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?

**Human Space Flight?**
- Orbital, 100 miles alt, 17,500 mph
- 4,000+ lb payload

**Inter-Continental Ballistic Missile? (ICBM)**
- 6,000+ mi range
- 900 mi alt
- 15,000+ mph

**Satellites?**
- boosters?, guidance?
- thermal protection?

**Nuclear Weapon Technology**
- Fat Man (1945)
- 10,800 lb, 21 kt
- warhead design?
The 3 year Bumper Program achieved ~ Mach 9 and included a teflon nose cone - the 1st ablative TPS.

**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**

<table>
<thead>
<tr>
<th></th>
<th>Weight</th>
<th>Thrust</th>
<th>Height</th>
<th>Speed</th>
<th>Altitude</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>28,000 lb</td>
<td>55,000 lb</td>
<td>46 ft</td>
<td>3,600 mph</td>
<td>300,000 ft</td>
</tr>
<tr>
<td></td>
<td>12,700 kg</td>
<td>24,900 kg</td>
<td>14 m</td>
<td>1.6 km/s</td>
<td>90 km</td>
</tr>
</tbody>
</table>

WAC-Corporal upper stage
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)

<table>
<thead>
<tr>
<th>Nuclear Weapon</th>
<th>Weight (lb)</th>
<th>Yield (Kt)</th>
<th>IOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fat Man</td>
<td>10,800</td>
<td>20</td>
<td>1945</td>
</tr>
<tr>
<td>Mark 5</td>
<td>3,200</td>
<td>50</td>
<td>1952</td>
</tr>
<tr>
<td><strong>Fusion WH</strong></td>
<td>1,500</td>
<td>500</td>
<td>195?</td>
</tr>
<tr>
<td>W-49</td>
<td>1,650</td>
<td>1,440</td>
<td>1958</td>
</tr>
</tbody>
</table>

Cold War ➔ ICBM Crash Program
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
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
Entry Systems & Technology Program

TPS Problem 1: Shape

Early Re-Entry Vehicle (RV) Concept

Initial RV Ground Test

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
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.

\[ \text{Ma} > 1 \]

\[ \text{Ma} < 1 \]

\[ \theta > \theta_{\text{max}} \]

\[ Q = (C_f/\pi)(1/2 m V_e^2) \]

\[ \text{detached bow shock wave} \]

\[ \text{NASA Aerodynamicist, Harvey Allen} \]
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
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)
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: 1\textsuperscript{st} 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
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

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>height (ft)</td>
<td>40.5</td>
</tr>
<tr>
<td>weight (lbs)</td>
<td>12,000</td>
</tr>
<tr>
<td>thrust, STAGE 1 (lbs)</td>
<td>48,000</td>
</tr>
<tr>
<td>thrust, STAGE 2 (lbs)</td>
<td>3x 39,300</td>
</tr>
<tr>
<td>thrust, STAGE 3 (lbs)</td>
<td>36,000</td>
</tr>
<tr>
<td>max speed (mph)</td>
<td>9,000</td>
</tr>
<tr>
<td>max altitude¹ (ft)</td>
<td>500,000</td>
</tr>
<tr>
<td>max altitude² (mi)</td>
<td>500</td>
</tr>
</tbody>
</table>

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

Launched using modified R-7 ICBM

SPUTNIK
Eisenhower

“outer space should be used only for peaceful purposes”

Space Race: Eisenhower & NASA

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

NACA (1915)

NASA (7/29/1958)
Space Race: Gagarin, 1st Human in Space 4/12/61
“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”
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

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

<table>
<thead>
<tr>
<th>Boosters</th>
<th>Redstone</th>
<th>Atlas LV-3B</th>
</tr>
</thead>
<tbody>
<tr>
<td>height (ft)</td>
<td>83</td>
<td>82</td>
</tr>
<tr>
<td>weight (lbs)</td>
<td>66,000</td>
<td>256,000</td>
</tr>
<tr>
<td>thrust (lbs)</td>
<td>78,000</td>
<td>357,000</td>
</tr>
</tbody>
</table>
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)

- 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

Energy = \( \frac{1}{2} m v^2 + m g h \)

Mercury capsule: 2,700 lb (1,230 kg)  
\[ \Rightarrow 30 \times 10^9 \text{ ft-lb} \] (41 GJ*)

\(~ 10 \text{ tons of TNT}~\)
Space Race: Return from LEO & TPS

Mercury Re-Entry

Altitude \( \sim 400,000 \text{ ft or 76 mi (120 km)} \)
Velocity \( \sim 26,000 \text{ ft/s or 17,900 mph (8 km/s)} \)

Energy \( = \frac{1}{2} \ m \ v^2 + m \ g \ h \)
Mercury capsule: 2,700 lb (1,230 kg)
\[30 \times 10^9 \text{ ft-lb} \quad (41 \text{ GJ}^*)\]

Two TPS Options Selected (1958)

Beryllium Heat Sink
- Polaris (U.S. Navy) SLBM heritage
- 6 units fabricated from hot-pressed Beryllium 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

\(~ 10 \text{ tons of TNT}~\)
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)
Gemini

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

Apollo

- Lunar Orbit & Return
- Lunar Landing & Return
Entry Systems & Technology Program

**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 reinforced with quartz fibers and phenolic microballoons
Density: 31 lb/ft³

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

**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

\[ \Rightarrow 340 \text{ GJ} \]

~ 8 times Mercury re-entry!

**Design Constraints**

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

Space Race: Return from the Moon & TPS
3 Weeks after Gagarin's Flight
and that's

The End

of the story of the beginning of

Thermal Protection Systems
since then
This Soviet spacecraft was the first to land successfully on another planet and to transmit data back to Earth. Venera 7 successfully touched down on the Venusian surface on December 15, 1970. Only the temperature data channel was working and the parachute failed ~ 10 meters above ground. Nearly 1 hour of data was transmitted.
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)
- 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

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.
Space Shuttle Orbiter

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td></td>
</tr>
<tr>
<td>150,000 lb (empty)</td>
<td></td>
</tr>
<tr>
<td>240,000 lb (gross)</td>
<td></td>
</tr>
<tr>
<td>Length</td>
<td>122 ft</td>
</tr>
<tr>
<td>Speed</td>
<td>17,300 mph</td>
</tr>
<tr>
<td>Wingspan</td>
<td>78 ft</td>
</tr>
<tr>
<td>Altitude</td>
<td>100 - 520 nmi</td>
</tr>
<tr>
<td>Height</td>
<td>59 ft</td>
</tr>
<tr>
<td>Cost per Launch</td>
<td>$500M - $1.3B</td>
</tr>
<tr>
<td>Payload Bay Door</td>
<td></td>
</tr>
<tr>
<td>Flight Deck</td>
<td></td>
</tr>
<tr>
<td>Nose Cap</td>
<td></td>
</tr>
<tr>
<td>Vertical Stabilizer</td>
<td></td>
</tr>
<tr>
<td>Remote Manipulator System</td>
<td></td>
</tr>
<tr>
<td>Advanced Flexible Reusable Surface Insulation</td>
<td></td>
</tr>
<tr>
<td>High-Temperature Reusable Surface Insulation Tiles</td>
<td></td>
</tr>
<tr>
<td>RCS Thruster</td>
<td></td>
</tr>
<tr>
<td>Wing Leading Edge</td>
<td>(reinforced carbon-carbon)</td>
</tr>
</tbody>
</table>

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.
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

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

---

**NASA**

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 unmanned Earth re-entry @ 12.9 km/s**

---

**BLUNT BODY CONCEPT**

Key enabling concept for entry vehicles

**U.S. civilian space agency established**

**Entry Systems & Technology Program**
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
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)
<table>
<thead>
<tr>
<th>ICMB</th>
<th>Spy Satellite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Human Exploration of Space</td>
<td>Hypersonic Aircraft</td>
</tr>
</tbody>
</table>
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

Earth's Origin

How was our solar system formed?

How have the orbits evolved?

How have chemical and physical processes that shaped our solar system operated, interacted, and evolved over time?

How did the giant planets and their satellite systems form?
Evidence of life?

Ancient aqueous environments?

Organic synthesis today?

Places conducive to life today?

Evidence of life?

Primordial sources of organic matter?
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?
Entry Systems & Technology Program

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

<table>
<thead>
<tr>
<th>Planet</th>
<th>Atmospheric Pressure</th>
<th>Composition (%)</th>
<th>Entry Speed / TPS constraint</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury</td>
<td>trace O (42), Na (29), H₂ (22), He (6) Solar radiation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Venus</td>
<td>9.3 MPa CO₂ (96), N₂ (3)</td>
<td>10 - 12 km/s</td>
<td></td>
</tr>
<tr>
<td>Earth</td>
<td>101 kPa N₂ (78), O₂ (21), Ar (1) LEO Return: 8 km/s Lunar Return: 11 km/s Sample Return 12+ km/s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mars</td>
<td>0.6 kPa CO₂ (95), N₂ (3), Ar (2)</td>
<td>5 - 8 km/s</td>
<td></td>
</tr>
<tr>
<td>Jupiter</td>
<td>100 kPa H₂ (90) He (10)</td>
<td>42 - 50 km/s</td>
<td></td>
</tr>
<tr>
<td>Saturn</td>
<td>140 kPa H₂ (96), He (3)</td>
<td>26 km/s</td>
<td></td>
</tr>
<tr>
<td>Uranus</td>
<td>Stratosphere: 10 kPa – 10 μPa H₂ (83), He (15), CH₄ (2)</td>
<td>24 - 26 km/s</td>
<td></td>
</tr>
<tr>
<td>Neptune</td>
<td>Stratosphere: 10 kPa – 1 Pa H₂ (80), He (19), CH₄ (1)</td>
<td>22 - 28 km/s</td>
<td></td>
</tr>
<tr>
<td>Pluto</td>
<td>0.3 Pa N₂, CH₄</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## TPS & Exploring the Solar System

<table>
<thead>
<tr>
<th>Moon</th>
<th>Atmospheric Pressure</th>
<th>Composition (%)</th>
<th>Entry Speed / TPS constraint</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Io</strong></td>
<td>2,260 mi</td>
<td>trace</td>
<td>5 - 12 km/s</td>
</tr>
<tr>
<td></td>
<td>Innermost of the 4 Galilean moons</td>
<td>SO$_2$ (90)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4$^{th}$ largest moon</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Most geologically active object in Solar System (400 active volcanoes)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Europa</strong></td>
<td>1,880 mi</td>
<td>0.1 μPa</td>
<td>5 - 12 km/s</td>
</tr>
<tr>
<td></td>
<td>Smallest of the Galilean moons</td>
<td>O$_2$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6$^{th}$ moon of Jupiter</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Slightly smaller than Earth's Moon</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>May contain water and perhaps life</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Titan</strong></td>
<td>3,090 mi</td>
<td>N$_2$ (98), CH$_4$ (1)</td>
<td>147 kPa</td>
</tr>
<tr>
<td></td>
<td>Largest moon of Saturn</td>
<td></td>
<td>5 - 12 km/s</td>
</tr>
<tr>
<td></td>
<td>2$^{nd}$ largest moon</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dense atmosphere with liquid bodies at surface</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Triton</strong></td>
<td>1,620 mi</td>
<td>N$_2$</td>
<td>1 - 2 Pa</td>
</tr>
<tr>
<td></td>
<td>Largest moon of Neptune</td>
<td></td>
<td>5 - 12 km/s</td>
</tr>
<tr>
<td></td>
<td>Retrograde orbit</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>7$^{th}$ largest moon in Solar System</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Geologically active</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
TPS & Near Earth Operations

Commercial Access to Space & Return

Key Technologies: Low Cost, Reliable
- TPS
- Launch systems
- Recovery systems

SpaceX Falcon 9

SpaceX Dragon with PICA-X TPS
TPS & Near Earth Operations

Military Access to Space & Return

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

X-37b, preparing for launch

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

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
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)
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?

TPS is a critical technology for Missions of National Interest

- Space Exploration
- Near Earth Space Operations
- Hypersonic Vehicles