APPENDIX III: UNIT CONVERSION FACTORS

<table>
<thead>
<tr>
<th>Unit</th>
<th>Conversion Factor</th>
</tr>
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<tbody>
<tr>
<td>1 cm</td>
<td>0.3937 in</td>
</tr>
<tr>
<td>1 m</td>
<td>3.28084 ft</td>
</tr>
<tr>
<td>1 m²</td>
<td>10.764 ft²</td>
</tr>
<tr>
<td>1 km/s</td>
<td>3280.8 ft/s</td>
</tr>
<tr>
<td>1 kg</td>
<td>2.20462 lb</td>
</tr>
<tr>
<td>1 kg/m²</td>
<td>0.2048 lb/ft²</td>
</tr>
<tr>
<td>1 kg/m³</td>
<td>0.06243 lb/ft³</td>
</tr>
<tr>
<td>1 Joule</td>
<td>0.9478 x 10⁻³ BTU</td>
</tr>
<tr>
<td>1 W</td>
<td>0.9478 x 10⁻³ BTU/s</td>
</tr>
<tr>
<td>1 J/cm²</td>
<td>0.88055 BTU/ft²</td>
</tr>
<tr>
<td>1 W/cm²</td>
<td>0.88055 BTU/ft².s</td>
</tr>
<tr>
<td>1 atm</td>
<td>1.01325 x 10¹³ Pa</td>
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Content Editor
Carol Davies, ELORET Corporation

Production Editor
Marla Arcadi, ELORET Corporation

Cover Graphics
Jay Nuez, University of California, Santa Cruz

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Jet Propulsion Laboratory
California Institute of Technology, Pasadena CA
and
Michael J. Taylor, Stardust Mission
Utah State University, Logan UT

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NASA Center for AeroSpace Information
National Technical Information Service
7121 Standard Drive
Hanover MD 21076-1320
(301) 621-0390

5285 Port Royal Road
Springfield VA 22161
(703) 487-4650
Analogous to a resin material in primary function, the matrix is typically stable and will not pyrolyze when heated, typically leaving a carbonaceous residue. The organic resin will pyrolyze when heated, typically leaving a carbonaceous residue.

Ballistic coefficient
The ratio of the product of drag coefficient \( C_d \) and projected reference area \( A \) to mass \( m \), giving \( m/C_dA \).

Stagnation heating rate
The maximum convective heat flux at the stagnation point. Depends on trajectory. The stagnation point is where the velocity to the surface adiabatically comes to zero. Location depends on angle of attack and deviation behind the shock. The stagnation point is often where the maximum heating rate occurs, but not always.

Integrated heat load
The convective heat flux integrated over flight time. The highest heat load is usually, but not always, at the stagnation point. The integrated heat load will vary over the vehicle surface.

Radiative heat flux at stagnation point
This is the heat flux radiated from the shock layer to the surface. It may or may not be a maximum at the stagnation point.

Peak heat stagnation pressure
The pressure at the time of maximum convective heat flux. This is not the peak pressure, which occurs later in the trajectory.

Material designation
This can be a material trade name, defined by the manufacturer (e.g., SLA-561V) or a generic designator applied to a class of materials (e.g., carbon phenolic). It provides little useful information about the material other than a broad description of its constituents.

Thickness
This is “as manufactured” thickness of the material, usually specified at the stagnation point. Useful for a TPS of uniform thickness; less useful for a “tailored” TPS. The “as manufactured” thickness includes the “nominal design thickness” to which additional thickness is added (margin) to accommodate uncertainties in the entry environment and/or material performance.

Resin material
This is the “organic matrix” (e.g., epoxy, silicone, phenolic) in an organic matrix composite wherein the matrix (glue) fills the voids and provides rigidity to the structural reinforcement (e.g., fibers, fabric, honeycomb). The organic resin will pyrolyze when heated, typically leaving a carbonaceous residue (char).

Matrix material
Analogous to a resin material in primary function, the matrix is typically stable and will not pyrolyze when heated. Examples include inorganic ceramics (e.g., glass, alumina) in ceramic matrix composites and carbon in carbon-carbon composites.
APPENDIX II: DEFINITIONS

Entry angle, $\gamma$
The angle between the local horizontal plane (orthogonal to the vector from the planet center to the vehicle) and the velocity vector of the vehicle, $V$, at a reference altitude, $h$. The entry angle can be inertial or relative, depending on entry velocity used. $\gamma$ is negative when $V$ is below the horizontal plane, as in planetary entry.

Inertial entry velocity
The vehicle velocity at reference altitude, $h$, assuming a non-rotating planet.

Relative entry velocity
The inertial entry velocity amended by the component of the planet’s rotation, assuming the atmosphere to be a solid body.

Velocity at peak heat
The velocity when the vehicle reaches the maximum convective heat flux at the stagnation point.

Control method
(a) Ballistic: no control, subject to drag forces only, with passive stability about zero lift condition;
(b) Controlled Ballistic: active control to maintain zero lift; and
(c) RCS: a set of small engines called the reaction control system (RCS) engines.

Center of gravity, $X_{cg}$
In the table, the value of $X_{cg}/D$ is given, where $D$ is the maximum diameter of the vehicle. On the diagram, the actual $X_{cg}$ is shown. Most CG are not exactly on the centerline because of manufacturing tolerances, but generally the $Y$ value wasn’t given or it is so close that it doesn’t show up in the diagram. The exceptions were Apollo command modules and the Viking landers, where the $Y$ offset was deliberate to achieve the desired angles of attack.

Shape
All vehicles are spherically blunted cones, or spherical, or conical.

Nose radius
The radius of the spherical nose, or the capsule radius.

Base area
The base area projected along the centerline.

Vehicle mass
The total vehicle mass of the vehicle at entry, including TPS and payload. Generally, the vehicle mass at entry is the same as take-off mass minus any fuel used for maneuvering. However, the mass can change after leaving the orbiter but before entry. An example is the small probe of Pioneer Venus where the spin yo-yo was jettisoned before entry. The mass can also change during entry if the heat shield material ablates. An (extreme) example was the Galileo probe that lost about 26% of its entry mass to ablation.

TPS mass fraction
The proportion of TPS mass to vehicle mass at entry. Insulator may or may not be included.

Payload mass
The proportion of payload mass (scientific instruments and may include transmitters, batteries etc.) to vehicle mass.
MISSION: FIRE II  
PLANET: EARTH  
LAUNCH: MAY 22, 1965  
ENTRY: MAY 22, 1965

Mission Description: Technology demonstrator for Apollo re-entry heating environment.

**INSTRUMENTATION:**
- Three forebody calorimeters, 11 forebody thermocouples, 12 offset radiometer thermocouples and one static pressure transformer on the afterbody.

**NOTES:**
- This aerothermal flight test was to evaluate radiative heating for Apollo.
- The reentry package consisted of three separate heat shield/calorimeter combinations, therefore the mass and OML changed with time.

**REFERENCES:**

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**INSTRUMENTATION:**
- Three forebody calorimeters, 11 forebody thermocouples, 12 offset radiometer thermocouples and one static pressure transformer on the afterbody.

**NOTES:**
- This aerothermal flight test was to evaluate radiative heating for Apollo.
- The reentry package consisted of three separate heat shield/calorimeter combinations, therefore the mass and OML changed with time.

**REFERENCES:**

**REFERENCES:**
MISSION: APOLLO AS-201
PLANET: EARTH

LAUNCH: Feb 26, 1966
ENTRY: Feb 26, 1966

MISSION DESCRIPTION:
First unmanned suborbital flight to test
the Saturn 1B launch vehicle,
and the command and service modules

INSTRUMENTATION:
- 36 pressure sensors all worked OK, 35 calorimeters worked
  initially

NOTES:
- TPS thickness: Ablator = 4.3 cm, braised stainless steel
  substructure (PH 15-7 MO) = 5.08 cm
- Insulation: (TG-15,000) = 2.03 cm, aluminum honeycomb
  (2014-T6 and 5052-H39) = 3.81 cm
- Peak heating is not at stagnation point
- Manufacturer: AVCO Corp

REFERENCES:

Data Collected by: C. Park and M.J. Wright

---

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<tr>
<th>Trajectory</th>
<th>Geometry</th>
<th>Aero/thermal</th>
<th>TPS</th>
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<td>Entry angle</td>
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<td></td>
<td>-9.03°</td>
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<td>Relative entry velocity</td>
<td>7.67 km/s</td>
<td>Base area</td>
<td>12.02 m²</td>
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<td>Stagnation heating rate</td>
<td>186 W/cm² at peak</td>
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<td>Radiative heat flux</td>
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<td>Total material density</td>
<td>Ablator: 544.6 kg/m³</td>
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<td>Sun</td>
<td>Solar orbit</td>
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<tr>
<td>Japan</td>
<td>01/15/76</td>
<td>Helios 2</td>
<td>Sun</td>
<td>Solar orbit</td>
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<tr>
<td>Europe</td>
<td>01/18/85</td>
<td>Sakigake</td>
<td>Comet</td>
<td>Halley flyby (3/1/86 - 4.3 mill. mi.)</td>
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<tr>
<td></td>
<td>08/19/85</td>
<td>Suisei</td>
<td>Comet</td>
<td>Halley flyby (3/8/86 - 93,600 mi.)</td>
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<td>09/04/98</td>
<td>Nozomi</td>
<td>Mars</td>
<td>Failed to reach Mars orbit (12/2003)</td>
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<td>Huygens</td>
<td>Titan</td>
<td>Carried by U.S.'s Cassini orbiter</td>
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<td>Suborbital test</td>
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<td>MR-2</td>
<td>Chimp &quot;Ham&quot;</td>
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<td>05/03/61</td>
<td>MR-3 (Freedom 7)</td>
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<td>07/21/61</td>
<td>MR-4 (Liberty Bell 7)</td>
<td>Suborbital flight</td>
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<tr>
<td></td>
<td>09/13/61</td>
<td>MA-4</td>
<td>Orbital test</td>
<td></td>
</tr>
<tr>
<td></td>
<td>11/21/61</td>
<td>MA-5</td>
<td>Chimp &quot;Enos&quot;</td>
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<td>02/20/62</td>
<td>MA-6 (Friendship 7)</td>
<td>Earth orbit</td>
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<td>05/24/62</td>
<td>MA-7 (Aurora 7)</td>
<td>Earth orbit</td>
<td></td>
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<td></td>
<td>10/03/62</td>
<td>MA-8 (Sigma 7)</td>
<td>Earth orbit</td>
<td></td>
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</table>
MISSION: **APOLLO AS-202**  
PLANET: **EARTH**  

**LAUNCH:** Aug 25, 1966  
**ENTRY:** Aug 25, 1966  

**MISSION DESCRIPTION:** Second unmanned suborbital flight to test the Saturn 1B launch vehicle, and the command and service modules.

---

**INSTRUMENTATION:**
- 36 pressure sensors all worked OK, 35 calorimeters worked initially

**NOTES:**
- TPS thickness: Ablator = 4.32 cm, braised stainless steel substructure (PH 15-7 MO) = 5.08 cm
- Insulation: (TG-15,000) = 2.03 cm, aluminum honeycomb (2014-T6 and 5052-H39) = 3.81 cm
- Manufacturer: AVCO Corp

**REFERENCES:**

---

**TRAJECTORY**
- Inertial entry velocity
- Relative entry velocity
- Velocity at peak heat

**GEOMETRY**
- Entry angle: -3.53° relative
- Shape: Capsule, 33° cone
- Trim L/D (specify trim at): 0.28< L/D <0.33 at 21° ± 3

**AERO/ THERMAL**
- Ballistic coeff:
- Stagnation heating rate
- Integrated heat load
- Material designation: Avco 5026-39 HCG
- Epoxy-novolac Quartz fiber +phenolic microballoon
- Resin mat. Matrix mat.
- Radiative heat flux
- Resin dens. Matrix density
- 244.6 kg/m^3
- 300 kg/m^3

**TPS**
- Ablator: 54.4 kg/m^2

---

**CENTERS OF GRAVITY, Xc/D**
- Vega 1: Venus flyby (communications failure)
- Vega 1: Venus flyby & landing (6/11/85)
- Vega 2: Venus flyby & landing (6/14/85)
- Phobos 1: Mars Phobos/Mars orbit (comm. failure)
- Mars 96: 2 Mars landers (launch failure)
MISSION: APOLLO 4  
PLANET: EARTH  

LAUNCH: Nov 9, 1967  
ENTRY: Nov 9, 1967  

MISSION DESCRIPTION:  
Test of Saturn V launch vehicle and overall re-entry operations  

<table>
<thead>
<tr>
<th>Trajectory</th>
<th>Geometry</th>
<th>Aero/thermal</th>
<th>TPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entry angle 6.92° initial, 7.13° relative</td>
<td>Shape</td>
<td>Capsule: 33° cone</td>
<td>Trim L/D (specify trim α) 0.37° &lt; L/D &lt; 0.44 24° &lt; α &lt; 28</td>
</tr>
<tr>
<td>Inertial entry velocity 11.14 km/s</td>
<td>Nose radius 4.69 m, 3 m effective</td>
<td>Ballistic coeff. 395.8 kg/m²</td>
<td>Thickness See note</td>
</tr>
<tr>
<td>Relative entry velocity 10.73 km/s</td>
<td>Base area 12.02 m²</td>
<td>Stagnation heating rate 490 W/cm² at peak</td>
<td>Ablating? Ejected? No</td>
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<tr>
<td>Velocity at peak heat 10.74 km/s</td>
<td>Vehicle mass 6474 kg</td>
<td>Integrated heat load 43,000 J/cm²</td>
<td>Resin mat. matrix mat. Epoxynovolac Quartz fiber +phenolic microballoon</td>
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<tr>
<td>Control method Roll modulation</td>
<td>TPS mass fraction, inc. insul. 13.7%</td>
<td>Radiative heat flux 115-264 W/cm²</td>
<td>Resin dens. matrix density 244.6 kg/m³</td>
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<tr>
<td>Center of Gravity, Xcg/D 0.27</td>
<td>Payload mass None</td>
<td>PH stag. pressure 0.35 atm</td>
<td>Total material density 300 kg/m³</td>
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</tbody>
</table>

### INSTRUMENTATION:  
- 17 pressure sensors all worked and 23 calorimeters worked initially. Radiometer functioned well.

### NOTES:  
- TPS thickness: Ablator = 4.32 cm, braised stainless steel substructure (PH 15-7 MO) = 5.08 cm
- Insulation: (TG-15,000) = 2.03 cm, aluminum honeycomb (2014-T6 and 5052-H39) = 3.81 cm
- Manufacturer: AVCO Corp

### REFERENCES:  
### Unmanned Planetary Probes

**United States**

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<thead>
<tr>
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<th>Spacecraft</th>
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<td>08/20/75</td>
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<td>Mars</td>
<td>Mars orbit &amp; landing (7/20/76)</td>
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<tr>
<td>09/09/75</td>
<td>Viking 2</td>
<td>Mars</td>
<td>Mars orbit &amp; landing (9/3/76)</td>
</tr>
<tr>
<td>08/12/77</td>
<td>ICE (ISEE-3)</td>
<td>Sun</td>
<td>Solar orbit</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Comet</td>
<td>Giacobini-Zinner flyby (9/11/85)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Comet</td>
<td>Halley flyby (3/25/86)</td>
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<td>09/03/77</td>
<td>Voyager 1</td>
<td>Jupiter</td>
<td>Jupiter flyby (3/5/79 - 174,000 m.i.)</td>
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<td>Saturn</td>
<td>Saturn flyby (11/12/80 - 77,000 m.i.)</td>
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<td>08/20/77</td>
<td>Voyager 2</td>
<td>Jupiter</td>
<td>Jupiter flyby (7/9/79 - 400,000 m.i.)</td>
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<td>Saturn flyby (8/25/81 - 63,000 m.i.)</td>
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<td>Uranus</td>
<td>Uranus flyby (1/24/86 - 44,000 m.i.)</td>
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<td>Neptune</td>
<td>Neptune flyby (8/25/89 - 15,500 m.i.)</td>
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<td>Venus</td>
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<td>Venus</td>
<td>Venus flyby (2/10/90 - 10,000 m.i.)</td>
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<td>Flyby (10/29/91 - 1,000 m.i.)</td>
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<td>Flyby (8/28/93 - 2,400 m.i.)</td>
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<td>Saturn</td>
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<td>Titan</td>
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<td>Moon</td>
<td>Lunar orbital mapper</td>
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**Notes:**

- **TPS thickness:** Ablator = 4.32 cm, braised stainless steel substrate (PH 15-7 MO) = 5.08 cm
- **Insulation:** TG-15,000 = 2.03 cm, aluminum honeycomb (2014-T6 and 5052-H39) = 3.81 cm
- **Manufacturer:** AVCO Corp

**References:**

## APPENDIX I

### LIST OF SPACE VEHICLES AND THEIR MISSIONS

#### Unmanned Planetary Probes

<table>
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<tr>
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<td>Pioneer 10</td>
<td>Jupiter</td>
<td>Jupiter flyby (12/3/73 - 81,000 mi.)</td>
</tr>
<tr>
<td>04/05/73</td>
<td>Pioneer 11</td>
<td>Jupiter</td>
<td>Jupiter flyby (12/27/74 - 26,600 mi.)</td>
</tr>
<tr>
<td>01/26/62</td>
<td>Ranger 3</td>
<td>Moon</td>
<td>Lunar flyby</td>
</tr>
<tr>
<td>04/23/62</td>
<td>Ranger 4</td>
<td>Moon</td>
<td>Lunar impact</td>
</tr>
<tr>
<td>10/10/62</td>
<td>Ranger 5</td>
<td>Moon</td>
<td>Lunar flyby</td>
</tr>
<tr>
<td>01/30/64</td>
<td>Ranger 6</td>
<td>Moon</td>
<td>Lunar impact</td>
</tr>
<tr>
<td>07/28/64</td>
<td>Ranger 7</td>
<td>Moon</td>
<td>Lunar impact/photos</td>
</tr>
<tr>
<td>02/17/65</td>
<td>Ranger 8</td>
<td>Moon</td>
<td>Lunar impact/photos</td>
</tr>
<tr>
<td>03/21/65</td>
<td>Ranger 9</td>
<td>Moon</td>
<td>Lunar impact/photos</td>
</tr>
<tr>
<td>08/26/62</td>
<td>Mariner 2</td>
<td>Venus</td>
<td>Venus flyby (12/14/65 - 22,000 mi.)</td>
</tr>
<tr>
<td>11/05/64</td>
<td>Mariner 3</td>
<td>Mars</td>
<td>Mars flyby (comm. failure)</td>
</tr>
<tr>
<td>11/28/64</td>
<td>Mariner 4</td>
<td>Mars</td>
<td>Mars flyby (7/14/65 - 6,100 km.)</td>
</tr>
<tr>
<td>06/14/67</td>
<td>Mariner 5</td>
<td>Venus</td>
<td>Venus flyby (10/19/67 - 2,500 km.)</td>
</tr>
<tr>
<td>02/25/69</td>
<td>Mariner 6</td>
<td>Mars</td>
<td>Mars flyby (7/31/69 - 2,100 km.)</td>
</tr>
<tr>
<td>03/27/69</td>
<td>Mariner 7</td>
<td>Mars</td>
<td>Mars flyby (8/5/69 - 2,200 km.)</td>
</tr>
<tr>
<td>05/30/71</td>
<td>Mariner 9</td>
<td>Mars</td>
<td>Mars orbit (11/13/71)</td>
</tr>
<tr>
<td>11/02/73</td>
<td>Mariner 10</td>
<td>Venus</td>
<td>Venus flyby (2/5/74 - 3,600 km.)</td>
</tr>
<tr>
<td>06/30/66</td>
<td>Surveyor 1</td>
<td>Moon</td>
<td>Lunar landing</td>
</tr>
<tr>
<td>09/20/66</td>
<td>Surveyor 2</td>
<td>Moon</td>
<td>Crashed on the Moon</td>
</tr>
<tr>
<td>04/17/67</td>
<td>Surveyor 3</td>
<td>Moon</td>
<td>Lunar landing</td>
</tr>
<tr>
<td>07/14/67</td>
<td>Surveyor 4</td>
<td>Moon</td>
<td>Crashed on the Moon</td>
</tr>
<tr>
<td>09/08/67</td>
<td>Surveyor 5</td>
<td>Moon</td>
<td>Lunar landing</td>
</tr>
<tr>
<td>11/07/67</td>
<td>Surveyor 6</td>
<td>Moon</td>
<td>Lunar landing</td>
</tr>
<tr>
<td>01/07/68</td>
<td>Surveyor 7</td>
<td>Moon</td>
<td>Lunar landing</td>
</tr>
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<td>08/10/66</td>
<td>Lunar Orbiter 1</td>
<td>Moon</td>
<td>Lunar orbit</td>
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<td>11/06/66</td>
<td>Lunar Orbiter 2</td>
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<td>Lunar orbit</td>
</tr>
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<td>02/04/67</td>
<td>Lunar Orbiter 3</td>
<td>Moon</td>
<td>Lunar orbit</td>
</tr>
<tr>
<td>05/04/67</td>
<td>Lunar Orbiter 4</td>
<td>Moon</td>
<td>Lunar orbit</td>
</tr>
<tr>
<td>08/01/67</td>
<td>Lunar Orbiter 5</td>
<td>Moon</td>
<td>Lunar orbit</td>
</tr>
</tbody>
</table>

### Trajectory, Geometry, Aero/thermal, TPS

<table>
<thead>
<tr>
<th>Entry angle</th>
<th>Shape</th>
<th>Nose radius</th>
<th>Ballistic coeff.</th>
<th>Stagnation heating rate</th>
<th>Radiative heat flux</th>
<th>Total material density</th>
</tr>
</thead>
<tbody>
<tr>
<td>-20.78°</td>
<td>5° half cone, 3.962 m long</td>
<td>.254 cm</td>
<td>-50,000 kg/m²</td>
<td>32 W/cm²</td>
<td>~0 W/cm²</td>
<td></td>
</tr>
<tr>
<td>Inertial entry velocity</td>
<td>6.28 km/s</td>
<td>0.3772 m²</td>
<td>Thickness</td>
<td>Be: 1.524 cm</td>
<td>Ablating? Ejected?</td>
<td>No</td>
</tr>
<tr>
<td>Relative entry velocity</td>
<td>5.96 km/s</td>
<td>Base area</td>
<td>272 kg</td>
<td>Integrated heat load</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Velocity at peak heat</td>
<td>5.47 km/s</td>
<td>Vehicle mass</td>
<td>250 atm</td>
<td>PH stag. pressure</td>
<td>3.962 m</td>
<td></td>
</tr>
</tbody>
</table>

### Instrumentation:
- Multiple thermocouples and pressure sensors at 21 stations on a 5° half cone, 4 heat-flux gauges and 2 pressure gauges on base.
- 3 thermocouples in nose-tip assembly.

### Notes:
- Nose-tip heating rate is not relevant for this flight, which was designed to measure heating on a sharp cone.
- The nose tip was meant to ablate during entry.
- The beryllium heat shield melted about 40 seconds after entry.

### References:

Data Collected by: M.J. Wright and G. Allen
MISSION: PAET
PLANET: EARTH
LAUNCH: JUN 2, 1971
ENTRY: JUN 2, 1971
MISSION DESCRIPTION:
To test the capability to determine the composition of unknown atmospheres during high-speed entry

<table>
<thead>
<tr>
<th>Trajectory</th>
<th>Geometry</th>
<th>Aero/thermal</th>
<th>TPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entry angle</td>
<td>Relative at 90 km: −40.8°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shape</td>
<td>Blunt-nosed, 51° half-cone angle</td>
<td>Trim L/D (specify trim α)</td>
<td>0</td>
</tr>
<tr>
<td>Material designation</td>
<td>See note</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inertial entry velocity</td>
<td>6.60 km/s</td>
<td>Nose radius</td>
<td>0.46 m</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ballistic coeff</td>
<td>69 kg/m²</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stagnation heating rate</td>
<td>(no ablation)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Max: 174 W/cm²</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ablating? Ejected?</td>
<td>Yes: frustrum</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>No</td>
</tr>
<tr>
<td>Relative entry velocity</td>
<td>6.56 km/s</td>
<td>Base area</td>
<td>0.66 m²</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stagnation heating rate</td>
<td>(no ablation)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Max: 174 W/cm²</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ablating? Ejected?</td>
<td>Yes: frustrum</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>No</td>
</tr>
<tr>
<td>Velocity at peak heat</td>
<td>5.6 km/s</td>
<td>Vehicle mass</td>
<td>62.1 kg</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Integrated heat load</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stag. pt. 1450 J/cm²</td>
<td></td>
</tr>
<tr>
<td>Control method</td>
<td>Ballistic</td>
<td>TPS mass fraction, inc. insul.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Forebody: 13.7% Afterbody: 3.5%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Radiative heat flux</td>
<td>negligible</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Resin mat. Matrix mat.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Resin dens. Matrix density</td>
<td></td>
</tr>
<tr>
<td>Center of Gravity, Xcg/D</td>
<td>.202</td>
<td>Payload mass</td>
<td>14 kg</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PH stag. pressure</td>
<td>.60 atm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Total material density</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Beryllium: 1858 kg/m³ Ablator: 450 kg/m³</td>
<td></td>
</tr>
</tbody>
</table>

INSTRUMENTATION:
• Forebody: 2 beryllium heat transfer gauges, 2 heat shield plugs in the ablator and pressure gauge in beryllium cap
• Afterbody: Thermocouple in low-density ablator (SLA-220) located slightly aft of shoulder

NOTES:
• Nose: Beryllium heatsink
• Conical frustrum: ESA 3560 ablator

REFERENCES:

Data Collected by: M. Tauber
### Mission: Viking Lander 1

**Planet:** Mars  
**Launch:** Aug 20, 1975  
**Entry:** Jul 20, 1976

**Mission Description:**
To characterize the structure and composition of the atmosphere and surface of Mars

**Data Collected by:** M. Tauber and G. Allen

<table>
<thead>
<tr>
<th>Trajectory</th>
<th>Geometry</th>
<th>Aero/thermal</th>
<th>TPS</th>
</tr>
</thead>
</table>
| Entry angle | Inertial  
\(\approx 16.90^\circ\) | Shape | 70° sphere-cone | Trim L/D (specify trim \(c\)) | \(\approx 11.1^\circ\) | Material designation | SLA561-V |
| Inertial entry velocity | 4.61 km/s | Nose radius | 0.88 m | Ballistic coeff. | At peak heat flux: 63.0 kg/m² | Thickness | Variable: max 1.38 cm |
| Relative entry velocity | 4.42 km/s | Base area | 9.65 m² | Stagnation heating rate | Peak: 21.02 W/cm² | Ablating? Ejected? | Ablating |

**Velocity at peak heat**  
\(4.02 \text{ km/s} \)  
Vehicle mass  
\(980 \text{ kg} \)  
Integrated heat load  
\(\approx 1100 \text{ J/cm}^2 \)  
Resin mat.  
Matrix mat.  
Resin

**Control method, e.g. flag deflection**  
3-axis RCS  
TPS mass fraction, inc. insul.  
2.8%  
Radiative heat flux  
0  
Resin dens.  
Matrix dens.  
185 kg/m³  
48 kg/m³

**Center of Gravity, \(X_{c/D} \)**  
.219  
(Ref. 3)  
Payload mass  
PH stag. pressure  
.06 atm  
Total material density  
233 kg/m³

**Instrumentation:**
- The forebody aeroshell was not instrumented, but the wake enclosure (backshell) had thermocouples.
- There was one pressure port off stagnation point and one on the base cover.
- Temperature gauges were on the back face and on both back-shell frustums.

**Notes:**
- Resin Material: silicone elastomer with glass microspheres and cork
- Matrix material: fiberglass-phenolic honeycomb
- RCS was used to maintain trim angle of attack

**References:**

---

### Mission: Mars Exploration Rovers

**“Spirit” and “Opportunity”**
**Planet:** Mars  
**Launch:** Jun 10, 2003 & Jul 7, 2003  
**Entry:** Jan 3, 2004 & Jan 24, 2004

**Mission Description:**
To place two rovers (A and B) on Mars to conduct remote geological investigations including search for past water activity

**Data Collected by:** M. Loomis

<table>
<thead>
<tr>
<th>Trajectory</th>
<th>Geometry</th>
<th>Aero/thermal</th>
<th>TPS</th>
</tr>
</thead>
</table>
| Entry angle | -11.5° @ 125 km | Shape | 70° sphere-cone | Trim L/D (specify trim \(c\)) | 0 | Material designation | SLA-561V  
(SLA-561S for backshell) |
| Inertial entry velocity | Nose radius | 0.66 m | Ballistic coeff. | 88 kg/m² | Thickness | 1.57 cm |
| Relative entry velocity | 5.55 km/s | Base area | 5.52 m² | Stagnation heating rate | 44 W/cm² | Ablating? Ejected? | Yes |

**Velocity at peak heat**  
\(4.93 \text{ km/s} \)  
Vehicle mass  
\(836 \text{ kg} \)  
Integrated heat load  
\(3687 \text{ J/cm}^2 \)  
Resin mat.  
Matrix mat.  
Resin

**Control method**  
Ballistic  
TPS mass fraction, inc. insul.  
3.6% fore body; 2% back shell  
Radiative heat flux  
-0  
Resin dens.  
Matrix density

**Center of Gravity, \(X_{c/D} \)**  
0.30  
Payload mass  
PH stag. pressure  
0.06 atm  
Total material density  
256 kg/m³

**Instrumentation:**

**Notes:**
- MER A and MER B are two separate missions, each carrying a rover to Mars. Data here are for MER B, the most severe entry environment.
- This mission uses an entry aeroshell similar to that of Pathfinder, however the enclosed rovers are larger than Sojourner and are self-contained.
- There are 3 TIRS (Transverse Impulse Rocket System) covers made of SIRCA spaced around the backshell.

**References:**
MISSION: BEAGLE 2  
PLANET: MARS  
LAUNCH: Jun 2, 2003  
ENTRY: Dec 25, 2003  
MISSION DESCRIPTION:  
To develop a low-cost low-mass system for placing an exobiology science payload on Mars  

Data Collected by: A. Smith  

INSTRUMENTATION:  
- No TPS instrumentation: axial accelerometers only  

NOTES:  
- Image (all rights reserved Beagle 2) is an impression of Beagle 2 post separation from Mars Express.  
- Beagle 2 landed on Mars but did not make radio contact.  

REFERENCES:  

MISSION: VIKING LANDER 2  
PLANET: MARS  
LAUNCH: Sep 9, 1975  
ENTRY: Sep 3, 1976  
MISSION DESCRIPTION:  
To characterize the structure and composition of the atmosphere and surface of Mars  

Data Collected by: M. Tauber and G. Allen  

INSTRUMENTATION:  
- The forebody aeroshell was not instrumented, but the wake enclosure (backshell) had thermocouples.  
- There was one pressure port off stagnation point and one on the base cover.  
- Temperature gauges were on the back face and on both back-shell frustums.  

NOTES:  
- Resin Material: silicone elastomer with glass microspheres and cork  
- Matrix material: fiberglass-phenolic honeycomb  
- RCS was used to maintain trim angle of attack  

REFERENCES:  
### HAYABUSA MISSION

**MISSON:** HAYABUSA  
**PLANET:** EARTH RETURN  
**LAUNCH:** May 9, 2003  
**ENTRY:** Jun 20, 2007  

**MISSION DESCRIPTION:** To collect samples from asteroid Itokawa (1998SF36) and return to Earth.

#### INSTRUMENTATION:
- A one-axis accelerometer for parachute deployment.

#### REFERENCES:

#### NOTES:
- The mission name was changed from MUSES-C to HAYABUSA.

---

### PIONEER-VENUS MISSION

**MISSION:** PIONEER-VENUS SMALL "NORTH PROBE"  
**PLANET:** VENUS  
**LAUNCH:** Aug 8, 1978  
**ENTRY:** Dec 9, 1978  

**MISSION DESCRIPTION:** A 60° N day entry to map atmosphere, including characterizing wind and turbulence.

#### INSTRUMENTATION:
- Thermocouples: one at 17° off stagnation point (0.41 cm below heat-shield surface); another on conical frustrum ahead of shoulder (0.30 cm below heat-shield surface) at R_n=2.2

#### REFERENCES:

#### NOTES:
- Heating rates and loads are probably for non-ablating conditions.

---

### Table and Diagram

<table>
<thead>
<tr>
<th>Trajectory</th>
<th>Geometry</th>
<th>Aero/thermal</th>
<th>TPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entry angle</td>
<td>11.5°</td>
<td>18°</td>
<td>3.0°</td>
</tr>
<tr>
<td>Mass</td>
<td>1.4 kg</td>
<td>10° 2°</td>
<td>1° 1°</td>
</tr>
<tr>
<td>Diameter</td>
<td>0.4 m</td>
<td>0.4 m</td>
<td>0.4 m</td>
</tr>
<tr>
<td>Base area</td>
<td>Same</td>
<td>Vehicle mass</td>
<td>Heat shield mass</td>
</tr>
<tr>
<td>Vehicle mass</td>
<td>1.8 kg</td>
<td>1.8 kg</td>
<td>1.8 kg</td>
</tr>
<tr>
<td>Heat shield mass</td>
<td>0.2 kg</td>
<td>0.2 kg</td>
<td>0.2 kg</td>
</tr>
</tbody>
</table>

---

### Notes
1. Data Collected by: C. Park
2. The mission name was changed from MUSES-C to PIONEER-VENUS SMALL "NORTH PROBE"
MISSION: **GENESIS**  
PLANET: **EARTH RETURN**  
**Launch:** Aug 8, 2001  
**Entry:** Sep 8, 2004  

**Mission Description:**  
To collect solar wind particles and return to Earth

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### Mission: Pioneer-Venus Small “Night Probe”  
PLANET: **VENUS**  
**Launch:** Aug 8, 1978  
**Entry:** Dec 9, 1978  

**Mission Description:**  
To map the atmosphere, including temperature and pressure, from a night side entry

---

**Entry angle** | 8° | Shape | 59.81° blunt cone | Trim L/D (specify trim ci) | 0 | Material designation | Fore: Carbon-carbon  
Aft: SLA-561V

**Inertial entry velocity** | 11.0 km/s | Nose radius | 0.43 m | Ballistic coeff. | 80 kg/m³ | Thickness | 6 cm

**Relative entry velocity** | 10.8 km/s | Base area | 1.78 m² | Stagnation heating rate | 700 W/cm² | Ablating? Ejected? | Partially No

**Velocity at peak heat** | 9.2 km/s | Vehicle mass | 210 kg | Integrated heat load | 16,600 J/cm² | Resin mat. Matrix mat.

**Control method** | Spin-stabilized aero-ballistic | TPS mass fraction, inc. insul. | ~18% | Radiative heat flux | 30 W/cm² | Resin dens. Matrix density

**Center of Gravity, Xc/D** | 0.3 | Payload mass | PH stag. pressure | Total material density

---

### Trajectory

| Entry angle | 41.5° at 200 km | Shape | Blunt-nosed, 45° half-cone angle | Trim L/D (specify trim ci) | 0 | Material designation | Carbon-phenolic

**Inertial entry velocity** | 11.54 km/s | Nose radius | 0.19 m | Ballistic coeff. | 190 kg/m³ | Thickness | 1.2 cm at stagnation point

**Relative entry velocity** | Same | Base area | 0.46 m² | Stagnation heating rate | 5500 W/cm² | Ablating? Ejected? | Yes

**Velocity at peak heat** | 10.40 km/s | Vehicle mass | 91 kg | Integrated heat load | At stag. pt, 12,500 J/cm² | Resin mat. Matrix mat. 89.8% Carbon 2.8% Hydrogen 6.9% Oxygen

**Control method** | Ballistic | TPS mass fraction, inc. insul. | 12.9% | Radiative heat flux | 2300 W/cm² | Resin dens. Matrix density

**Center of Gravity, Xc/D** | 0.40 | Payload mass | 3.60 kg | PH stag. pressure | 6.30 atm | Total material density | 1490 kg/m²

---

**Instrumentation:**
- Thermosensitive paint strips

**Notes:**
- The capsule crashed violently into the desert after failing to deploy the drag devices.  
- Despite this mishap, many of the collectors remained intact and most of the mission goals should be accomplished.

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### References:

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**MISSION: **PIONEER-VENUS**  
**PLANET: **VENUS**  
**Launch:** Aug 8, 1978  
**Entry:** Dec 9, 1978  

**Mission Description:**  
To map the atmosphere, including temperature and pressure, from a night side entry

---

### Mission: Pioneer-Venus Small “Night Probe”  
PLANET: **VENUS**  
**Launch:** Aug 8, 1978  
**Entry:** Dec 9, 1978  

**Mission Description:**  
To map the atmosphere, including temperature and pressure, from a night side entry

---

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Aft: SLA-561V

**Inertial entry velocity** | 11.0 km/s | Nose radius | 0.43 m | Ballistic coeff. | 80 kg/m³ | Thickness | 6 cm

**Relative entry velocity** | 10.8 km/s | Base area | 1.78 m² | Stagnation heating rate | 700 W/cm² | Ablating? Ejected? | Partially No

**Velocity at peak heat** | 9.2 km/s | Vehicle mass | 210 kg | Integrated heat load | 16,600 J/cm² | Resin mat. Matrix mat.

**Control method** | Spin-stabilized aero-ballistic | TPS mass fraction, inc. insul. | ~18% | Radiative heat flux | 30 W/cm² | Resin dens. Matrix density

**Center of Gravity, Xc/D** | 0.3 | Payload mass | PH stag. pressure | Total material density

---

### Trajectory

| Entry angle | 41.5° at 200 km | Shape | Blunt-nosed, 45° half-cone angle | Trim L/D (specify trim ci) | 0 | Material designation | Carbon-phenolic

**Inertial entry velocity** | 11.54 km/s | Nose radius | 0.19 m | Ballistic coeff. | 190 kg/m³ | Thickness | 1.2 cm at stagnation point

**Relative entry velocity** | Same | Base area | 0.46 m² | Stagnation heating rate | 5500 W/cm² | Ablating? Ejected? | Yes

**Velocity at peak heat** | 10.40 km/s | Vehicle mass | 91 kg | Integrated heat load | At stag. pt, 12,500 J/cm² | Resin mat. Matrix mat. 89.8% Carbon 2.8% Hydrogen 6.9% Oxygen

**Control method** | Ballistic | TPS mass fraction, inc. insul. | 12.9% | Radiative heat flux | 2300 W/cm² | Resin dens. Matrix density

**Center of Gravity, Xc/D** | 0.40 | Payload mass | 3.60 kg | PH stag. pressure | 6.30 atm | Total material density | 1490 kg/m²

---

**Instrumentation:**
- Thermocouples: one at 17° off stagnation point (0.41 cm below heat-shield surface); another on conical frustum ahead of shoulder (0.30 cm below heat-shield surface) at s/Rn=2.2

**Notes:**
- Heating rates and loads are probably for non-ablating conditions.

---

### References:
MISSION: PIONEER-VENUS
SMALL “DAY PROBE”
PLANET: VENUS
LAUNCH: AUG 8, 1978
ENTRY: DEC 9, 1978
MISSION DESCRIPTION:
To map the atmosphere, including radiative energy, from a day side entry

INSTRUMENTATION:
- Thermocouples: one at 17° off stagnation point (0.41 cm below heat-shield surface); another on conical frustum ahead of shoulder (0.30 cm below heat-shield surface) at s/R_n=2.2

NOTES:
- Heating rates and loads are probably for non-ablating conditions.

REFERENCES:

Data Collected by: M. Tauber and G. Allen

MISSION: STARDUST
PLANET: EARTH RETURN
LAUNCH: FEB 7, 1999
ENTRY: JAN 15, 2006
MISSION DESCRIPTION:
To collect comet material from Wild 2 and return to Earth

INSTRUMENTATION:

NOTES:
- The Stardust capsule made a successful return to Earth on Jan 15, 2006.

REFERENCES:

Data Collected by: M. Tauber
MISSION: **PIONEER-VENUS**  
PLANET: **VENUS**  
LAUNCH: Aug 8, 1978  
ENTRY: Dec 9, 1978  

**Mission Description:**  
This probe contained 7 experiments, including one to measure the atmospheric composition.

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MISSION: **DEEP SPACE 2**  
PLANET: **MARS**  
LAUNCH: Jan 3, 1999  
ENTRY: Dec 3, 1999  

**Mission Description:**  
To penetrate the Martian surface with two small probes.

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**Instrumentation:**

- Thermocouples: one at the stagnation point (0.41 cm below heat-shield surface); another on conical frustum ahead of shoulder (0.30 cm below heat-shield surface) at \( s/R_n = 2.2 \)

**Notes:**
- Heating rates and loads are probably for non-ablating conditions.

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**References:**


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**Data Collected by:** M. Murbach and M. Tauber
MISSION: GALILEO
PLANET: JUPITER
LAUNCH: Oct 18, 1989
ENTRY: Dec 7, 1995
MISSION DESCRIPTION: To descend into the Jovian atmosphere, collect atmospheric data and relay to the orbiter.

<table>
<thead>
<tr>
<th>Trajectory</th>
<th>Geometry</th>
<th>Aero/thermal</th>
<th>TPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entry angle</td>
<td>Inertial: -6.64°, Rel: -8.5°, @ 450 km</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nose radius</td>
<td>0.222 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ballistic coeff. at entry</td>
<td>256 kg/m²</td>
<td>Thickness</td>
<td>14.6 cm at stagnation</td>
</tr>
<tr>
<td>Velocity at peak heat (relative)</td>
<td>39.0 km/s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vehicle mass at entry</td>
<td>335 kg</td>
<td>Integrated heat load</td>
<td>200,000 J/cm² with ablation</td>
</tr>
<tr>
<td>Radiative heat flux (stagnation)</td>
<td>17,000 W/cm²</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control method</td>
<td>Ballistic</td>
<td>TPS mass fraction, inc. insul.</td>
<td>Forebody: 45.4%, Afterbody: 5%</td>
</tr>
<tr>
<td>Center of Gravity, Xc/D</td>
<td>0.447</td>
<td>Payload mass</td>
<td>Science 8.3%</td>
</tr>
<tr>
<td>Peak Heat stag. pressure</td>
<td>7.3 atm</td>
<td>Total material density</td>
<td>1450 kg/m³</td>
</tr>
</tbody>
</table>

INSTRUMENTATION:
- Forebody TPS: ablation recession gauges
- Afterbody TPS: thermocouples in the nylon phenolic

NOTES:
- Reported CG estimates varied widely.

REFERENCES:

MISSION: ARD
“Atmospheric Reentry Demonstrator”
PLANET: EARTH
LAUNCH: Oct 21, 1998
ENTRY: Oct 21, 1998
MISSION DESCRIPTION: To undertake a complete space flight cycle for ESA, with emphasis on reentry technologies.

<table>
<thead>
<tr>
<th>Trajectory</th>
<th>Geometry</th>
<th>Aero/thermal</th>
<th>TPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entry angle</td>
<td>-2.6°</td>
<td>Shape</td>
<td>Apollo-like capsule, 33° cone</td>
</tr>
<tr>
<td>Nose radius</td>
<td>3.36 m</td>
<td>Ballistic coeff.</td>
<td>403 kg/m²</td>
</tr>
<tr>
<td>Radiative heat flux</td>
<td>17,000 W/cm²</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control method</td>
<td>RCS: 7 thrusters</td>
<td>TPS mass fraction, inc. insul.</td>
<td>23% (626 kg TPS)</td>
</tr>
<tr>
<td>Center of Gravity, Xc/D</td>
<td>0.256</td>
<td>Payload mass</td>
<td>No payload</td>
</tr>
<tr>
<td>Peak Heat stag. pressure</td>
<td>110 W/cm²</td>
<td>Total material density</td>
<td>88 atm</td>
</tr>
<tr>
<td>Material designation</td>
<td>Fore: Aleastril tiles. Aft: Norcoat 622-50F1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Material designation</td>
<td>19mm Alcatralsil 40-65 mm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

INSTRUMENTATION:
- The capsule afterbody was instrumented with 7 surface pressure sensors, 2 thermal plugs with 2 thermocouples each on the back cover, and 4 surface-mounted copper calorimeters on the cylindrical section.
- The front cone contained 18 pressure sensors, 14 thermal plugs with 3 or 5 TC each.

NOTES:
- Aleastril: silica fibers with phenolic resin; Norcoat: cork powder and phenolic resin.
- 4 experimental Ceramic Matrix Composite (CMC) tiles and samples of Flexible External Insulation (FEI)

REFERENCES:
<table>
<thead>
<tr>
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<th>Geometry</th>
<th>Aero/thermal</th>
<th>TPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entry angle</td>
<td>Relative $\theta$</td>
<td>Shape</td>
<td>$\frac{D}{L}$</td>
</tr>
<tr>
<td>Entry angle</td>
<td>Inertial</td>
<td>Nose radius</td>
<td>Base area</td>
</tr>
<tr>
<td>Entry velocity</td>
<td>Inertial</td>
<td>1270 km</td>
<td>345-375 (\text{km}^2)</td>
</tr>
<tr>
<td>Relative entry velocity</td>
<td>Vehicle</td>
<td>6.0 km/s at 1270 km</td>
<td>318 kg</td>
</tr>
<tr>
<td>Velocity at peak heat</td>
<td>Control</td>
<td>2586 m/s</td>
<td>0.64 kg</td>
</tr>
<tr>
<td>Control method</td>
<td>Center of gravity</td>
<td>0.244</td>
<td>200 kg (\text{m}^2)</td>
</tr>
</tbody>
</table>

**NOTES:**
- RCS was used to maintain a trim angle of attack of zero.
### MISSION: PATHFINDER

**"SOJOURNER"**

**PLANET:** MARS

**Launch:** Dec 4, 1996

**Entry:** Jul 4, 1997

**Mission Description:**
To demonstrate a simple, low-cost system for placing a science payload on the surface of Mars

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#### INSTRUMENTATION:
- TPS instrumented with thermocouples only

#### NOTES:
- Spin stabilized

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#### REFERENCES:

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### MISSION: MIRKA

**PLANET:** EARTH

**Launch:** Oct 9, 1997

**Entry:** Oct 23, 1997

**Mission Description:**
To qualify a re-entry heat-shield concept with scientific and engineering experiments conducted by German researchers

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#### INSTRUMENTATION:
- 3 acceleration sensors, 3 angular rate sensors, 24 thermocouples, RAFLEX (pressure, temperature & heat flux sensors) and PYREX (pyrometric temperature measurements)

#### NOTES:
- CFRP: Carbon Fiber Reinforced Plastics
- SPA: Surface Protected Ablator
- This was the first successful Western European re-entry mission.

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#### REFERENCES: