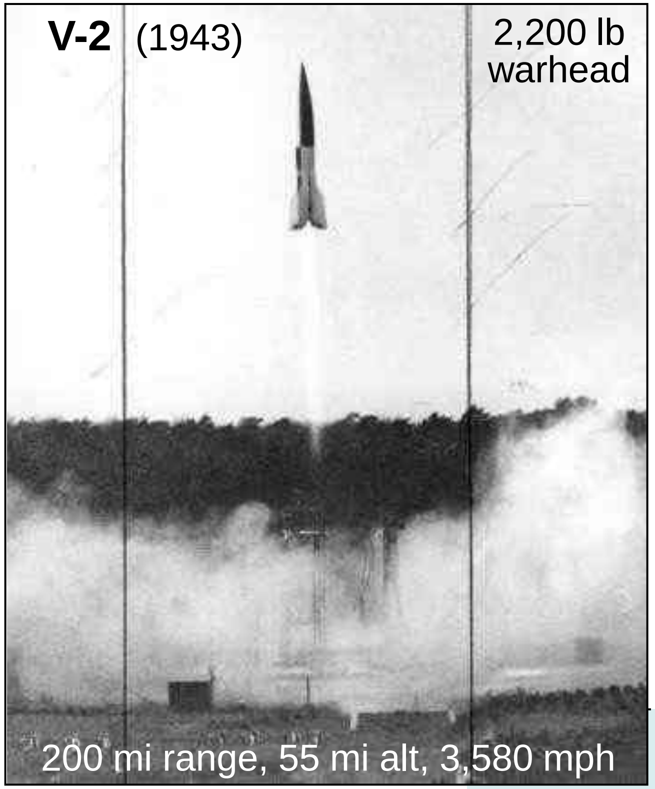
What are the origins of

Thermal Protection Systems?

Thermal Protection Systems: The Beginning

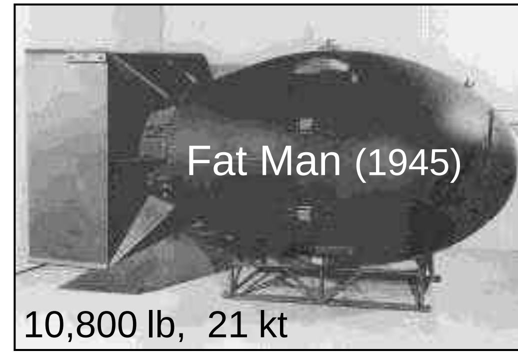
Game Changing Technologies from World War II



Missile Technology

boosters
guidance
life support
thermal protection?

Satellites?



Nuclear Weapon Technology

warhead design?

boosters?, guidance?

thermal protection?

Human Space Flight?

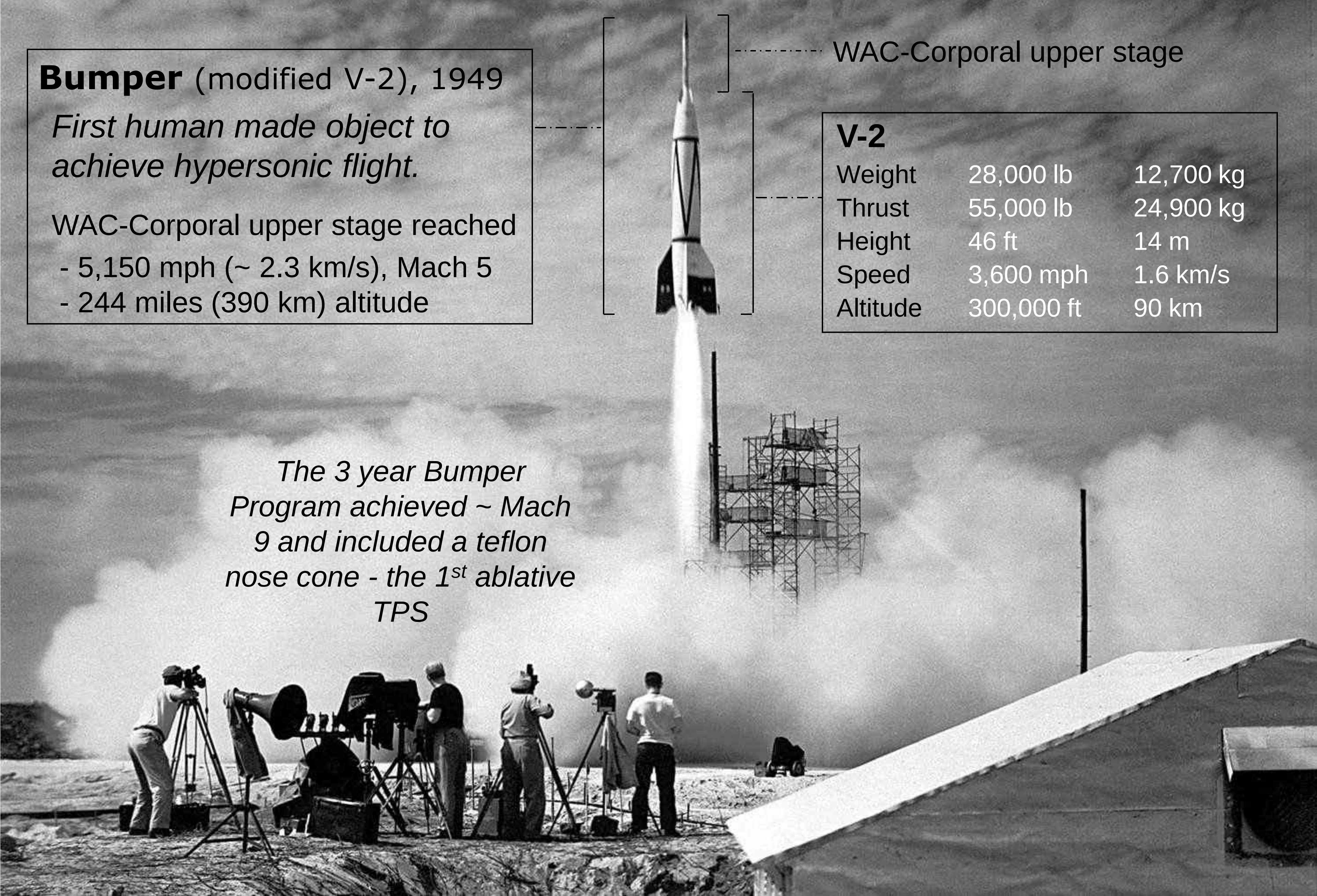
Orbital, 100 miles alt, 17,500 mph

Inter-Continental Ballistic Missile?

(ICBM)

6,000+ mi range
900 mi alt
15,000+ mph

Thermal Protection Systems: First Flight Test



Bumper (modified V-2), 1949

First human made object to achieve hypersonic flight.

WAC-Corporal upper stage reached

- 5,150 mph (~ 2.3 km/s), Mach 5
- 244 miles (390 km) altitude

V-2

Weight	28,000 lb	12,700 kg
Thrust	55,000 lb	24,900 kg
Height	46 ft	14 m
Speed	3,600 mph	1.6 km/s
Altitude	300,000 ft	90 km

The 3 year Bumper Program achieved ~ Mach 9 and included a teflon nose cone - the 1st ablative TPS

Thermal Protection Systems: The Motivation

Geo-Politics & Development of the U.S. ICMB

- **Iron Curtain** (1945-49), **Berlin blockade** (1948-49)
- **Soviets detonate their first atomic bomb** (1949)
- **Mao defeats China's ruling Nationalist party, proclaims People's Republic of China** (1949)
- **North Korea attacks South Korea** (1950)

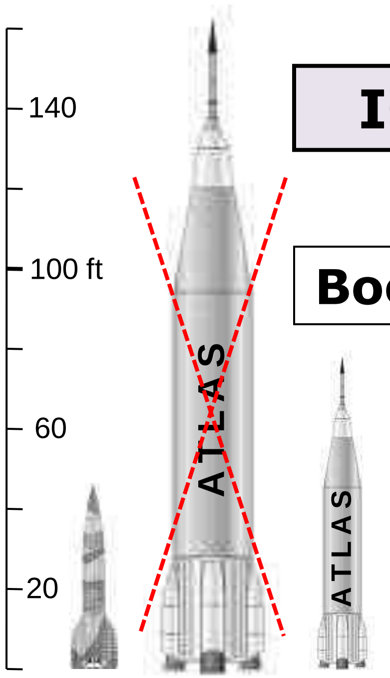
. . . .

- **U.S. develops dramatically lighter / more powerful nuclear weapons**
  - Thermonuclear (Hydrogen or fusion) bomb (1951)
  - Fission trigger, other design improvements (1951-53)
  - Lightweight fusion warhead proposed (1953) ------▸

Nuclear Weapon	Weight (lb)	Yield (Kt)	IOC
Fat Man	10,800	20	1945
Mark 5	3,200	50	1952
Fusion WH	*1,500*	*500*	*195?*
W-49	1,650	1,440	1958

Cold War → **ICBM Crash Program**

Thermal Protection System: The Problems



ICBM Technology Challenges, 1953 - 57

- **Boosters**
- **Thermal Protection**
  1. Re-entry vehicle / nose cone shape
  2. Heat mitigation approach
  3. High temperature materials
- **Guidance**

In the aerodynamics field . . . over the next 10 years the most important and vital subject for research and development is the field of hypersonic flows; and in particular, hypersonic flows with [temperatures at a nose-cone tip] which may run up to the order of thousands of degrees.

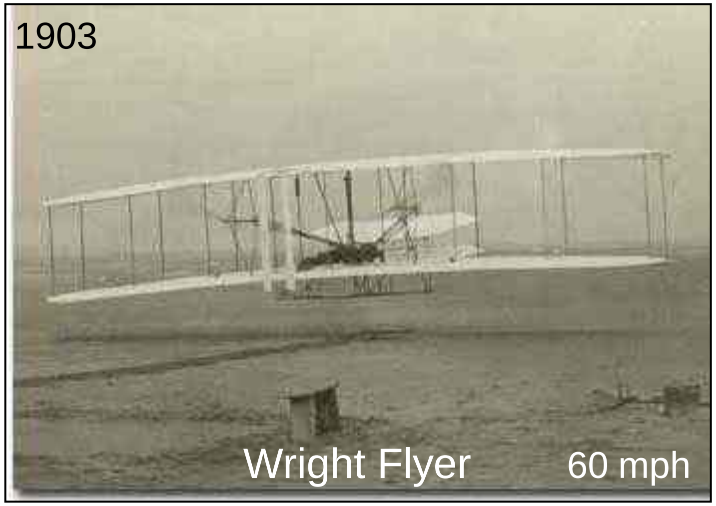
- Scientific Advisory Board, U.S. Air Force, October 1954

TPS Problem 1: Shape

Evolution of Vehicle Design

Over time, aero vehicle shapes became sleeker with sharper leading edges

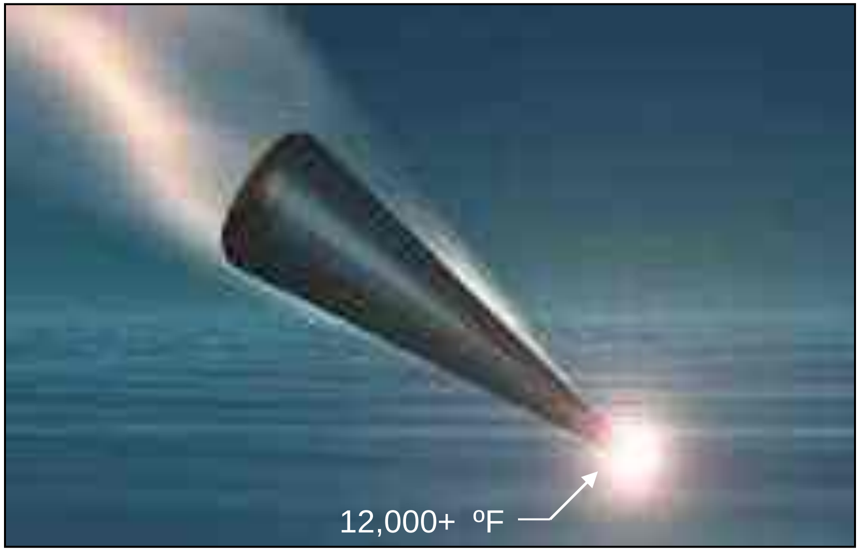
⇒ minimize drag



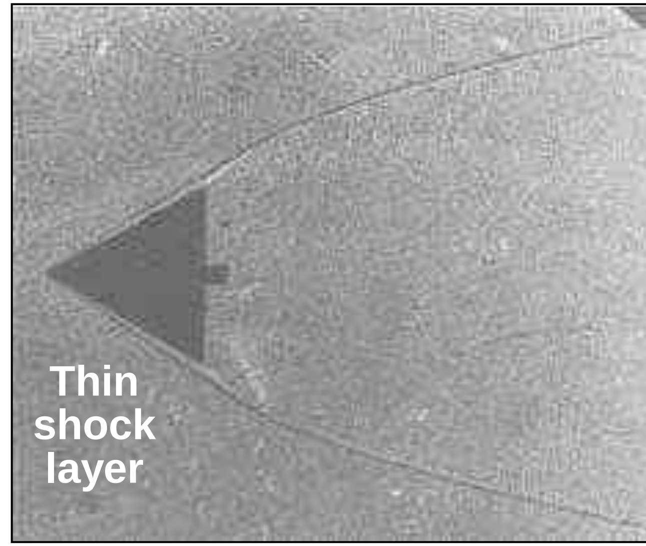
So, all initial re-entry vehicle concepts had sharp tipped, conical noses

TPS Problem 1: Shape

Early Re-Entry Vehicle (RV) **Concept**



Initial RV Ground Test



⇒ very high vehicle heating

Initial testing / analysis showed

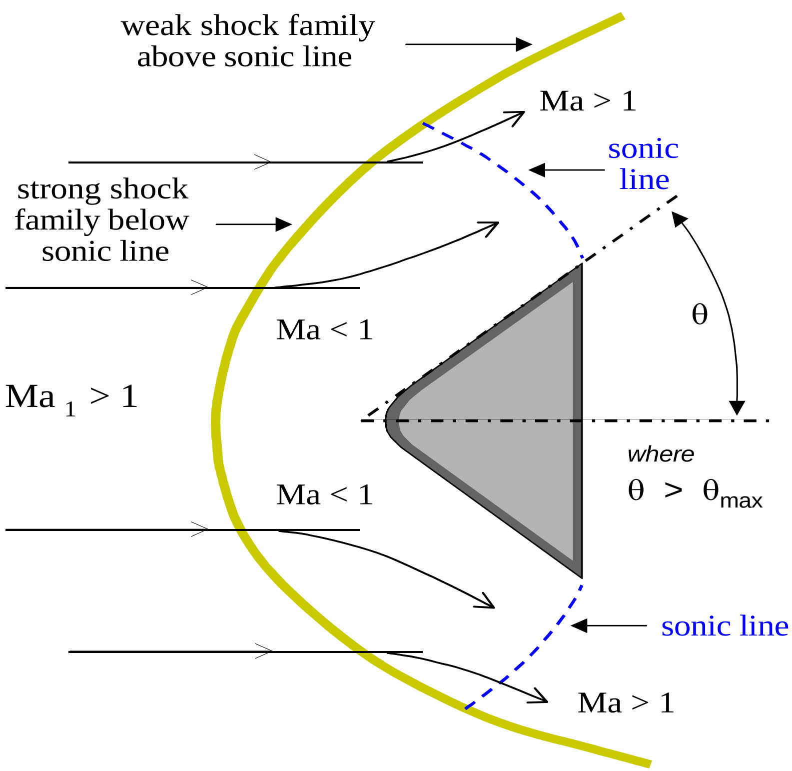
- Attached conical shock wave close to surface of vehicle
- Most of the high boundary-layer heating was transmitted to vehicle
- Nose tip predicted temp 12,000° F* - too high for any known material, melting the sharp nose and destroying the vehicle
- New material required . . . (Unobtanium?)

* Sun's surface is ~ 10,000° F

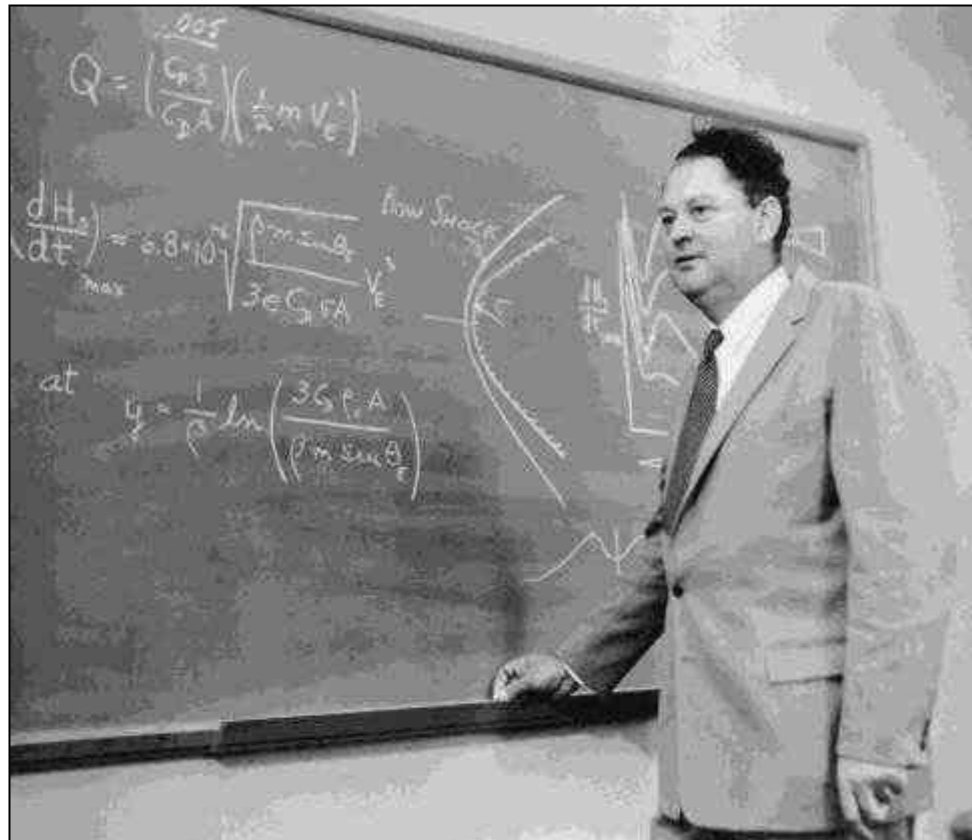
TPS Problem 1: Shape

Blunt Body Concept

In 1951, H. Allen proposed the counter-intuitive blunt body concept which pushed the shockwave away from the vehicle wherein most of the re-entry energy was put into the airflow



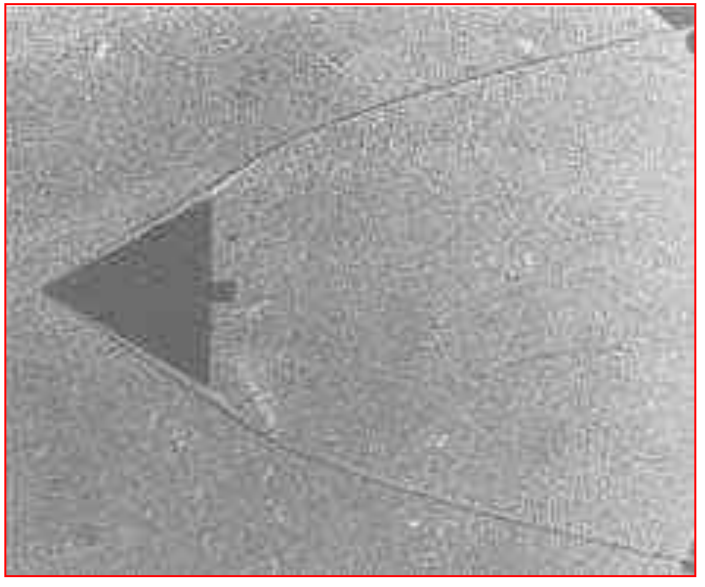
detached bow shock wave

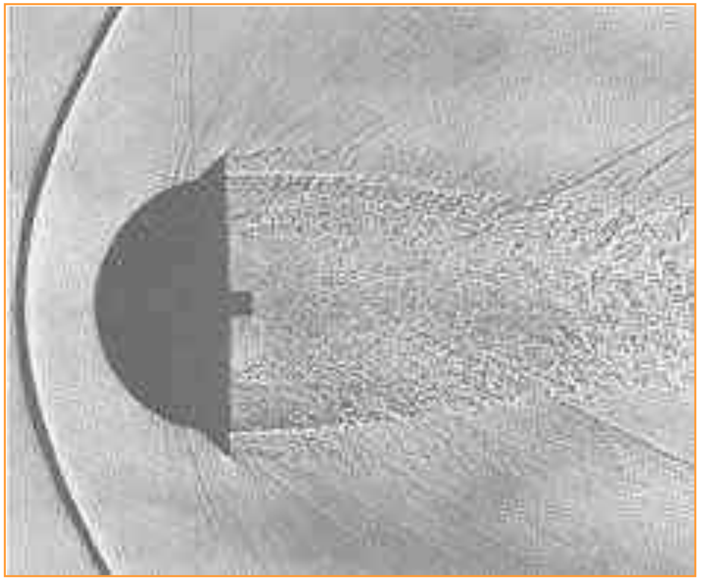


NASA Aerodynamicist, Harvey Allen

TPS Problem 1: Shape

Results from Ames' 1950s era Aero-physics Ground Test Facility*





Sharp Nose Re-Entry Vehicle

- Weak shock wave
- Thin shock layer, very close to vehicle
- Mixing of shock and boundary layer

⇒ **Extreme vehicle heating**

Blunt Nose Re-Entry Vehicle

- Strong, detached shock wave
- Thicker shock layer
- Significant heating away from the vehicle outside the boundary layer

⇒ **Acceptable vehicle heating**

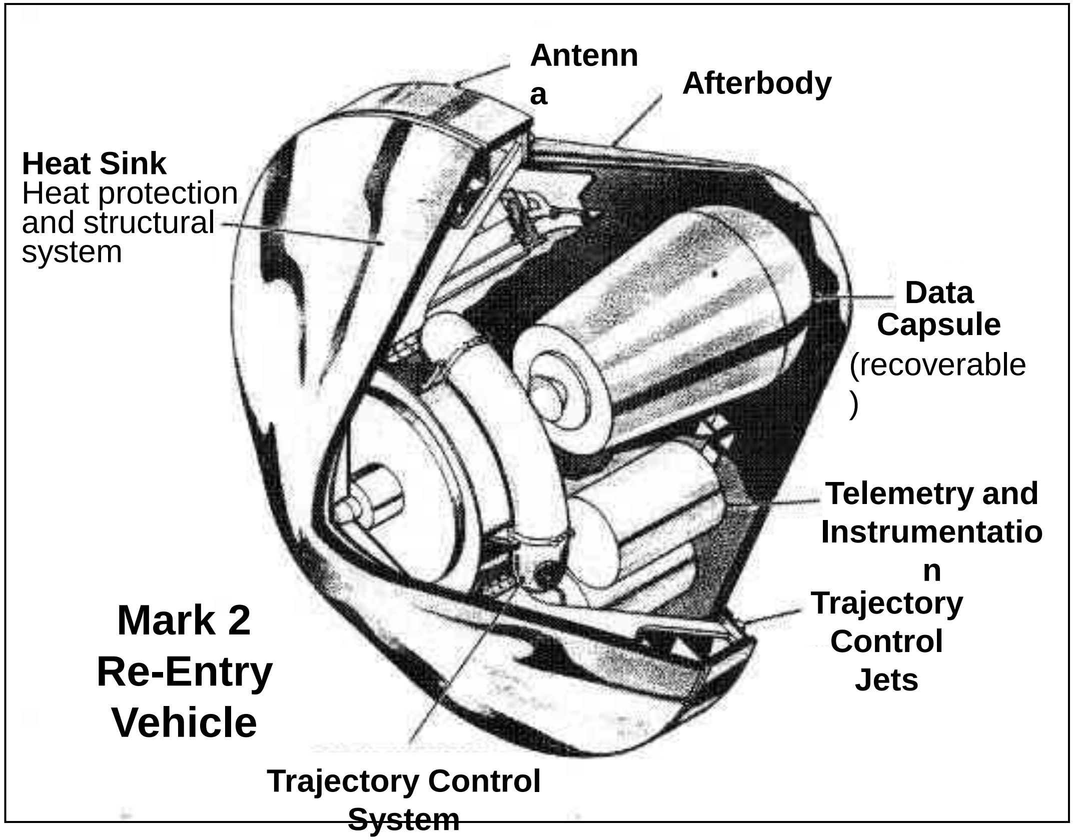
* The Small-Scale Atmospheric Entry Simulator

TPS Problems 2 & 3: Concept & Materials

Heat Sink

- Absorbs, dissipates heat from other objects in contact
- First type of re-entry thermal protection system

more was known about heat sink materials, behavior at high heating



Mark 2

- First heat sink RV
- Produced from high purity copper alloy with highly polished surface
- Designed to maintain laminar flow as late as possible in the flight
- Protected W-49 (1.4 Mt) thermonuclear warhead (Mk-2 + W-49 = 3,700 lbs)
- First flight in June, 1958. Operational 1960: Thor IRBM, Atlas D ICBM

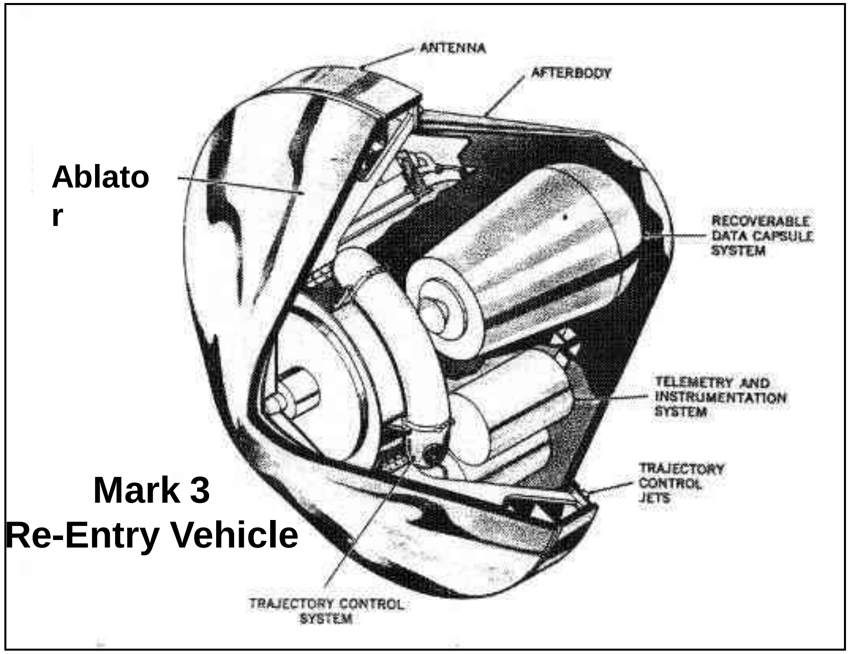
TPS Problems 2 & 3: Concept & Materials

Ablative Thermal Protection System

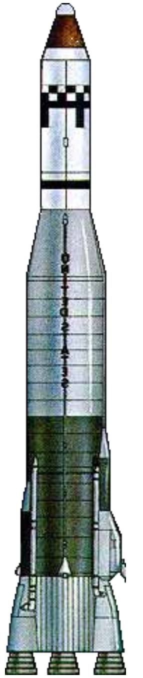
- **Designed to slowly burn in a controlled manner**
  - Heat is carried away from the vehicle by the generated gases
  - Remaining material insulates the vehicle from the plasma flow

Mark 3: 1st Ablative RV

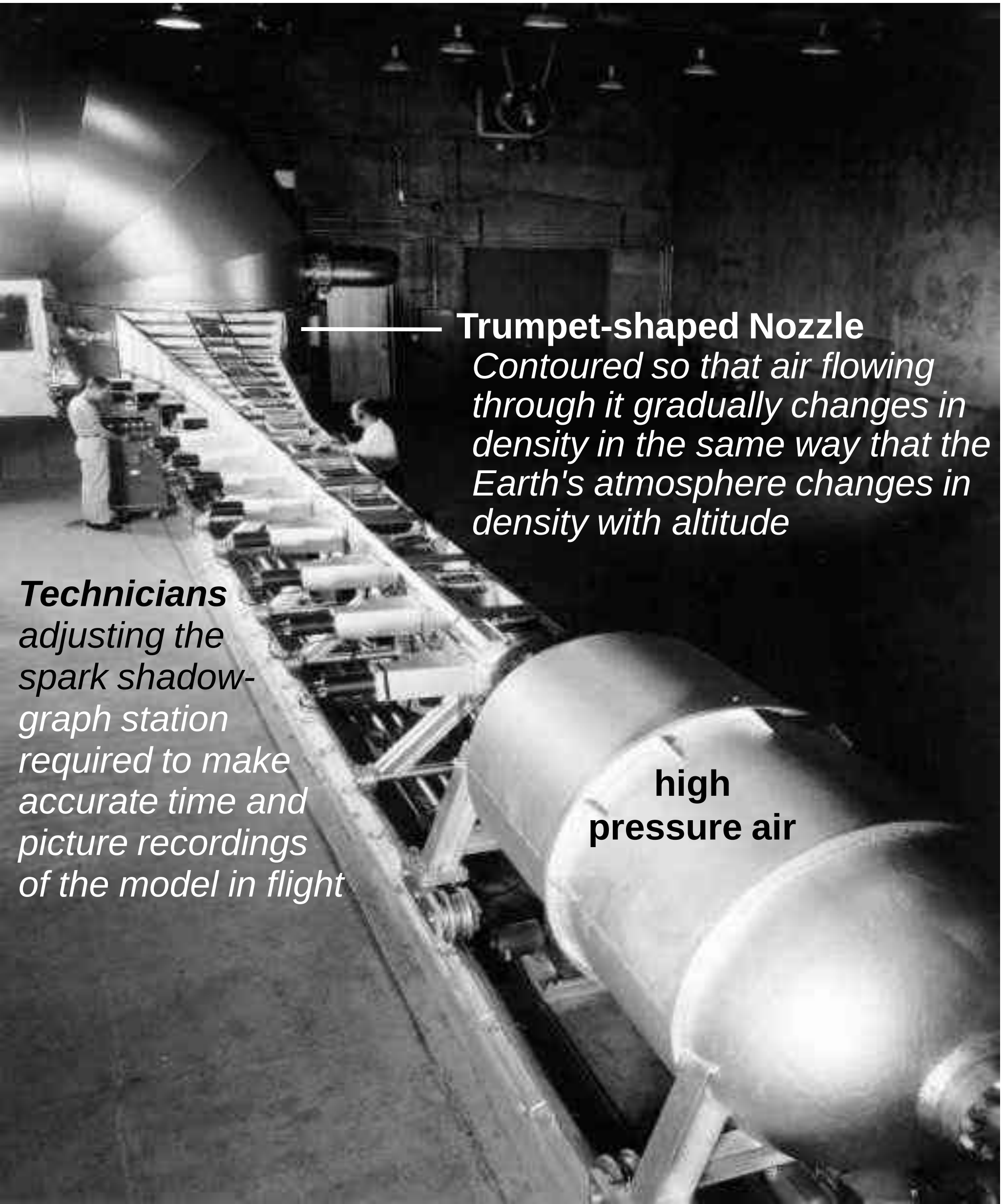
- First flight in March, 1959
- G.E.'s ablator: phenolic resin with randomly oriented 1 inch^2 pieces of nylon cloth (density of 72 lb/ft^3)
- Avco's heavier ablator consisted of opaque quartz (hot pressed fused silica)
- 1,300 lbs lighter than Mark 2
- G.E.'s ablator selected
- Operational, 1961 on Atlas E ICBM



Atlas E



Early RV Designs: Proof-of-Concept Testing



Atmospheric Entry Simulator

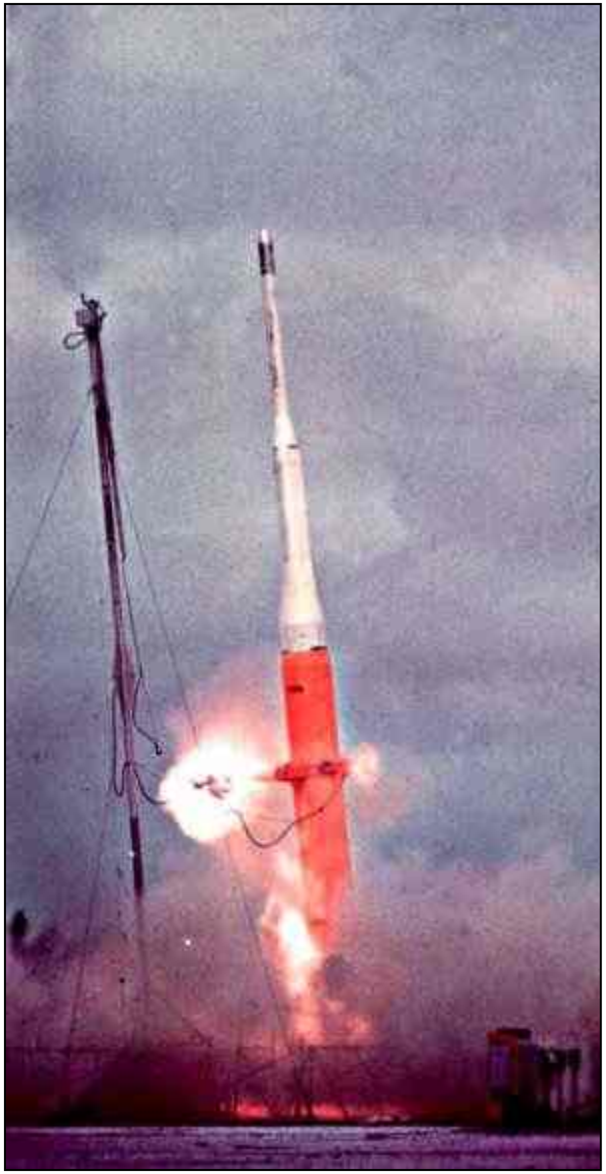
- Built in the 1950s at Ames' Aeronautical Laboratory, it was a **combined ballistic range, shock tube** and was able to test free flying test articles at very high Mach numbers (i.e. > 10,000 ft/s)
- Not visible in this photograph is a **high speed gun** used to launch a test model at earth re-entry speed (17,000 mph) upstream through the nozzle while air is flowing through it
- When a gun-launched model flies at full re-entry velocity into the simulator nozzle, it experiences the decelerations, stresses, pressures and temperatures of actual re-entry during a few thousandths of a second
- The simulator quickly and economically determined in the laboratory whether a specific design could survive atmospheric re-entry

Early RV Designs: Proof-of-Concept Testing

X-17

- 3 stage solid-fuel research rocket to test the effects of high mach atmospheric reentry on nose cones
- Program ran from 1955 to 1958 with 26 flights
- First stage carried the rocket to a height of 17 miles (27 km) and then coasted to 100 miles altitude before nosing down to simulate reentry speeds
- Second, third stages accelerated the test articles to high mach numbers (Mach 11 - 14.5)

Lockheed X-17	
height (ft)	40.5
weight (lbs)	12,000
thrust, STAGE 1 (lbs)	48,000
thrust, STAGE 2 (lbs)	3x 39,300
thrust, STAGE 3 (lbs)	36,000
max speed (mph)	9,000
max altitude[1] (ft)	500,000
max altitude[2] (mi)	500



1 nose over mission
2 normal ascent mission

Early RV Designs: Proof-of-Concept Testing

Jupiter 1C

- First ablative heat shield nose cone (1/3 scale) to be recovered from space
- Launched August 1957 on a Jupiter IRBM; traveled 1,150 miles
- Nose cone reached a peak heating of 2,000 °F

RVX: Re-Entry Nose Cone Flight Test Program

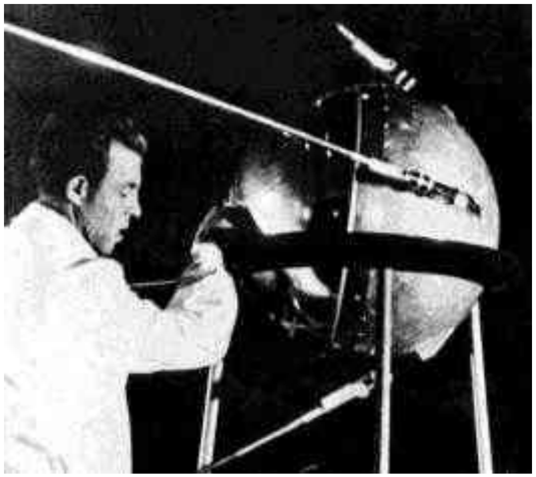
- 6 launches in 1959 on Thor-Able II
- 2 RVs recovered (5,000+ mi flight)
- Peak heating: Mach 16, 60K ft, 12,000 °F
- 2 ablative, instrumented heat shields
  - G.E.'s phenolic nylon ablator
  - Avcoite: fused silica hot pressed into Inconel (1 cm spaced) honeycomb

1st U.S. RV recovered after intercontinental flight, 1959

Space Race: The Beginning

SPUTNIK

Launched using modified R-7 ICBM



"All the News That's Fit to Print"

The New York Times.

LATE CITY EDITION

SOVIET FIRES EARTH SATELLITE INTO SPACE; IT IS CIRCLING THE GLOBE AT 18,000 M. P. H.; SPHERE TRACKED IN 4 CROSSINGS OVER U. S.

10/4/57

Space Race: Eisenhower & NASA

NACA (1915)

+ Vanguard, JPL, ABMA and other Military R&D Space Programs

⇓ ⇓

NASA (7/29/1958)

Space Race: Gagarin, 1st Human in Space 4/12/61

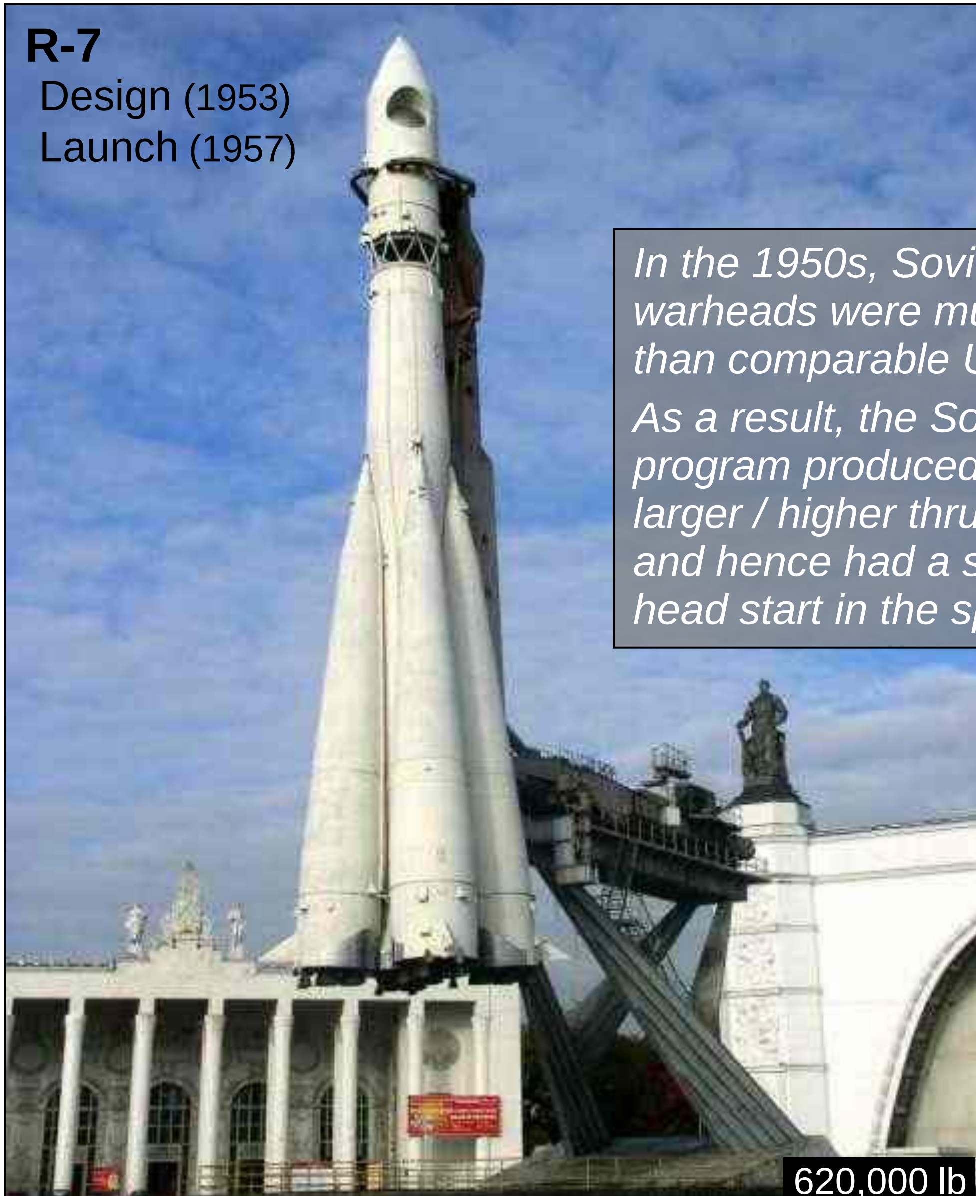
Space Race: Kennedy's Bold Challenge

"I believe that his nation should commit itself to achieving the goal, before this decade is out, of landing a man on the Moon and returning him safely to the Earth" 5/25/61

Ames Research Center

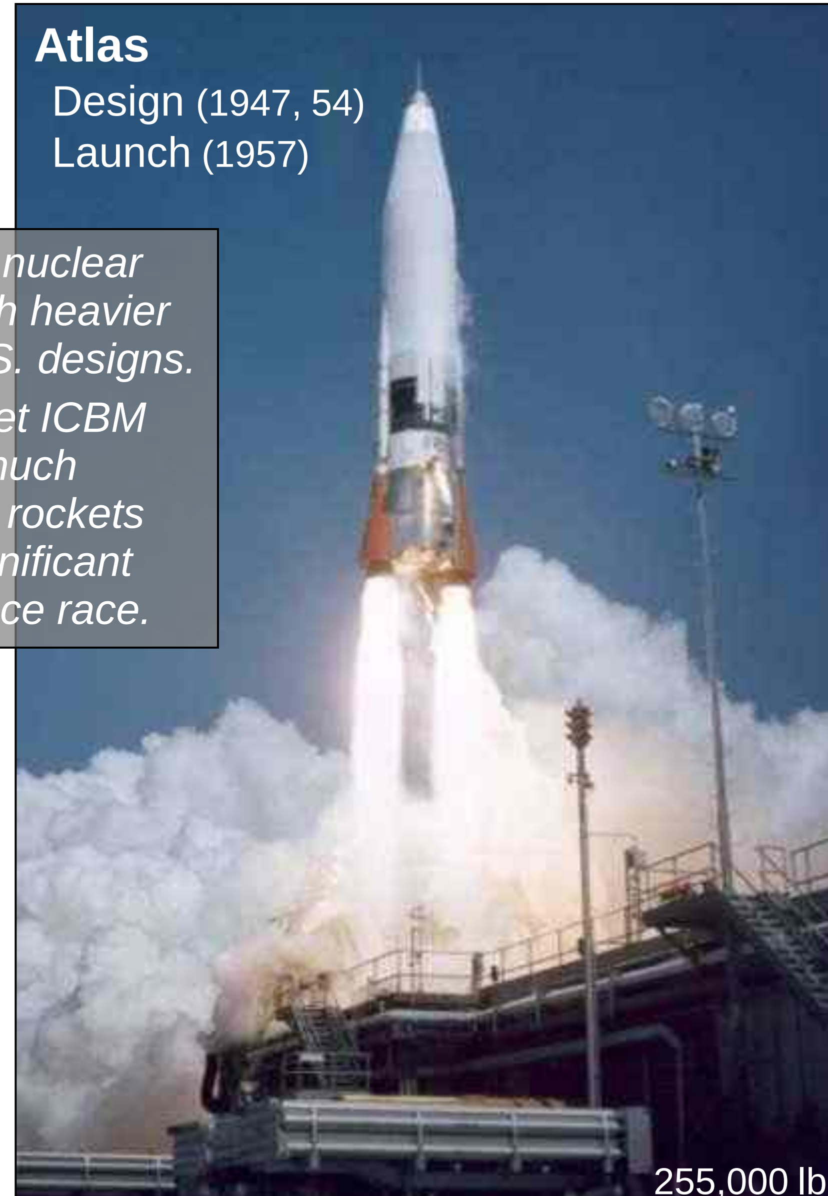
The Space Race: Early Soviet Lead

Entry Systems & Technology Program



In the 1950s, Soviet nuclear warheads were much heavier than comparable U.S. designs.

As a result, the Soviet ICBM program produced much larger / higher thrust rockets and hence had a significant head start in the space race.



Space Race: The U.S. Plan, Part I

Mercury-Redstone

Develop Spacefaring Capabilities

- **Sub-orbital Flight**: Mercury-Redstone
  - Human rated launch system
  - Launch escape system
  - Vehicle tracking
  - Landing, crew recovery

- **Orbital Flight:** Mercury-Atlas

  same as above plus
  - Assess human performance in space
  - De-orbit
  - Re-entry

Boosters	Redstone	Atlas LV-3B
height (ft)	83	82
weight (lbs)	66,000	256,000
thrust (lbs)	78,000	357,000

Mercury-Atlas

Space System Requirements: Military vs NASA

Re-Entry Conditions

Altitude ~ 400,000 ft or 76 mi (120 km)

Velocity ~ 26,000 ft/s or 17,900 mph (8 km/s)

$$\text{Energy} = \frac{1}{2}\, m\, v^2 + m\, g\, h$$

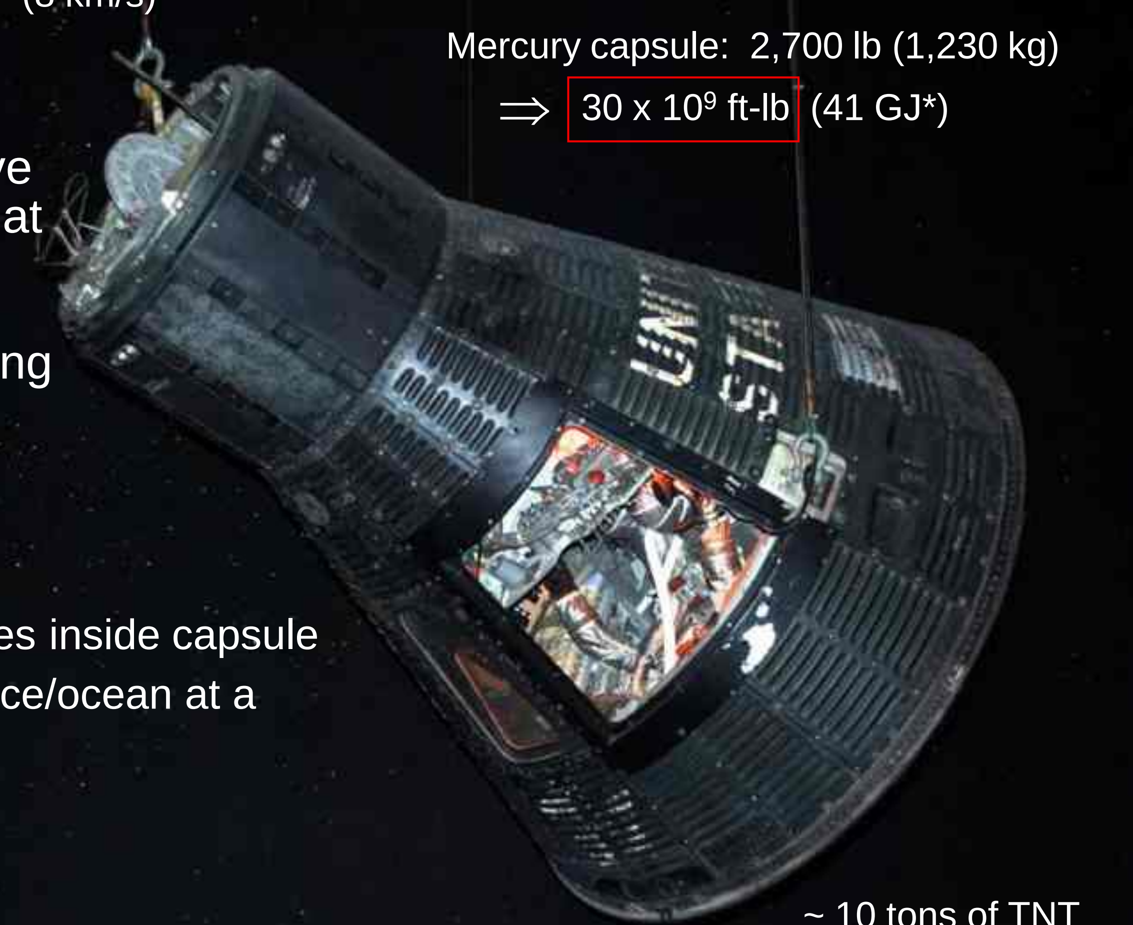
Mercury capsule: 2,700 lb (1,230 kg)

$\Rightarrow$ 30 x 10^9 ft-lb (41 GJ*)

- Warhead only required to survive until detonation (at high speed) at or near the target (x, y, z)
- Human reentry requires delivering astronauts safely to the ground

Design constraints

- deceleration < 20g
- maintain survivable temperatures inside capsule
- deliver astronaut(s) to the surface/ocean at a nominal impact velocity



~ 10 tons of TNT

Ames Research Center

Space Race: Return from LEO & TPS

Entry Systems & Technology Program

Mercury Re-Entry

Altitude ~ 400,000 ft or 76 mi (120 km)

Velocity ~ 26,000 ft/s or 17,900 mph (8 km/s)

$$\text{Energy} = \frac{1}{2}\, m\, v^2 + m\, g\, h$$

Mercury capsule: 2,700 lb (1,230 kg)

$\Rightarrow$ 30 x 10^9 ft-lb (41 GJ*)

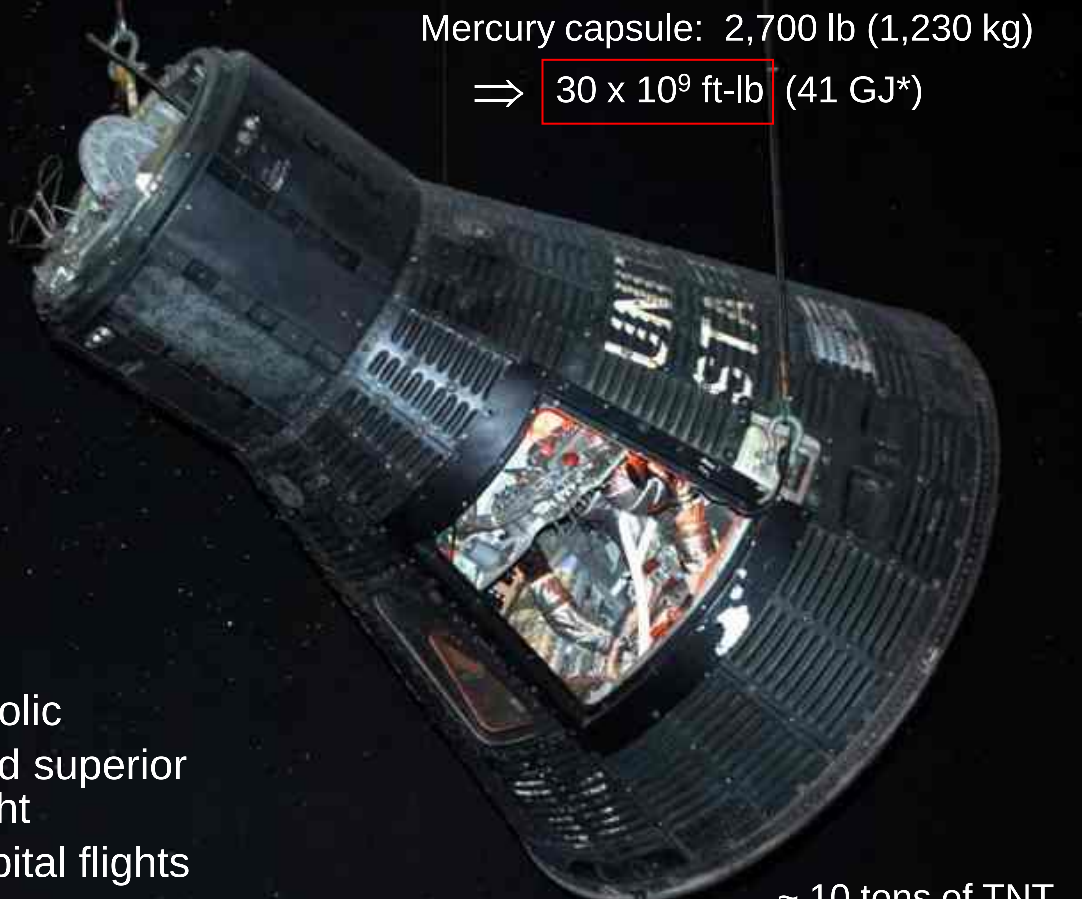
Two TPS Options Selected (1958)

Beryllium Heat Sink

- Polaris (U.S. Navy) SLBM heritage
- 6 units fabricated from hot-pressed Berylllium blocks (limited suppliers)
- Used on 4 unmanned / 2 manned suborbital flights

Ablative Heat Shield

- Jupiter (U.S. Army) IRBM heritage
- 12 units fabricated
- Material consisted of fiberglass phenolic
- Big Joe flight test (1959) demonstrated superior performance, reliability at lower weight
- Used on 2 unmanned / 4 manned orbital flights



~ 10 tons of TNT

Mercury Heat Shield: Proof-of-Concept Testing

Big Joe

- Atlas 10-D launch in September, 1959
- **Objective**: test ablative heat shield on an unmanned boilerplate Mercury capsule
- 13 minute ballistic flight to an altitude of 90 miles (140 km), 1,400 mile (2,300 km) range, reaching a max velocity of 14,900 mph (6.7 km/s)
- Instrumented with 100+ thermocouples to measure temperature inside and under the heatshield, sides, and afterbody
- Heat shield survived reentry
- Retrieved from the Atlantic Ocean in remarkably good condition
- Capsule weight 2,555 lb (1,159 kg)

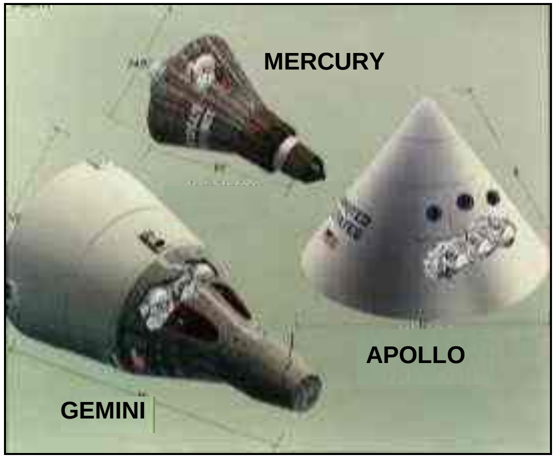
Space Race: The U.S. Plan, Part II

Gemini

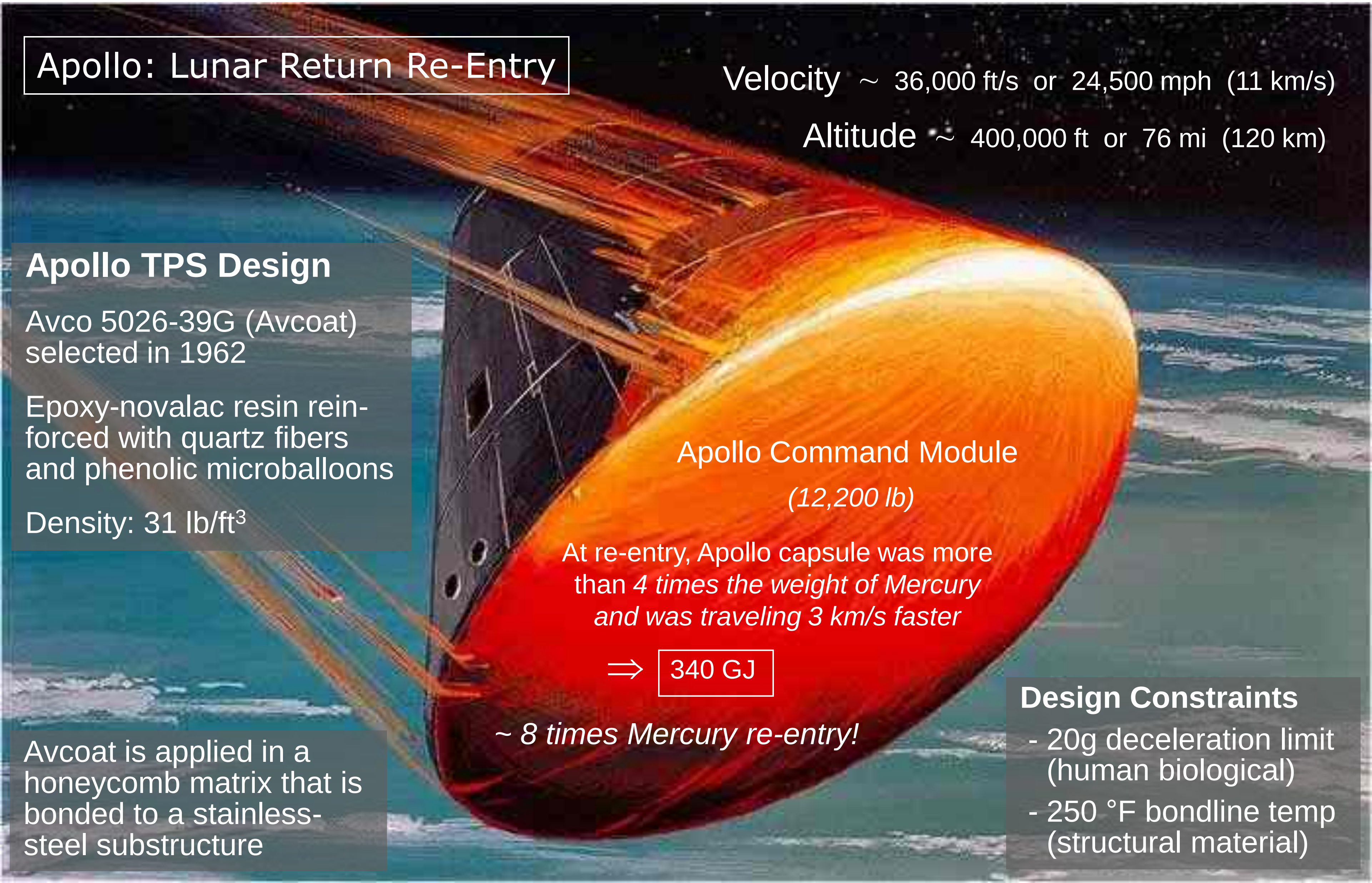
- **Orbital Systems**
  - extended spaceflight endurance
  - rendezvous and docking
  - extra-vehicular activity (EVA)

Apollo

- **Lunar Orbit & Return**
- **Lunar Landing & Return**



Space Race: Return from the Moon & TPS



Apollo: Lunar Return Re-Entry

Velocity ~ 36,000 ft/s or 24,500 mph (11 km/s)

Altitude ~ 400,000 ft or 76 mi (120 km)

Apollo TPS Design

Avco 5026-39G (Avcoat) selected in 1962

Epoxy-novalac resin rein-forced with quartz fibers and phenolic microballoons

Density: 31 lb/ft^3

Apollo Command Module

(12,200 lb)

At re-entry, Apollo capsule was more than *4 times the weight of Mercury and was traveling 3 km/s faster*

⇒ 340 GJ

~ 8 times Mercury re-entry!

Avcoat is applied in a honeycomb matrix that is bonded to a stainless-steel substructure

Design Constraints

- 20g deceleration limit (human biological)
- 250 °F bondline temp (structural material)

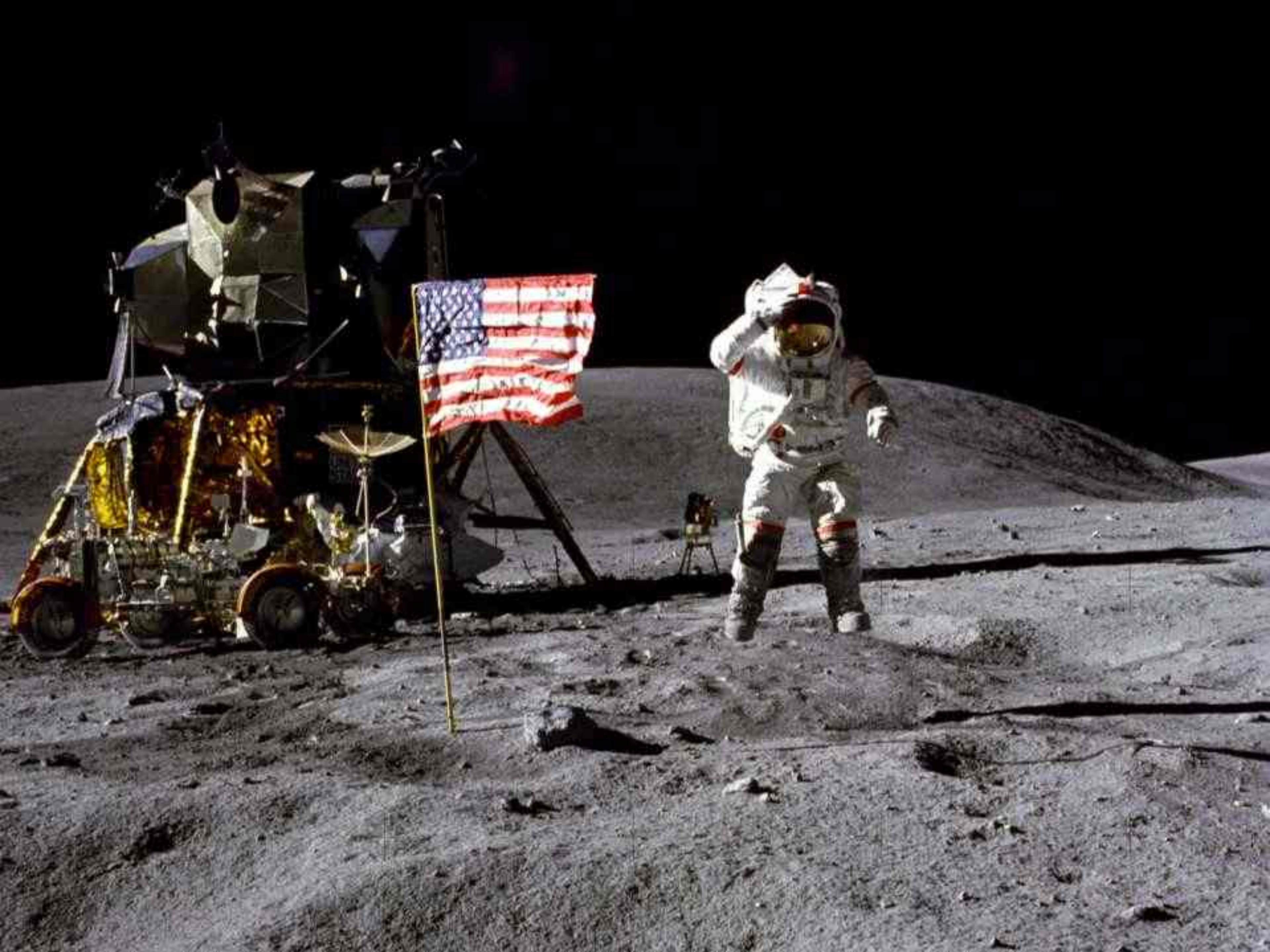
3 Weeks after Gagarin's Flight


5/19/63


Gemini
UNITED STATES
9/12/66


11/9/67


7/16/69



and that's

The End

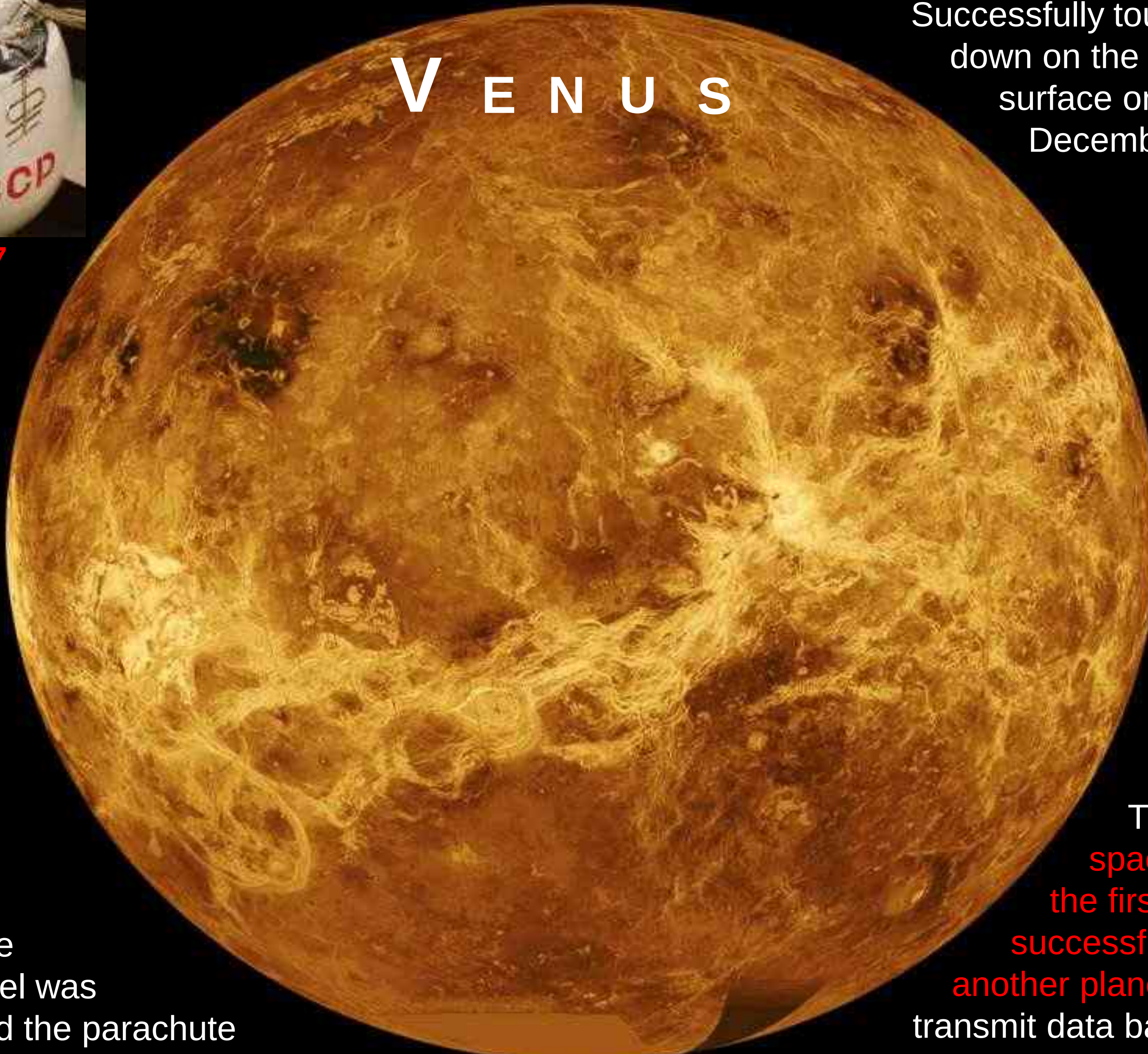
of the story of the beginning of

Thermal Protection Systems

since then

Venera 7

V E N U S



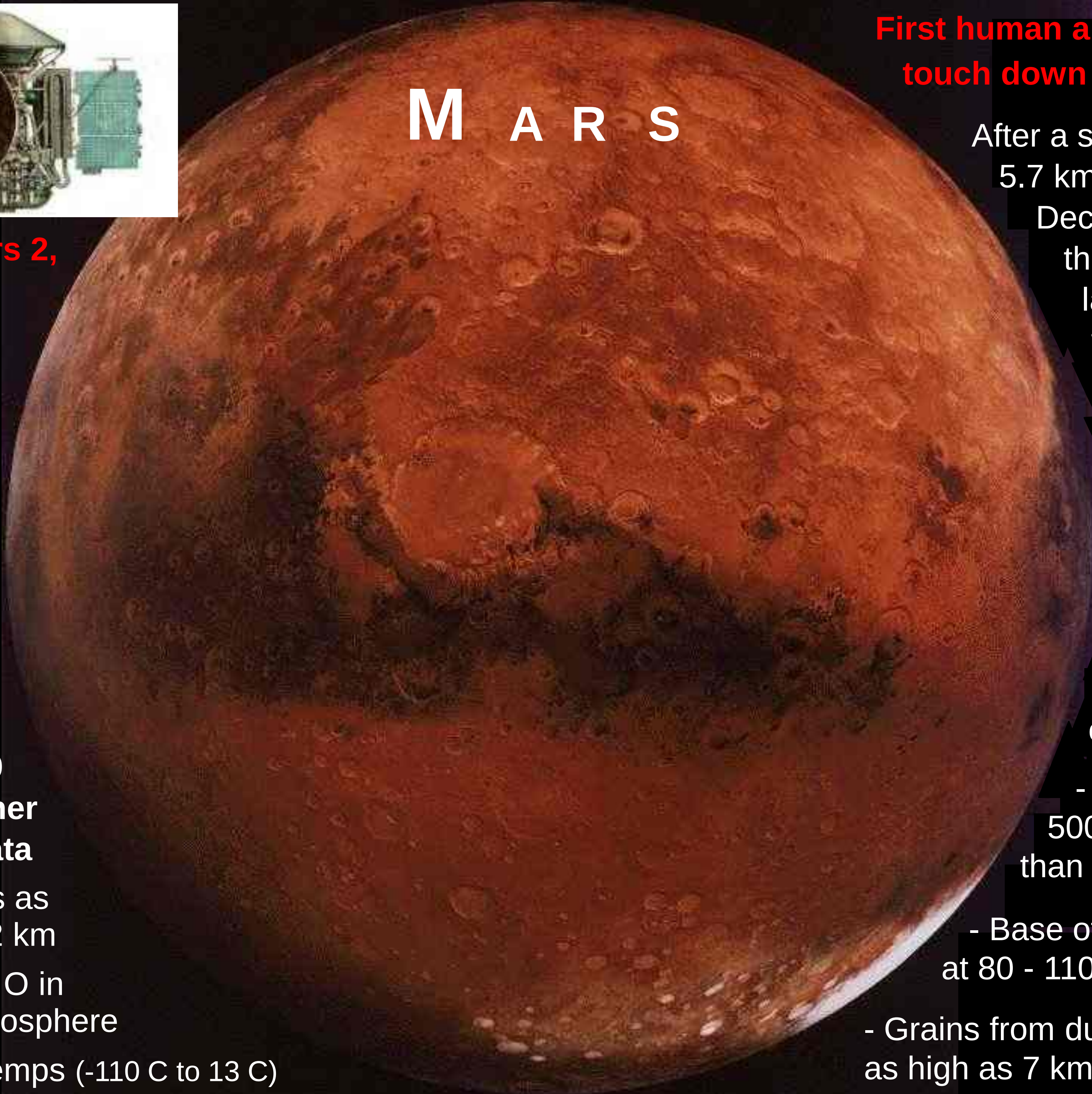
Successfully touched down on the Venusian surface on December 15, 1970

This Soviet spacecraft was the first to land successfully on another planet and to transmit data back to Earth

Only the temperature data channel was working and the parachute failed ~ 10 meters above ground

Nearly 1 hour of data was transmitted

M A R S



Soviet Mars 2, 3 missions consisted of identical spacecraft

Each had an orbiter and an attached lander (1210 kg)

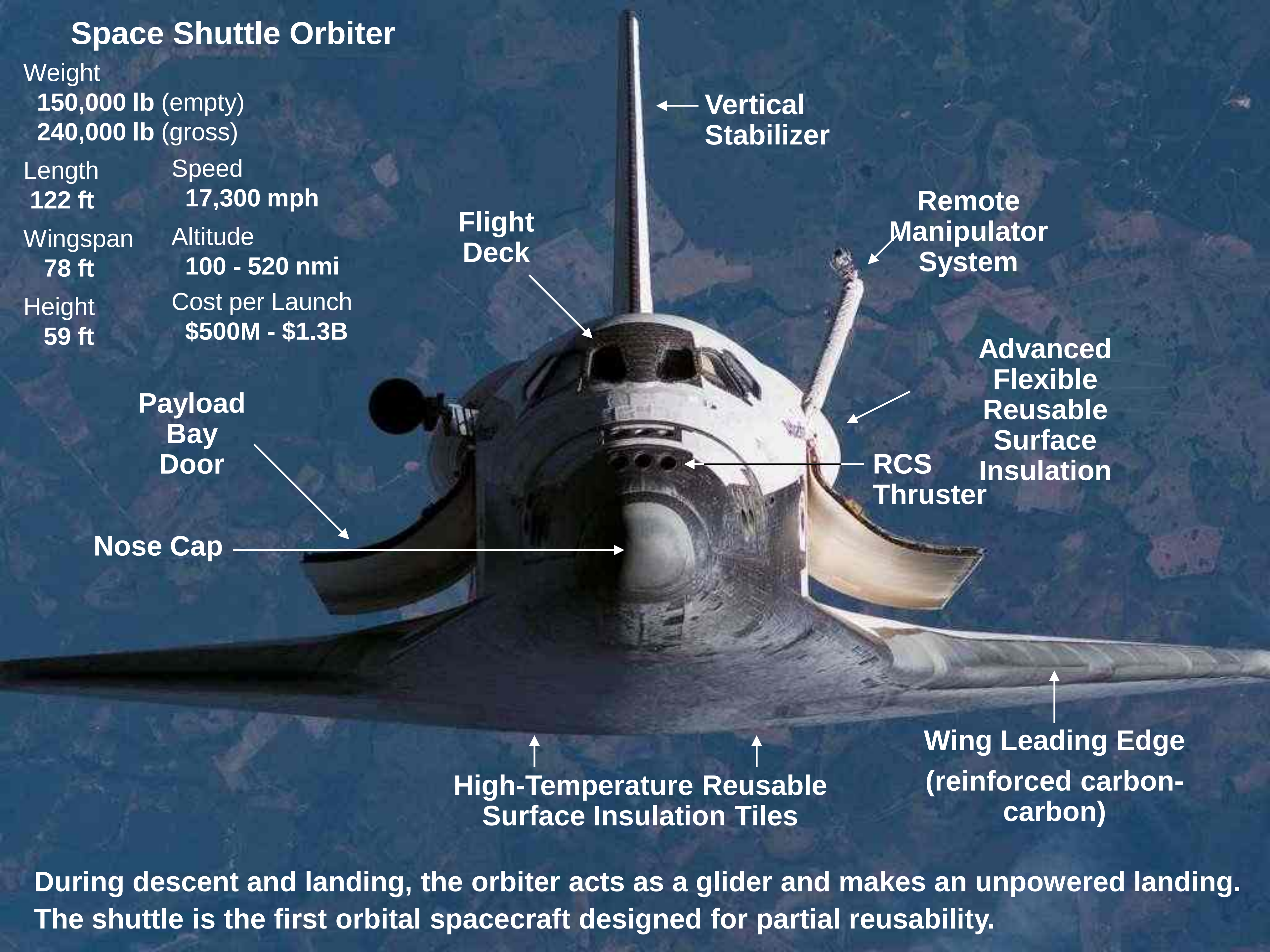
Orbiters returned 60 images, other valuable data

- Mountains as high as 22 km
- Atomic H, O in upper atmosphere
- Surface temps (-110 C to 13 C)

First human artifacts to touch down on Mars

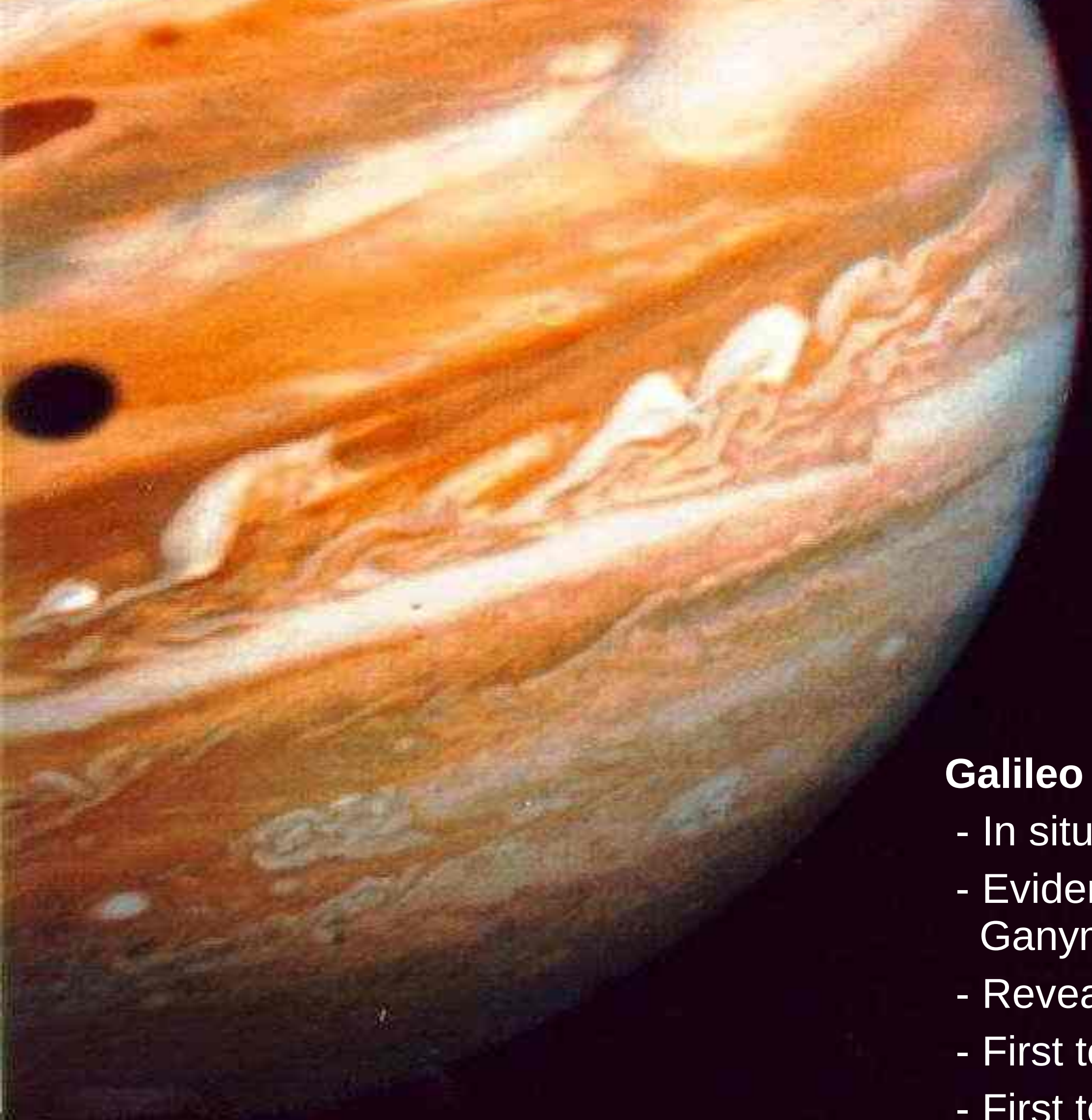
After a successful 5.7 km/s entry Dec 2, 1971, the module landed and transmitted ~ 15 to 20 sec of data and then the signal was lost

- Surface pressure of 5.5 - 6 mb
- Water vapor 5000 times less than Earth
- Base of ionosphere at 80 - 110 km altitude
- Grains from dust storms as high as 7 km



Space Shuttle Orbiter
Weight
150,000 lb (empty)
240,000 lb (gross)
Length
122 ft
Speed
17,300 mph
Wingspan
78 ft
Altitude
100 - 520 nmi
Height
59 ft
Cost per Launch
$500M - $1.3B
Vertical Stabilizer
Flight Deck
Remote Manipulator System
Advanced Flexible Reusable Surface Insulation
Payload Bay Door
RCS Thruster
Nose Cap
Wing Leading Edge (reinforced carbon-carbon)
High-Temperature Reusable Surface Insulation Tiles
During descent and landing, the orbiter acts as a glider and makes an unpowered landing.
The shuttle is the first orbital spacecraft designed for partial reusability.

JUPITER



On Sep 21 2003, after conducting long term observation of the Jovian system, Galileo plunged into Jupiter's crushing atmosphere

Galileo accomplished many firsts:

- In situ measurement of Jupiter's atmosphere
- Evidence of subsurface saltwater on Europa, Ganymede and Callisto
- Revealed the intensity of volcanic activity on Io
- First to fly past an asteroid
- First to discover a moon of an asteroid
- Provided the only direct observations of a comet colliding with a planet

Saturn, Huygens

Launched Feb 7 1999, Stardust's primary purpose was to investigate the makeup of the comet Wild 2 and its coma

The NASA spacecraft traveled nearly 3 billion miles during its 7 year mission and returned to Earth on January 15, 2006 to release a sample material capsule.

It is the first sample return mission to collect cosmic dust and return the sample to Earth

Stardust holds the record for the fastest Earth reentry for a manned made object - 12.9 km/s or 28,900 miles per hour

B A C K U P

Entry Systems: Historic Milestones

1st sub-orbital space flight

V-2

1st artificial satellite to orbit the ***Earth***

SPUTNIK

1st entry and soft landing on ***Venus***

VENERA 3, 7

1st entry and soft landing on ***Mars***

MARS 2, 3

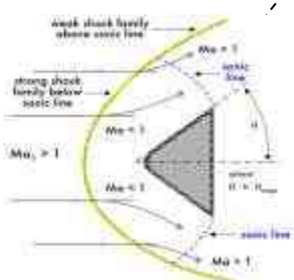
1st probe to enter ***Jupiter****'s atmosphere*

GALILEO

1st entry and soft landing on ***Saturn***

HUYGENS

19|50 — 19|60 — 19|70 — 19|80 — 20|00 — 20|10



BLUNT BODY CONCEPT

Key enabling concept for entry vehicles

NASA

U.S. civilian space agency established

VOSTOK 1

1st human in space, to orbit the ***Earth****, and re-enter*

APOLLO 10

Fastest human ***Earth*** *re-entry @ 11.1 km/s*

SPACE SHUTTLE

1st spacecraft with a reusable thermal protection system

STARDUST

Fastest umanned ***Earth*** *re-entry @ 12.9 km/s*

Early Hypersonics in the mid 20th Century

Adoption of the Blunt Nose Concept

- **Analytical details of the blunt nose concept were completed in 1952 and circulated for internal government peer review**
- **The concept met initial resistance from the U.S. Army and Air Force**
- **However, by 1954 the U.S. Air Force dropped all existing architectures for re-entry bodies and adopted the blunt nose concept**
- **All successful re-entry bodies have relied on the blunt nose concept**

The Space Race: NASA's Charter

March 26, 1958 Science Advisory Committee report to President Eisenhower

It is useful to distinguish among four factors which give importance, urgency, and inevitability to the advancement of space technology

- The compelling urge of man to explore and to discover, the thrust of curiosity that leads men to try to go where no one has gone before
- We wish to be sure that space is not used to endanger our security. If space is to be used for military purposes, we must be prepared to use space to defend ourselves.
- Enhance the prestige of the United States among the peoples of the world and create added confidence in our scientific, technological, industrial, and military strength
- New opportunities for scientific observation and experiment which will add to our knowledge and understanding of the earth, the solar system, and the universe

*For the present, the rocketry and other equipment used in space technology must usually be employed at the very limit of its capacity. This means that **failures of equipment** and **uncertainties of schedule** are to be **expected**.*

The Space Race: Early U.S. Failures

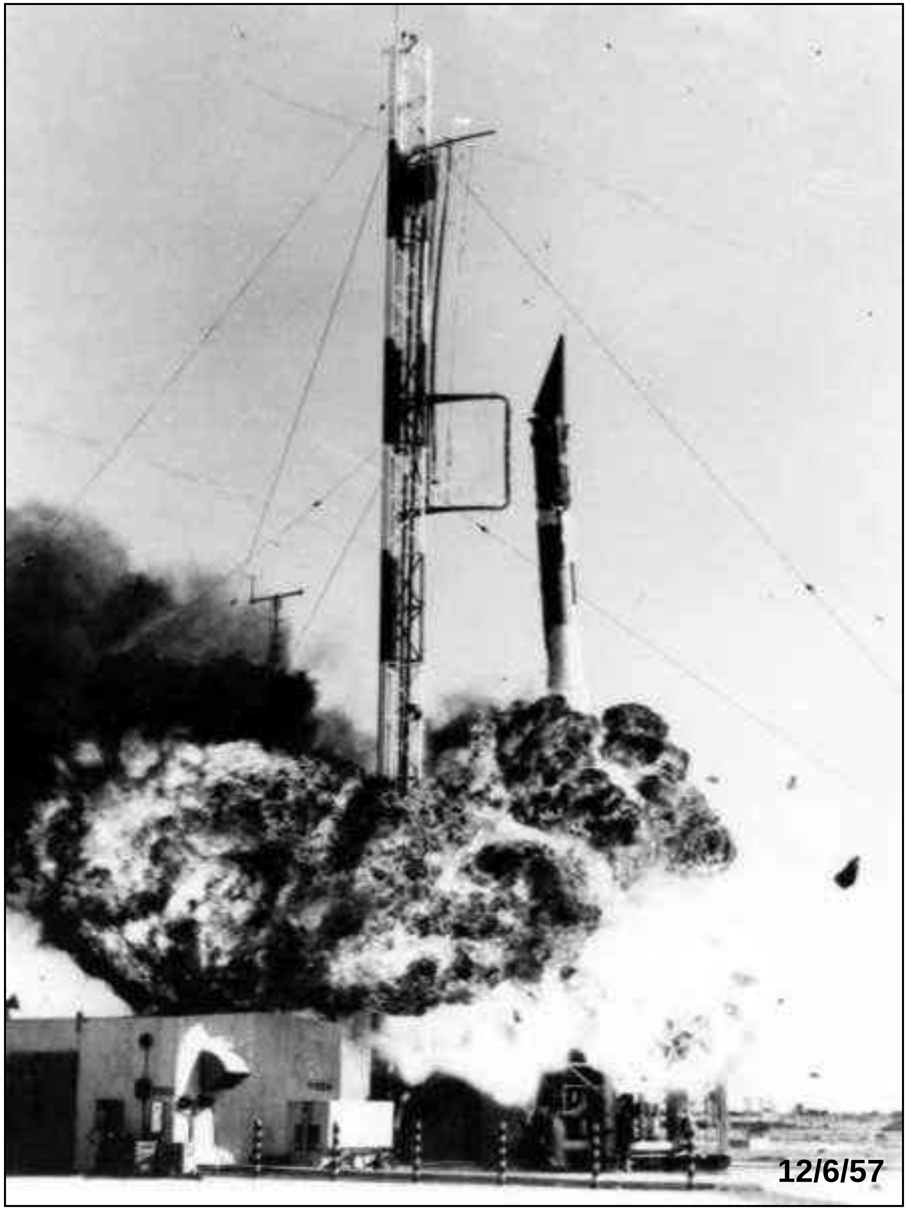
Vanguard TV3

•First attempt by the U.S. to launch a satellite into orbit

•Two seconds after liftoff, after rising about four feet, the rocket lost thrust and began to settle back down to the launch pad

•As it settled against the launch pad, the fuel tanks ruptured and exploded, destroying the rocket and severely damaging the launch pad

•The Vanguard satellite was thrown clear and landed on the ground a short distance away with its transmitters still sending out a signal



First Hominid in Space

- Mercury-Redstone's first launch from Cape Canaveral on January 31, 1961 carried 3 year old chimpanzee "Ham" over 400 miles down range in an arching trajectory that reached a peak altitude of 158 miles above the Earth
- The suborbital flight reached a maximum velocity of 5,900 mph or Mach 7.7
- The successful flight and recovery confirmed the soundness of the Mercury-Redstone systems

Ham settling into his biopack couch before the MR-2 suborbital test flight

Receiving an apple after his successful recovery from the Atlantic, still strapped into his special flight couch.

Ham performed his tasks well, pushing levers about 50 times during the flight in response to a flashing light.

Apollo 10

Fastest
Human Flight
24,000 mph
(11.1 km/s)

ICMB

Spy Satellite

Human Exploration of Space

Hypersonic Aircraft

Operation Paperclip


Why do we* care about
Thermal Protection Systems
now?
Keith Peterson
ERC
NASA Ames Research Center
* NASA and the NASA community

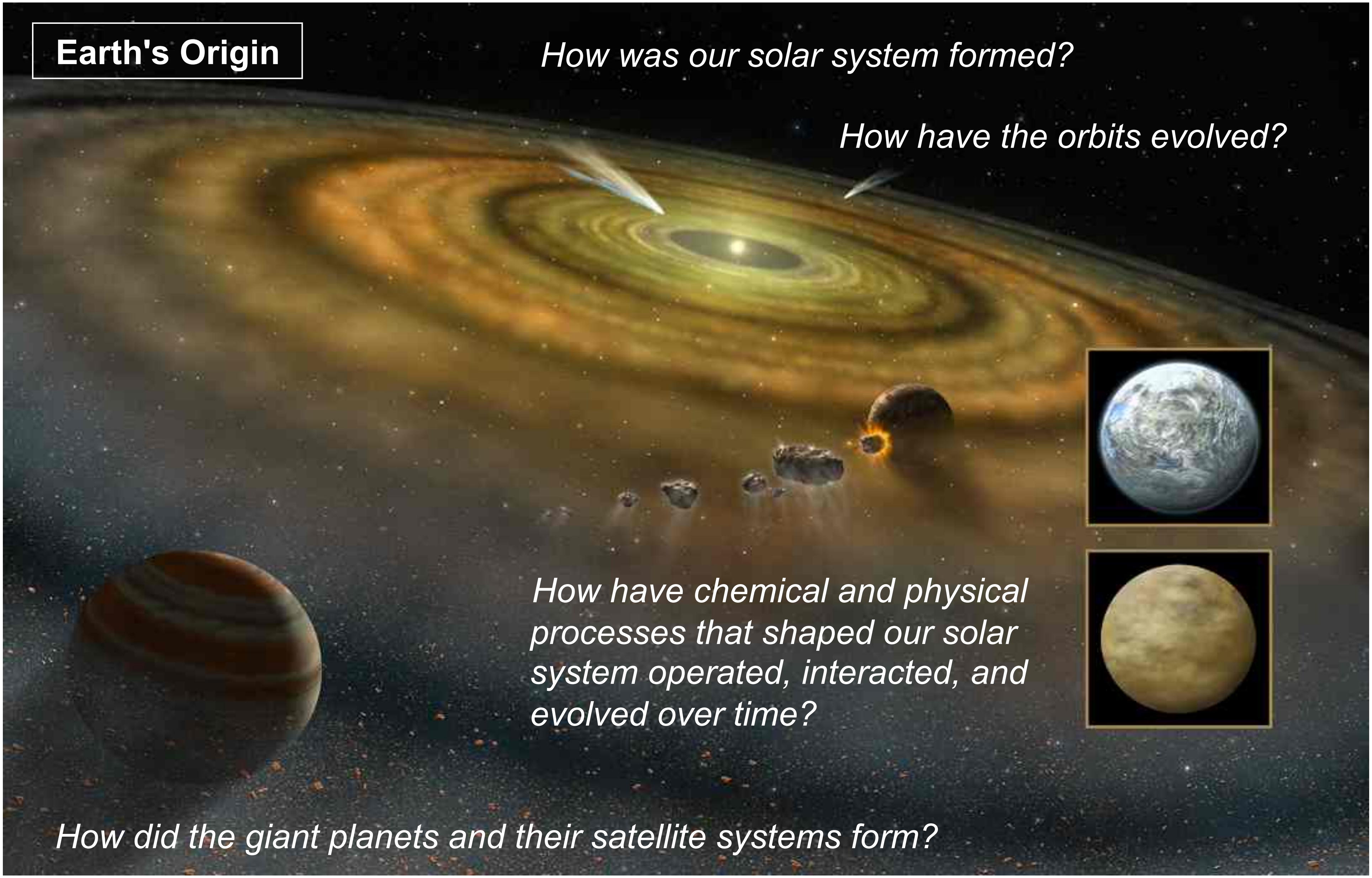
Why are we still working TPS?

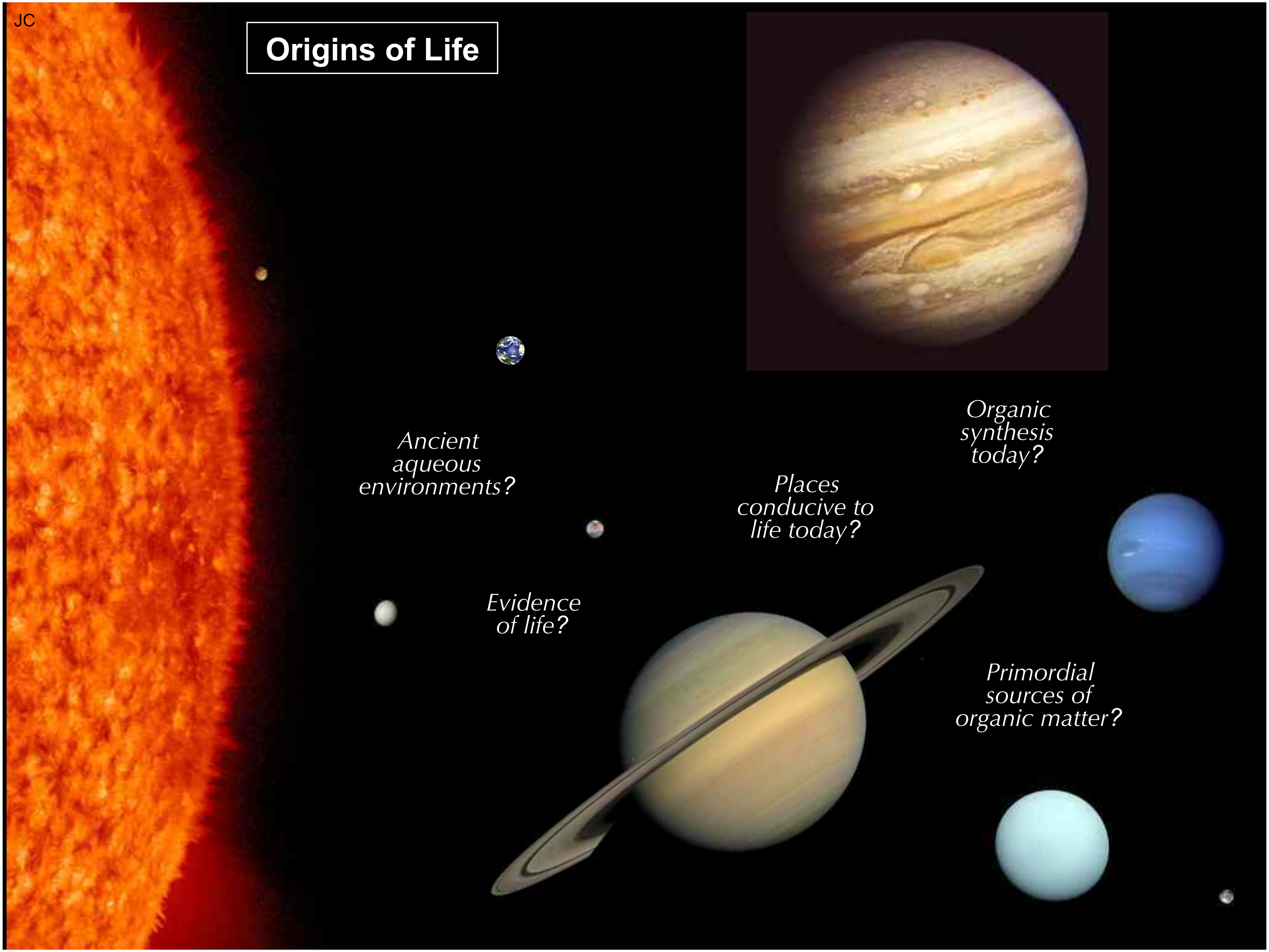
- **Thermal Protection Systems are typically critical technologies and often the key enabling technology for the following Mission areas**
  - Space Exploration
  - Near Earth Space Operations
  - Hypersonic Vehicles

- **For missions requiring TPS, given its baseline mass and uncertainties in**
  - Properties of TPS constituent materials
  - Composition and structure of TPS during development and processing
  - Damage to TPS due to micro-meteoroid impact / other sources
  - Trajectory of the entry system
  - Atmospheric composition and conditions (weather)
  - Aerothermal predictions
  - Material response predictions

TPS design is challenging and a major driver in overall vehicle design

Space Exploration & Fundamental Questions



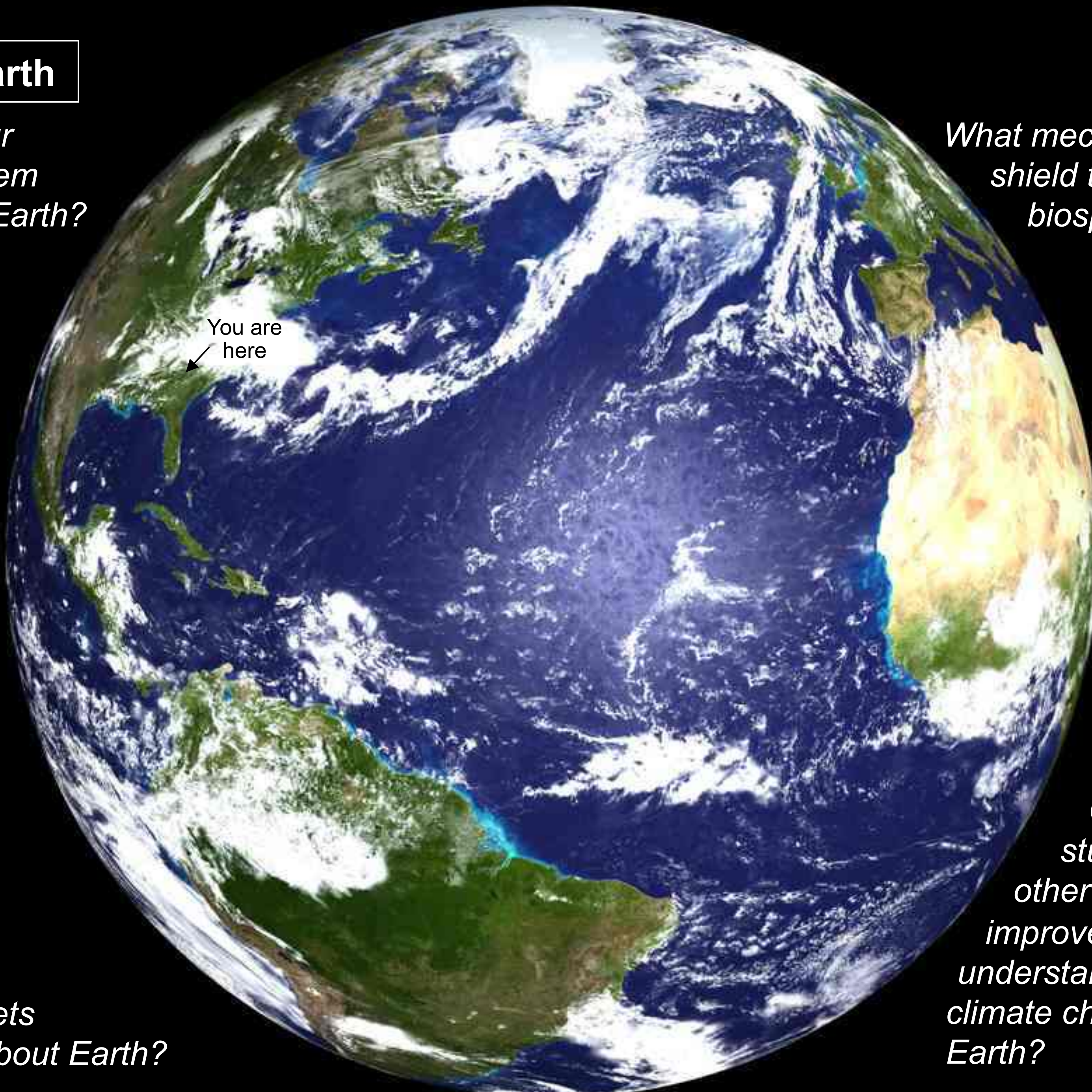

JC
Origins of Life
Ancient aqueous environments?
Organic synthesis today?
Places conducive to life today?
Evidence of life?
Primordial sources of organic matter?

JC

Safer Earth

What in our Solar System threatens Earth?

What mechanisms shield the Earth's biosphere?



Can studying other planets improve our understanding of climate change on Earth?

What can other planets teach us about Earth?

TPS & Exploring the Solar System

Answering these fundamental questions will require extensive exploration of our Solar System including robotic and human site visits

- The following solar system destinations have atmospheres and therefore require a thermal protection system to survive entry

  Venus, Mars, Jupiter, Saturn, Uranus, Neptune, Pluto
  and the moons: Io, Europa, Titan, and Triton

- Missions returning samples to Earth require high performance / ultra-high confidence TPS

- Missions to the Sun or Mercury (or nearby) require radiation shielding and potentially other forms of TPS

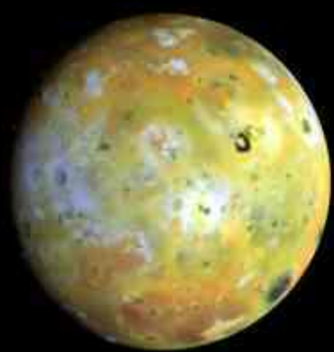
TPS & Exploring the Solar System

Planet	Atmospheric Pressure	Composition (%)	Entry Speed / TPS constraint
Mercury	trace	O (42), Na (29), H_2 (22), He (6)	Solar radiation
Venus	9.3 MPa	CO_2 (96), N_2 (3)	10 - 12 km/s
Earth	101 kPa	N_2 (78), O_2 (21), Ar (1)	LEO Return: 8 km/s Lunar Return: 11 km/s Sample Return 12+ km/s
Mars	0.6 kPa	CO_2 (95), N_2 (3), Ar (2)	5 - 8 km/s
Jupiter	100 kPa	H_2 (90) He (10)	42 - 50 km/s
Saturn	140 kPa	H_2 (96), He (3)	26 km/s
Uranus	Stratosphere: 10 kPa – 10 μPa	H_2 (83), He (15), CH_4 (2)	24 - 26 km/s
Neptune	Stratosphere: 10 kPa – 1 Pa	H_2 (80), He (19), CH_4 (1)	22 - 28 km/s
Pluto	0.3 Pa	N_2, CH_4	

TPS & Exploring the Solar System

Moon | **Atmospheric Pressure** | **Composition (%)** | **Entry Speed / TPS constraint**

Io Innermost of the 4 Galilean moons



2,260 mi

4th largest moon

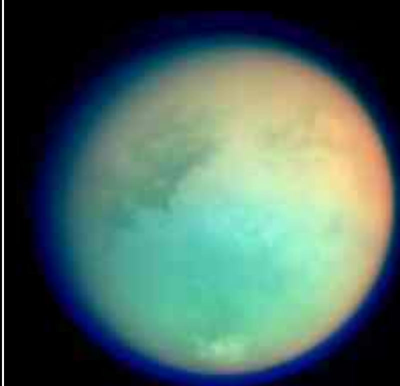
Most geologically active object in Solar System (400 active volcanoes)

trace

SO_2 (90)

5 - 12 km/s

Titan Largest moon of Saturn



3,090 mi

2nd largest moon

Dense atmosphere with liquid bodies at surface

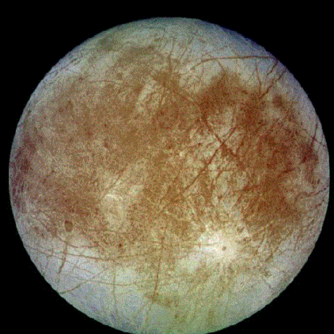
Visited by Cassini-Huygens probe (2004)

147 kPa

N_2 (98), CH_4 (1)

5 - 12 km/s

Europa Smallest of the Galilean moons



1,880 mi

6th moon of Jupiter

Slightly smaller than Earth's Moon

May contain water and perhaps life

0.1 µPa

O_2

5 - 12 km/s

Triton Largest moon of Neptune

1,620 mi

Retrograde orbit

7th largest moon in Solar System

Geologically active

1 - 2 Pa

N_2

5 - 12 km/s

TPS & Near Earth Operations

SpaceX Falcon 9

Commercial Access to Space & Return

Key Technologies: Low Cost, Reliable

- TPS
- Launch systems
- Recovery systems

SpaceX Dragon with PICA-X TPS

TPS & Near Earth Operations

X-37b, preparing for launch

Military Access to Space & Return

Critical Technologies

- Nose cone, leading edge, acreage TPS
- Hot structures and materials
- Advanced guidance, navigation, and control

X-37b: Returning after 270 days in orbit

TPS & Near Earth Operations

Space Station Down-Mass

Critical Technologies

- TPS
- Recovery Systems

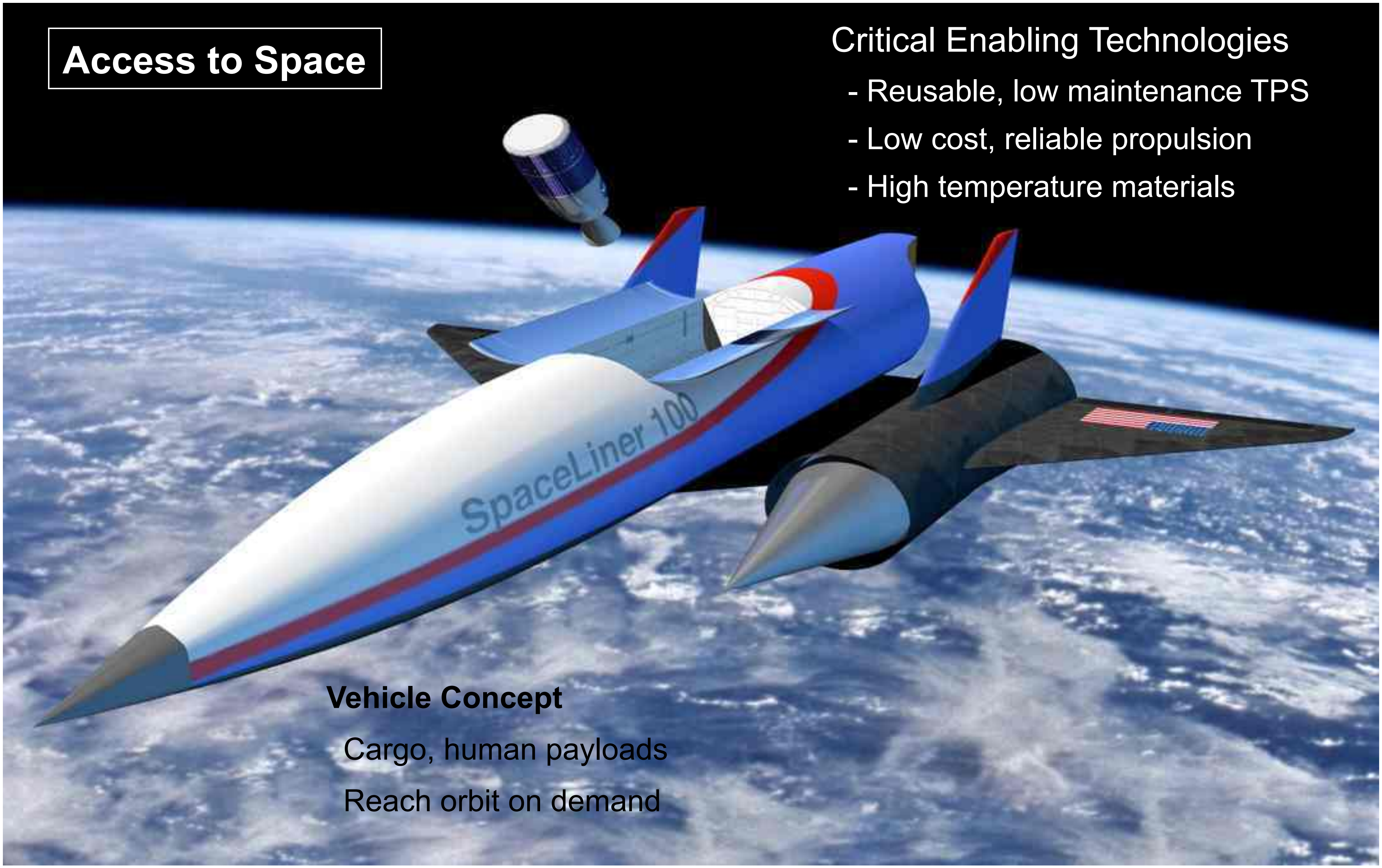
TPS & Near Earth Ops / Hypersonic Vehicles

Entry Systems & Technology Program

Access to Space

Critical Enabling Technologies

- Reusable, low maintenance TPS
- Low cost, reliable propulsion
- High temperature materials



Vehicle Concept

Cargo, human payloads

Reach orbit on demand

TPS & Hypersonic Vehicles

Military applications: quick response strike and reconnaissance

- Reusable TPS for leading edges is a critical enabling technology
- other enabling technologies include scramjet propulsion and high temperature structural materials

Vehicle Concept (DARPA)

10,000+ lb payload

Conventional (runway) take off and landing

Reach targets 9,000 nautical miles away in less than 2 hours (Mach 5 – 10)

TPS & Hypersonic Vehicles

Commercial applications: quick, global cargo delivery

Vehicle Concept

- Railgun launch
- Conventional landing
- Global destinations in hours

Critical enabling technologies

- Launch systems
- Reusable TPS
- Rocket based combined cycle propulsion
- High temperature structural materials

Why are we still working TPS?

Entry Systems & Technology Program