laboratory (APL) of the Johns Hopkins University
- Hypersonic Mach 6+ ramjet-powered cruise missile
- Air-launched from an F-15E aircraft and accelerated to ramjet ignition speed by a solid-propellant rocket booster
- Engine is a dual-combustion ramjet (DCR), which can operate as a ramjet with subsonic combustion, or for hypersonic speeds as a scramjet
- Runs on conventional liquid hydrocarbon fuel



Hypersonic Examples: II. Space Planes





- Mission: orbital re-entry
- Aerodynamics: gliders with thermal protection
- Propulsion: none (except small control thrusters)
- Examples: Space Shuttle, Buran, Hermes

Design drivers

- Decelerate at high altitude using high drag
- Must survive high heating
- Low deceleration levels
- High reliability

NASA space shuttles

- OV-098 - Space Shuttle Pathfinder
  - Structural mockup to test transport and storage facilities
  - Now at the *U.S. Space & Rocket Center* in Huntsville, AL
- OV-099 - Space Shuttle Challenger
  - Originally a test shuttle, refitted for spaceflight (1983)
  - Exploded right after launch in 1985, after 10 successful missions
- OV-101 - Space Shuttle Enterprise
  - Constructed for test flights in the atmosphere
  - No heat-shield and no engines
  - Now at the *Intrepid Sea, Air & Space Museum* in New York City, NY

NASA space shuttles

- OV-102 - Space Shuttle Columbia
  - First functional space shuttle (1981)
  - Disintegrated during re-entry in 2003, after 26 successful missions
- OV-103 - Space Shuttle Discovery
  - Third operational orbiter (1984)
  - 27 years of service, decommissioned in 2010, after 39 missions
  - Now at the *Steven F. Udvar-Hazy Center of the Smithsonian National Air and Space Museum*, Washington, DC.
- OV-104 - Space Shuttle Atlantis
  - Fourth operational orbiter (1985)
  - 26 years of service, decommissioned in 2011, after 33 missions
  - Now at the *Kennedy Space Center Visitor Complex*, Cap Canaveral, FL.
- OV-105 - Space Shuttle Endeavour
  - Built in 1987 to replace Challenger
  - 19 years of service, decommissioned in 2011, after 25 missions
  - Now at the *California Science Center* in Los Angeles, CA

Space shuttle Buran

- Only fully completed and operational Russian space shuttle vehicle
- Design that borrowed heavily from the American Space Shuttle
- Completed one unmanned spaceflight in 1988
- Cancel with the Soviet shuttle program in 1993
- Destroyed by a hangar collapse in 2002

Space Shuttle Buran

- For transit, transported on the back of the Antonov An-225 Mriya aircraft, designed for this task (still the largest powered aircraft in the world)

- Lifted into orbit by the specially designed *Energia* booster rocket

Hermes shuttle

- Mini-shuttle designed by the French *Centre national d'études spatiales* (CNES) in 1975
- Superficially similar to the US X-20
- Project started in November 1987, scheduled for service in 1995, and was terminated in 1993
- No Hermes shuttles were ever built

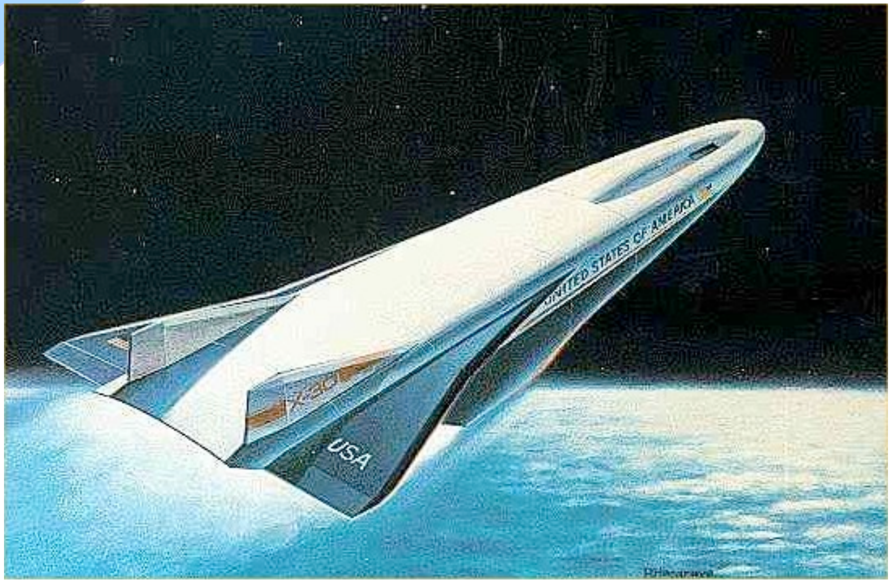
Boeing X-37

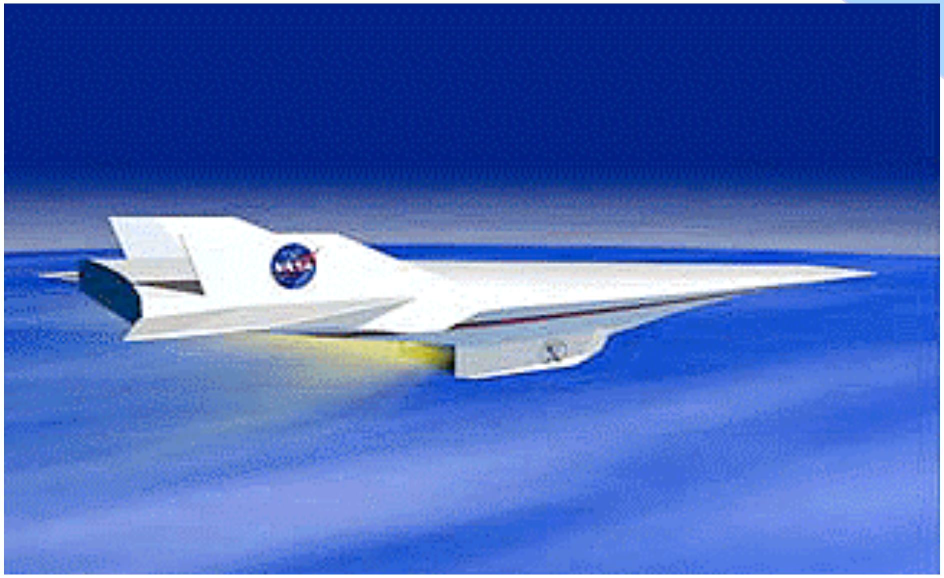
- Reusable robotic spacecraft
- Boosted into space by a launch vehicle, then re-enters Earth's atmosphere and lands as a spaceplane.
- Operated by the United States Space Force for orbital spaceflight missions
- Intended to demonstrate reusable space technologies
- 5 spaceflights completed (6th is in progress)
- Two models, three shuttles built
  X-37A (1), X-37B (2)

Intermediate eXperimental Vehicle (IXV)

- European Space Agency (ESA) experimental suborbital re-entry vehicle
- Technology demonstrator
- The vehicle is the first ever lifting body to perform full atmospheric reentry from orbital speed
- February 2015, the IXV conducted its first 100-minute space flight, successfully completing its mission upon landing intact on the surface of the Pacific Ocean

Hypersonic Examples: III. Air-breathing Systems





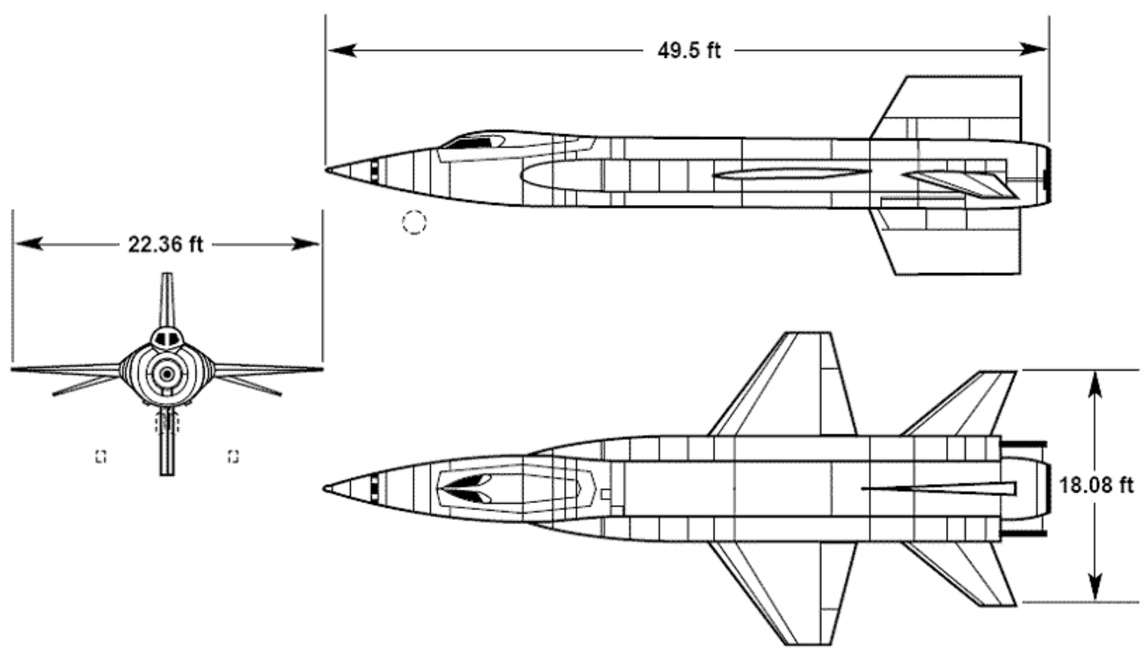
- Missions: launch, cruise, orbital re-entry
- Aerodynamics: slender with integrated engines
- Propulsion: ram/scram-jets, rockets, turbojets
- Examples: X-15, NASP, X-43, X-51

Design drivers

- Air breathing propulsion (low altitude operation)
- Low drag, low heating
- Efficient
- Low deceleration
- High reliability

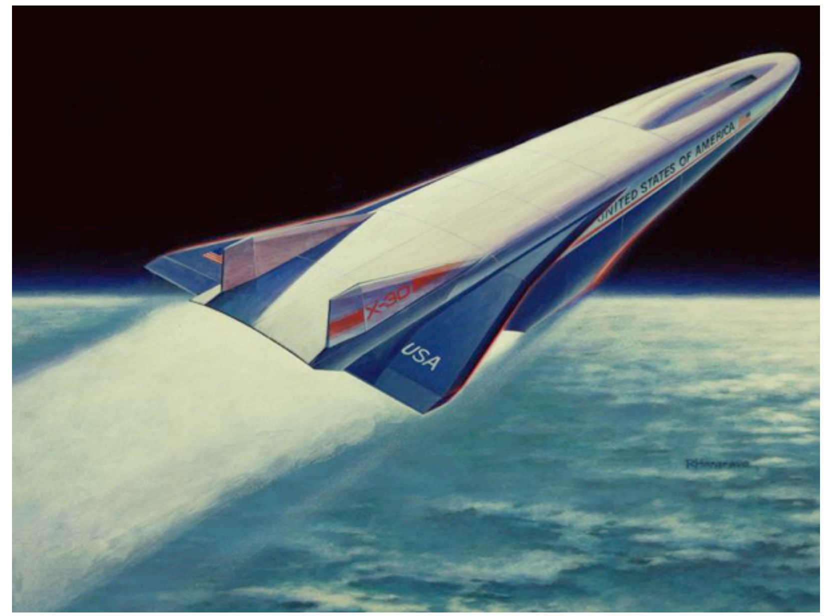
North American X-15

- Part of the X-series of experimental aircraft
- First flew in 1959
- Some flights qualified as space flights
- Powered by a single XLR-99 rocket engine delivering 311kN at peak altitude.



Rockwell X-30 (NASP)

- Originated from a DARPA in the 80s
- Attempt to create a viable single stage to orbit (SSTO) spacecraft
- Project was cancelled in 1993 prior to the first craft being built, because of DoD unrealistic requirements
- The engine was intended to be a scramjet



NASA X-43

- Unmanned experimental hypersonic aircraft
- Designed to test different aspects of hypersonic flight
- Part of NASA's Hyper-X program
- Launched from a carrier plane

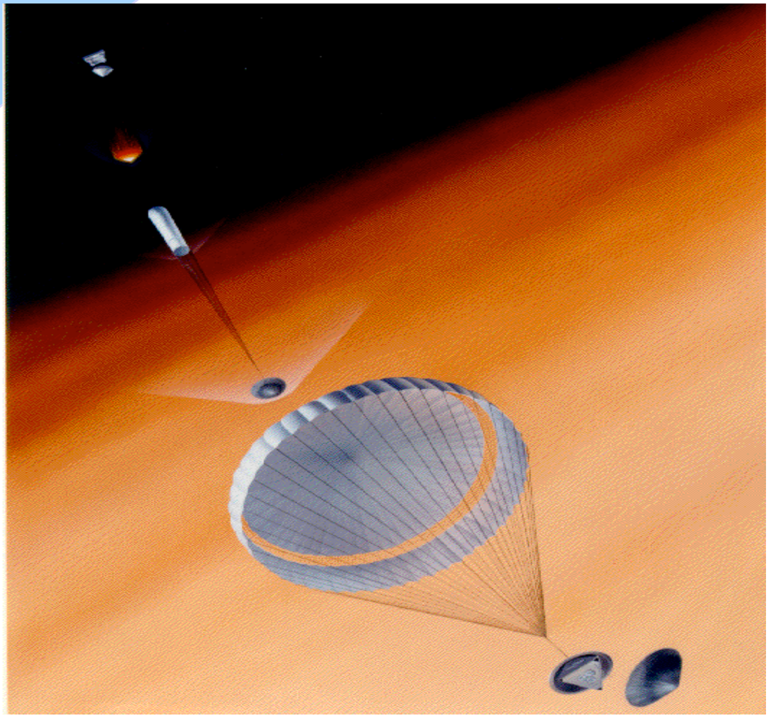
- A booster rocket brings the aircraft to the target speed and altitude
- X-43 flies free using its own engine, a scramjet

Boeing X-51

- Scramjet demonstration vehicle
- Expected to fly by 2009
  at hypersonic speeds
  close to Mach 7
- Preliminary tests
  conducted in 2006-2007

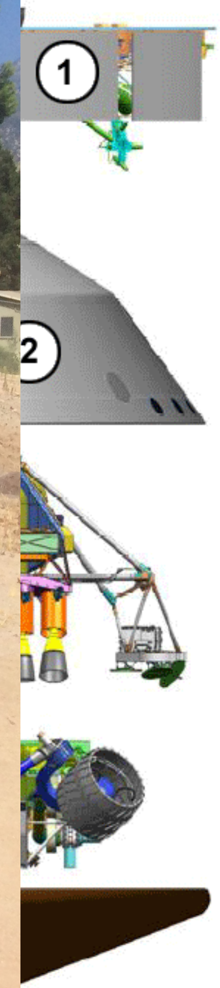
- A B-52 carries the vehicle to an altitude of about 35,000 feet and then release it
- Initially propelled by a solid rocket booster, the scramjet takes over at Mach 4.5

Hypersonic Examples: IV. Planetary Entry



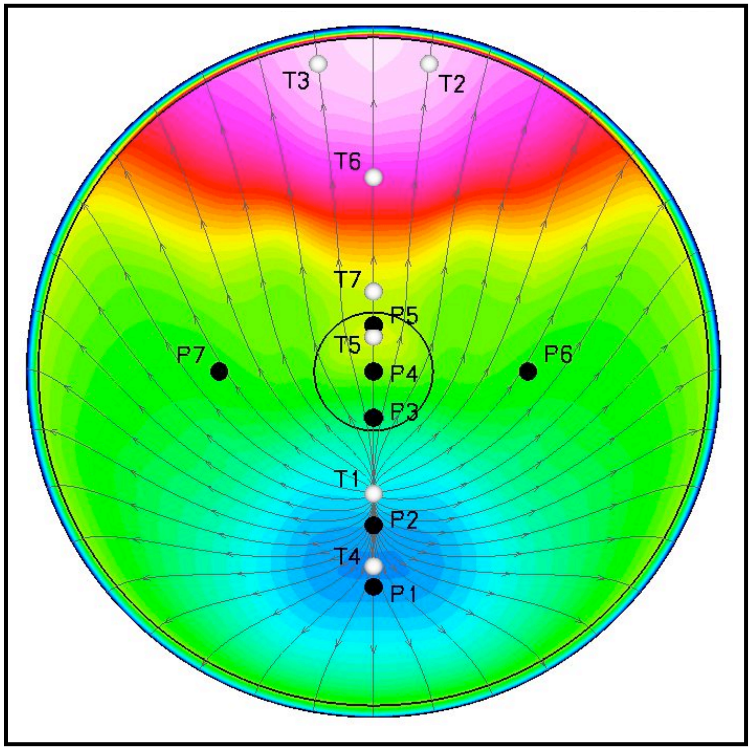
- Missions: EDL, aero-braking, aero-capture
- Aerodynamics: very blunt, thick heat shield
- Propulsion: none (sometimes RCS)
- Examples: Apollo, MSL, CEV (Orion)

Mars Science Laboratory



Instrument Your Science Missions!

MSL Heatshield Layout

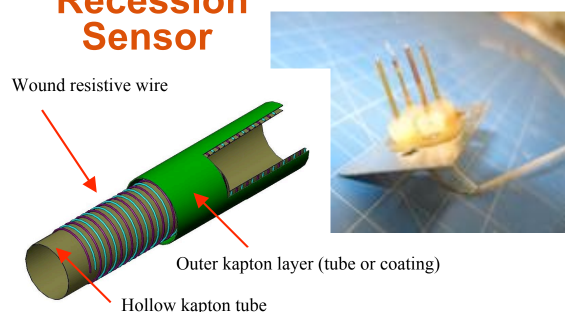


7 locations

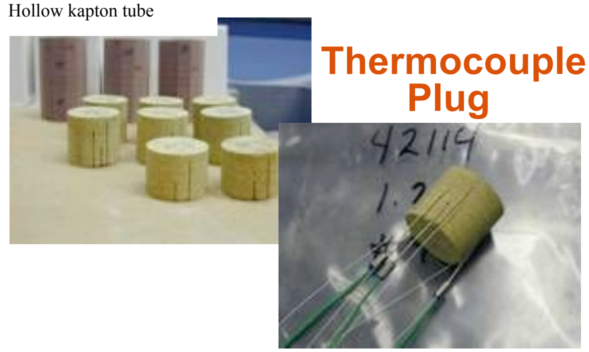
35 Sensor Channels
- **7 Pressure Transducers**
- **6 Recession Sensors**
- **20 Thermocouples**
- **2 Reference Temperature Sensors**

- **HQ approval for MSL instrumentation suite!**
- **High TRL sensors to be installed in seven locations on heatshield**
- **Flight data obtained will go a long way toward validating current modeling tools to drive down uncertainties discussed herein**
- **No backshell instrumentation (backshell is on critical path)**

Recession Sensor



Thermocouple Plug



Pressure Sensor

Other recent/active capsules

- Orion vehicle: EFT-1, Artemis-1, Artemis-2
- Stardust: fastest man-made object to ever re-enter earth!
- MSR: Mars Sample Return Vehicle (planned)
- Other sample return: Hayabusa (2010), Hayabusa2 (2020), OSIRIS-REx (2023)
- ISS return capsules: Dragon, Soyuz
- Small ISS return capsule: REBR, Red-DATA, **KRUPS**, Qarman

Some Current Hypersonic Programs

HyBoLT (NASA/ATK)

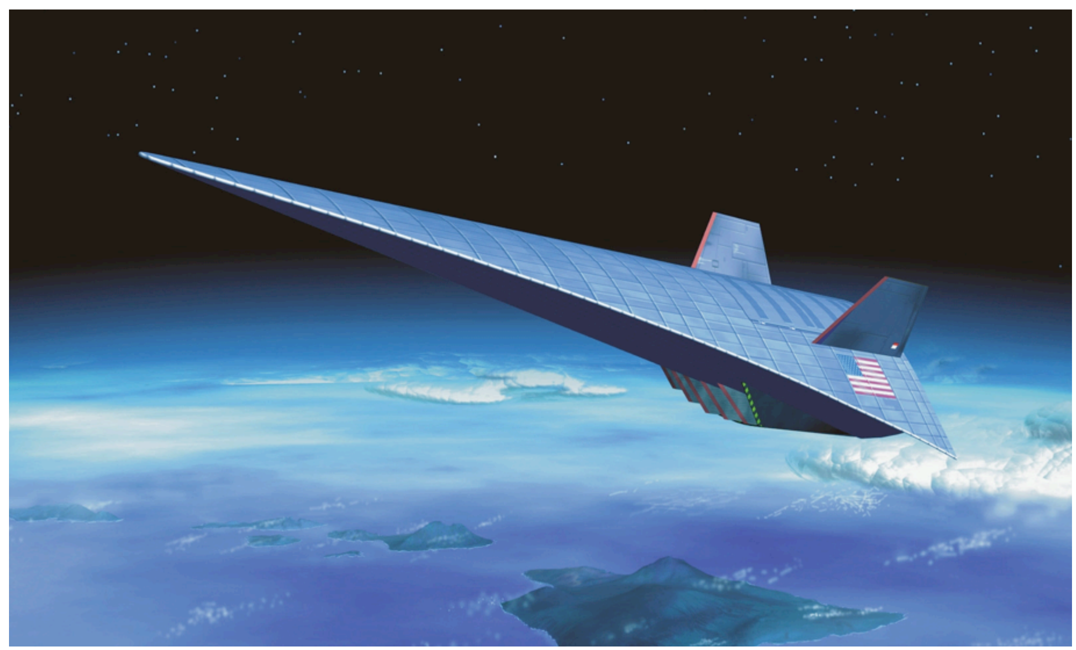
Falcon (DARPA)

X51 (AFRL)

Orion (NASA)

DARPA Falcon

- Reusable Hypersonic Cruise Vehicle (HCV) capable of delivering 12,000 pounds of payload at a distance of 16 668 km in less than two hours
- Leveraging technology developed under the Hypersonic Flight (HyFly) program
- Takeoff from runway under turbojet power, acceleration to Mach 6 speed under combined turbojet and scramjet propulsion, controlled deceleration, and runway landings



Hypersonic Boundary Layer Transition (HyBoLT) & Sub-Orbital Aerodynamics Re-Entry Experiments (SOAREX)

STS-114 gap-filler incident served as a potent reminder of the importance of pursuing mastery of the fundamentals of hypersonic flight.

Mission Objective: Obtain unique flight data for basic flow physics and Mars entry technology

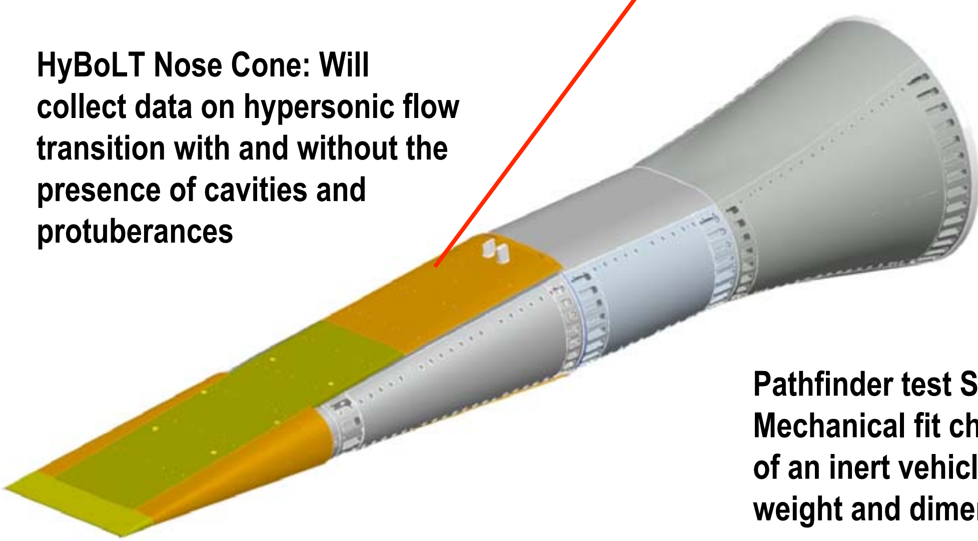
Estimated launch date:
Late 2007

Cost-sharing partners:
NASA
ATK

ATK Launch Vehicle (ALV X-1)

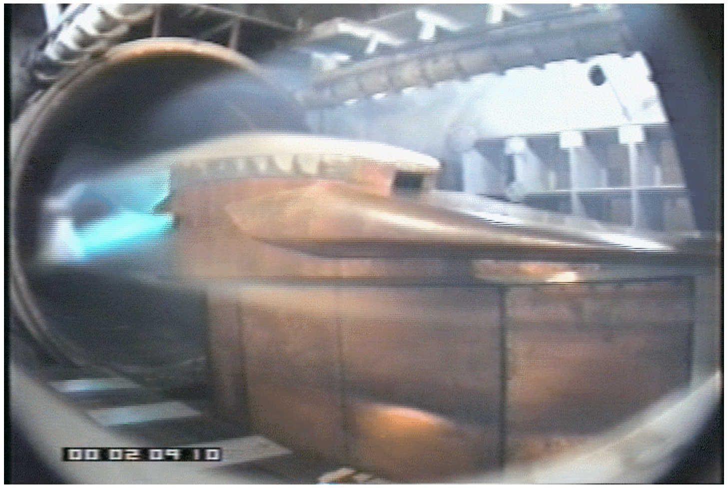
SOAREX will collect aerodynamic data on a re-entry shape during descent. Probe carried internally and ejected at 500 km altitude

HyBoLT Nose Cone: Will collect data on hypersonic flow transition with and without the presence of cavities and protuberances



Pathfinder test Sept 2006: Mechanical fit check of an inert vehicle with proper weight and dimensions

Hypersonics: X-51A Scramjet Engine Demonstrator



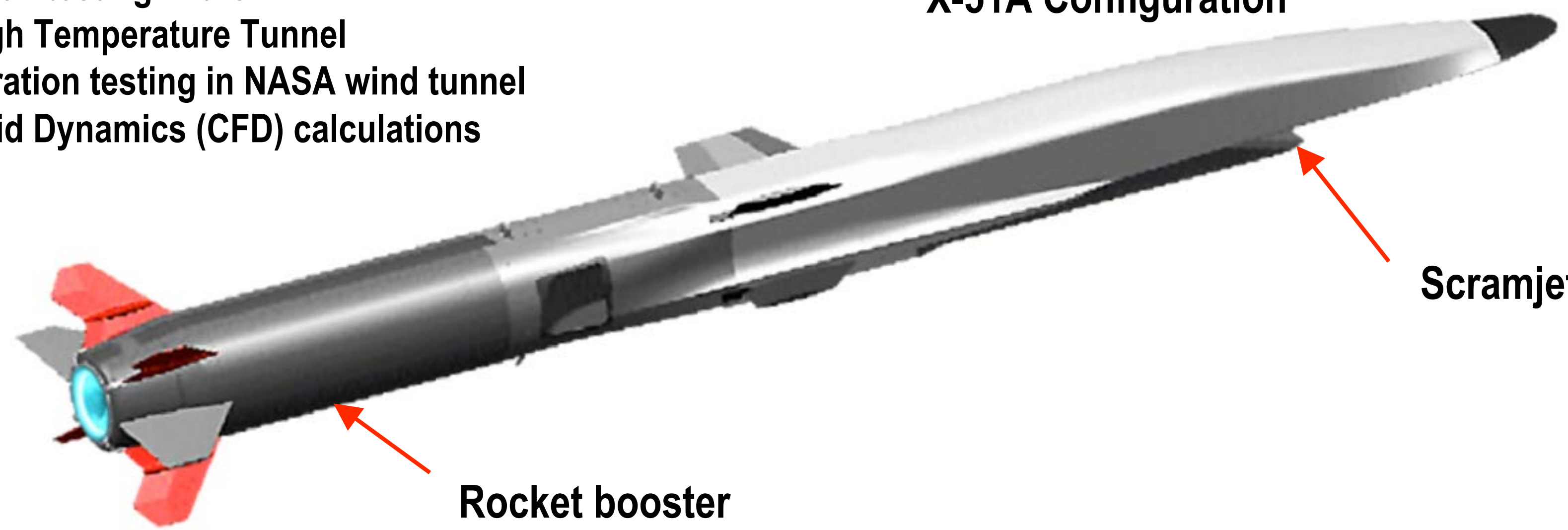
NASA Ground Demonstration Engine 2 Testing

Program Overview

- Joint AFRL/DARPA/NASA flight demo
- Hydrocarbon-fueled and cooled scramjet
- Scramjet flight from Mach 4.5 to 6.5
- 5 minute-plus flight duration
- Four to eight flights (FY09 1st flight)

NASA's Role:
- Full-scale propulsion testing in the NASA 8-Foot High Temperature Tunnel
- Sub-scale configuration testing in NASA wind tunnel
- Computational Fluid Dynamics (CFD) calculations

X-51A Configuration



Hypersonic Tales of Woe

- Hypersonics produces unexpected phenomena
- X15 test flight with dummy scramjet installed:
  - unexpected shock interactions generated
  - burned holes in connection pylon
- First re-entry of Space Shuttle (STS-1):
  - larger than expected nose-up pitch generated
  - required near-maximum deflection of body flap
- Shock-shock interactions:
  - heating amplified significantly
  - leading edges, cowl lips, engine flow paths