**Introduction**

- **PEP**: Planetary entry probes
- On request of SRE-PA
- Assess the feasibility and preliminary design of entry and descent probes to investigate the characteristics of Planetary atmospheres of:
  - Venus
  - Saturn
  - Uranus
  - Neptune
- In preparation of the next Cosmic Vision call
- Sixteen sessions (14 April – 30 June)
- Today is the Internal Final Presentation (IFP)
  - This is also a final iteration to verify each other’s results
  - Science issues should be discussed off-line
**Study objectives**

- Assess the feasibility and preliminary design of entry and descent probes to investigate the characteristics of Planetary atmospheres of:
  - Venus
  - Saturn
  - Uranus
  - Neptune
- Enhance the ESA knowledge of entry and descent conditions at these planets
- Provide the Scientific community with a starting point for future mission proposals
- Allow ESA technical preparation for better evaluation of future mission proposals related to this study
- Produce an overview of the entry conditions and required technologies for all relevant target in our Solar System

**Study flow**

- First six sessions were dedicated to a Venus entry probe
- Remaining sessions to Outer planets
- The JEP CDF study on JEP was often taken as a starting point
  - Though finally, many changes were made w.r.t. JEP
- Report layout will correspond to study flow
  - Three parts: Venus, Outer Planets, and synthesis
  - Synthesis will also be compiled separately for attachment to the Call for Proposals
Agenda

• 9:30 – 13:00: systems, mission, aerothermodynamics, thermal, EDS
• 13:00-14:00: lunch break
• 14:00-17:00: payload, configuration, structures, mechanisms, GNC, power, comms, DHS, GS & Ops, Programmatics, risk, cost
**PEP**
**Planetary Entry Probes**

*Systems*

IFP
ESTEC, 30th June 2010

Prepared by the PEP/ CDF* Team

(*') ESTEC Concurrent Design Facility

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**Focus of PEP CDF Study**

- Definition of entry conditions and required technologies for the investigated planets
- Preliminary design of the probe with a focus on the Entry and Descent System (EDS), for an overall probe mass of ~300kg (ref. JEP CDF Study)
- Parametric approach (as far as possible)
- Identification of system design commonalities, similarities and differences between the four planets
### MISSION REQUIREMENTS

<table>
<thead>
<tr>
<th>SR-1</th>
<th>Mission launch timeframe 2020-2035.</th>
</tr>
</thead>
<tbody>
<tr>
<td>SR-2</td>
<td>Launcher shall be Soyuz-Fregat 2-1b from Kourou (baseline), Ariane 5 ECA (backup).</td>
</tr>
<tr>
<td>SR-3</td>
<td>The mission design shall be composed of a carrier and a Planetary Entry Probe (PEP)</td>
</tr>
<tr>
<td>SR-4</td>
<td>The PEP shall perform a direct entry.</td>
</tr>
<tr>
<td>SR-5</td>
<td>The carrier shall perform a deflection maneuver to have a fly-by trajectory and achieve a telecom relay function.</td>
</tr>
<tr>
<td>SR-6</td>
<td>During entry and descent, the apparent carrier elevation will be at least deg (TBC) with respect to the local horizon to optimise the communication budget.</td>
</tr>
<tr>
<td>SR-7</td>
<td>During entry and descent, the carrier to PEP range shall not exceed km (TBC) to optimise the communication budget.</td>
</tr>
<tr>
<td>SR-8</td>
<td>The time between probe separation and entry date shall be minimised to keep the FPA error as low as possible and in any case lower than TBD deg.</td>
</tr>
<tr>
<td>SR-9</td>
<td>Mission design shall allow the PEP to perform entry in the planet atmosphere at near equatorial latitude (baseline) or up to TBD deg latitude (option). This requirement is not applicable to Uranus due to its tilted polar axis. Specific entry trajectories</td>
</tr>
<tr>
<td>SR-10</td>
<td>The PEP shall perform an entry followed by a parachute phase.</td>
</tr>
<tr>
<td>SR-11</td>
<td>The probe shall operate down to an altitude corresponding to at least 30 bars and up to 100 bars pressure.</td>
</tr>
<tr>
<td>SR-12</td>
<td>The PEP data shall be transmitted in real time to the carrier, which shall serve as a relay to the Earth.</td>
</tr>
<tr>
<td>SR-13</td>
<td>The PEP coast phase and entry should occur in visibility from Earth (TBC).</td>
</tr>
<tr>
<td>SR-14</td>
<td>If mass margins are sufficient, the mission shall achieve 2 probes release.</td>
</tr>
</tbody>
</table>
SR-15 The PEP mass shall be minimised (reference mass envelope taken from the Jupiter Entry Probe CDF design ~ 300 kg).
SR-16 The ballistic coefficient of the PEP shall be in the range (TBD).
SR-17 The PEP half cone angle shall be set to 45 deg as a starting point.
SR-18 The PEP shall be compatible with the payload interface requirements as defined in the payload requirements section.
SR-19 The PEP shall carry, in addition to science payload, flight instrumentation to validate aerothermodynamic and ablation models.
SR-20 For the design of the PEP the following mass margins shall be used:
- Conventional maturity margins for all sub-systems, between 5 and 20% depending on the level of maturity to be agreed with the Agency
- A system margin of 20% on top of all PEP equipments, except for the heat shield material (back and forward)
- The heat shield mass will be computed using the aerothermodynamics data including their margins and based on a PEP mass including margins (and heat shield mass).
- A 50% maturity margin shall be added to the mass of the heat shield material computed as mentioned above if the current TRL is lower than 5.
SR-21 The PEP shall be uncontrolled and unguided after release.

EDS REQUIREMENTS
SR-22 The PEP entry and descent system (EDS) shall be composed of a front shield, a back cover (both being jettisoned after the entry phase), a parachute system (deployed at the end of the entry phase) composed by one or two parachutes (possibly featuring a pilot chute).
SR-23 The PEP shall accommodate and operate the payload and the avionics and power subsystems in a descent module compatible with the atmospheric conditions down to 100 bars (target) / 30 bars (threshold).

COMMUNICATION REQUIREMENTS
SR-24 The PEP communication subsystem shall transmit periodically a minimum telemetry set of critical parameters to the carrier during the coast phase.
SR-25 The PEP communication subsystem shall maintain a communication link with the carrier during entry and descent (except during RF blackout) and shall relay in real time the flight and payload measurements data.
SR-26 RF carrier recovery and Doppler tracking shall be performed from Earth after separation.

VENUS SPECIFIC REQUIREMENTS
SR-30 The Venus PEP analyses shall consider 2 scenarios: one scenario where the PEP is released as a piggyback during a GAM of a larger mission, Laplace mission shall be considered as a reference), and one scenario featuring a stand alone mission as for outer planets.
SR-31 Note: DTE refers to science payload and Probe telemetry data, but it not to RF carrier recovery and Doppler tracking from Earth, which is specified in any case, provided in visibility from Earth.
SR-32 In the case of a DTE link, no deflection manoeuvre nor relay function shall be considered for the carrier.
SR-33 The Venus PEP shall be sized to sustain the surface pressure of 92 bars (but no landing system shall be analysed).
SR-34 The Venus PEP shall operate down to the surface.
SR-35 As an option, the feasibility of releasing the parachute before reaching the surface (in order to accelerate the final descent phase) shall be analysed, including analyses of the descent module stability.
Geometry

Geometry of the Probe

Internal Sphere (DM) diam: 650 mm

Pioneer Venus Aerodynamic Parameters

• Pioneer Venus
  - CoG/diam = 580,000/1420 = 0.410
• PEP Venus
  - CoG/diam = 456,418/1250 = 0.365

CoG properly placed from stability point of view (ref. Pioneer Venus).

Outer planets:
TPS thickness increase improve the stability
**Margin Philosophy**

*PEP - Assessment Study*

**System - 9**

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**Margin Philosophy for TPS Sizing**

**Venus:**
- Correlations for Heat Fluxes available (Pioneer Venus) -> low margin on the Heat Fluxes
- Blockage impact on Heat Fluxes in Pioneer Venus shown in vfg 29-30
- Not taking margin on heat fluxes and not considering Blockage is a Conservative Approach

**Outer planets:**
- No Correlations for Heat Fluxes (100% margin)
  - ~ 10 MW/m² (wo margin) Max Heat Fluxes -> Blockage ~ 0.4-0.5 (max). Average is lower, 80% fluxes pass through TPS
  - Blockage ~ 20%
**Design Process**

PEP - Assessment Study

BALLISTIC COEFFICIENT Assumption based on:
- **VENUS**: Mass and Dimensions from JEP Design refined for PEP Venus, including accommodation of PEP/PL and anticipating TPS
- **OUTER PLANETS**: Mass of 300kg (JEPI) and dimensions coming from PEP/Venus design
PEP – Planetary Entry Probes

**Venus**
- FPA = 35 deg
- OPTION 1
- Descent Time 60 min
- Mach 1.5
- Optimum FPA

**Saturn**
- FPA = 35 deg
- OPTION 2
- Descent Time 90 min
- Mach 1.5
- Optimum FPA

**Uranus**
- FPA = 45 deg
- Descent Time 50 min
- Mach 1.5
- Optimum FPA

**Neptune**
- FPA = 35 deg
- Descent Time 50 min
- Mach 1.5
- Optimum FPA

**Optimum FPA**, minimizing:
- Heat Fluxes
- Max Deceleration
- Descent Time

**Rationale for descent time selection and constraints**
- Descent Time Options
- Selection based on environmental and operational constraints.

**Descent Strategy**
- Parachutes
- Mach at Parachute Opening

**PEP** - Assessment Study
## Assumptions

<table>
<thead>
<tr>
<th>AREA</th>
<th>ASSUMPTION ITEM</th>
<th>VALUE</th>
<th>UNIT</th>
<th>REMARKS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometry</td>
<td>Front Shield Cone Angle</td>
<td>45</td>
<td>deg</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Nose Radius</td>
<td>0.256</td>
<td>m</td>
<td>JEP ref.</td>
</tr>
<tr>
<td>Comms</td>
<td>Telecommand Capability during Coasting</td>
<td>No</td>
<td></td>
<td>Ref. vfg 35</td>
</tr>
<tr>
<td></td>
<td>Frequency Band</td>
<td>UHF</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Comms Duration during Coasting</td>
<td>1</td>
<td>hour</td>
<td>(6 slots of 10 min)</td>
</tr>
<tr>
<td>Aerothermodynamics</td>
<td>Mach at Parachute Opening</td>
<td>M = 2 Venus</td>
<td></td>
<td>Due to Scientific Requirements</td>
</tr>
<tr>
<td></td>
<td></td>
<td>M = 1 Outer Planets</td>
<td></td>
<td>Better Scenario for Parachute Opening</td>
</tr>
<tr>
<td>Margin Philosophy</td>
<td>TPS sizing</td>
<td>50</td>
<td>%</td>
<td>Thickness Margin</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20</td>
<td>%</td>
<td>Maturity Margin</td>
</tr>
<tr>
<td></td>
<td>Heat Flux Margin</td>
<td>0</td>
<td>%</td>
<td>Venus</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100</td>
<td>%</td>
<td>Outer Planets</td>
</tr>
<tr>
<td></td>
<td>Blockage</td>
<td>0</td>
<td>%</td>
<td>Venus</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20</td>
<td>%</td>
<td>Outer Planets</td>
</tr>
<tr>
<td>System Modes</td>
<td>1. Coast</td>
<td>All planets: 20 days</td>
<td>days</td>
<td>Mode 2 (Intermediate): For power subsystem</td>
</tr>
<tr>
<td></td>
<td>2. Intermediate Mode (Mode 2), including:</td>
<td>All planets: 106 s</td>
<td>s</td>
<td>sizing purposes, a + b: assumed of constant</td>
</tr>
<tr>
<td></td>
<td>a. Entry</td>
<td>Venus: 60 min</td>
<td>min</td>
<td>duration.</td>
</tr>
<tr>
<td></td>
<td>b. Parachute Deployment Sequence</td>
<td>Outer Planets: 90 min</td>
<td>min</td>
<td>The actual duration has a different value for each planet (ref vfg 18), but this has a minor impact on the design (same order of magnitude)</td>
</tr>
</tbody>
</table>

## System Trade - Offs

<table>
<thead>
<tr>
<th>AREA</th>
<th>Planet</th>
<th>REMARKS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mission Architecture</td>
<td>Dedicated Mission</td>
<td>Piggyback Mission Architecture</td>
</tr>
<tr>
<td></td>
<td>Piggyback Option, Laplace Mission Architecture</td>
<td></td>
</tr>
<tr>
<td>Mission Analysis</td>
<td>Transfer Scenarios</td>
<td>All</td>
</tr>
<tr>
<td>Coast Duration</td>
<td>Several durations investigated</td>
<td>All</td>
</tr>
<tr>
<td></td>
<td>20 days coasting has been baseline for all planets</td>
<td></td>
</tr>
<tr>
<td>Entry Conditions</td>
<td>Daylight Entry</td>
<td>All</td>
</tr>
<tr>
<td></td>
<td>Outer Planets: night entry = not in visibility from Earth</td>
<td></td>
</tr>
<tr>
<td>Earth Visibility</td>
<td>No Earth visibility</td>
<td>All</td>
</tr>
<tr>
<td>Inertial FPA</td>
<td>- 25 deg</td>
<td>Venus</td>
</tr>
<tr>
<td></td>
<td>- 50 deg</td>
<td>Venus</td>
</tr>
<tr>
<td></td>
<td>Venus</td>
<td>For all the planets an optimization of the entry inertial FPA has been performed, for Venus 2 dedicated options (FPA -25deg and FPA -50 deg) have been studied</td>
</tr>
<tr>
<td>Thermal</td>
<td>TPS Concepts and Materials</td>
<td>All</td>
</tr>
<tr>
<td></td>
<td>RHU</td>
<td>All</td>
</tr>
<tr>
<td></td>
<td>No RHU</td>
<td>Need during Coasting to be checked (later phases)</td>
</tr>
<tr>
<td>Communications</td>
<td>DTE</td>
<td>All</td>
</tr>
<tr>
<td></td>
<td>Relay Orbiter</td>
<td>Outer Planets: DTE not feasible</td>
</tr>
<tr>
<td></td>
<td>Comms during entry</td>
<td>All</td>
</tr>
<tr>
<td></td>
<td>No comms during entry</td>
<td>Flight housekeeping data can be transmitted out of the blackout period</td>
</tr>
<tr>
<td>GNC</td>
<td>IMU</td>
<td>All</td>
</tr>
<tr>
<td></td>
<td>No IMU</td>
<td></td>
</tr>
</tbody>
</table>
**System Trade – Offs (cont’d)**

<table>
<thead>
<tr>
<th>AREA</th>
<th>Main Parachute Type</th>
<th>Planet</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Parachutes</td>
<td>Main parachute</td>
<td>All</td>
<td>Drogue is needed for TPS release. Need for main is related to free fall duration of DM sphere, compared with the scientific requirements to perform measurements at a specified pressure/altitude, maintaining link with the carrier</td>
</tr>
<tr>
<td></td>
<td>No main parachute</td>
<td>All</td>
<td></td>
</tr>
</tbody>
</table>

| Main Chute Jettisoning    | No jettisoning     | Venus  | To maximize scientific measurements at interesting altitudes (68 – 45 km) |
|                           | Jettisoning at 45 km | Outer Planets | To maximize scientific measurements at interesting pressures |

| Drogue Chute Jettisoning  | No jettisoning     | Based on TPS release | Based on descent time All |
|                           | Jettisoning at given pressure (or altitude) | All |

| Parachute sizing          | Based on TPS release | All |
|                           |                      |     |

| Mach at Parachute Opening | M = 2               | M = 1 | All |

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**System Modes and Duration**

<table>
<thead>
<tr>
<th>MODE NAME</th>
<th>DESCRIPTION</th>
<th>DURATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coast</td>
<td>From probe’s release from carrier till atmosphere entry. The probe uses its own Power system and timer switches to activate automatic sequences. NO Telecommand Capability assumed.</td>
<td>20 days</td>
</tr>
<tr>
<td>Intermediate</td>
<td>From the point where the probe reaches the interface altitude to the Front Shield Release and Main Parachute Deployment (when applicable). During this phase the probe relays flight instrumentation data. A black-out is caused by a plasma sheath around the probe</td>
<td>~106.20 s</td>
</tr>
<tr>
<td>Descent</td>
<td>After the Front Heat Shield release the DM is ready to: -perform scientific measurements, -relay data (communication window allows link budget with compatible range and elevation), - survive Thermal Environment</td>
<td>~ 60 minutes VENUS (VENERA) ~ 90 minutes OUTER PLANETS</td>
</tr>
</tbody>
</table>

**ATMOSPHERE ENTRY AND PARACHUTE DEPLOYMENT/TPS RELEASE SEQUENCE**

**VENUS:**
- M = 2 at 36.8 s from atmosphere interface + 20 s for drogue opening, 30s for FS release, 2s for BC release, 20s for main opening
- BC is released at 106.20 s from atmosphere interface

**SATURN:**
- M = 1 at 76.0 s from atmosphere interface + 30 s for drogue opening and TPS release
- BC is released at t = 1625 s from atmosphere interface

**URANUS:**
- M = 1 at 65.0 s from atmosphere interface + 30 s for drogue opening and TPS release
- BC is released at t = 3260 s from atmosphere interface

**NEPTUNE:**
- M = 1 at 58.7 s from atmosphere interface + 30 s for drogue opening and TPS release
- BC is released at t = 3260 s from atmosphere interface
### Subsystem Level

**PEP - Assessment Study**

**System - 21**

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## Thermal Design - TPS

<table>
<thead>
<tr>
<th></th>
<th>Venus FPA = -25°</th>
<th>Venus FPA = -50°</th>
<th>Saturn FPA = -25°</th>
<th>Uranus FPA = -45°</th>
<th>Neptune FPA = -55°</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Thickmess</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Front Shield Ablator</td>
<td>CP 16.2mm</td>
<td>CP 8.1mm</td>
<td>CP 36.9mm</td>
<td>CP 27.9mm</td>
<td>CP 27.9mm</td>
</tr>
<tr>
<td></td>
<td>(31.6kg)</td>
<td>(15.5kg)</td>
<td>(70.6kg)</td>
<td>(53.38kg)</td>
<td>(53.38kg)</td>
</tr>
<tr>
<td></td>
<td>Narmco4028 23.4mm (64.77kg)</td>
<td>Narmco4028 13.9mm (25.83kg)</td>
<td>Narmco4028 49.5mm (94.71 kg)</td>
<td>Narmco4028 38.7 mm (74.05 kg)</td>
<td>Narmco4028 38.7 mm (74.05 kg)</td>
</tr>
<tr>
<td></td>
<td>FM5055 26.1mm (49.34)</td>
<td>FM5055 11.7mm (22.38kg)</td>
<td>FM5055 54.3mm (105.04 kg)</td>
<td>FM5055 42.3 (80.93 kg)</td>
<td>FM5055 42.3 (80.93 kg)</td>
</tr>
<tr>
<td>Front Shield C/SiC</td>
<td>2.4 mm</td>
<td>2.4 mm</td>
<td>2.4 mm</td>
<td>2.4 mm</td>
<td>2.4 mm</td>
</tr>
<tr>
<td>Back Cover Ablator</td>
<td>5 mm</td>
<td>5 mm</td>
<td>5 mm</td>
<td>5 mm</td>
<td>5 mm</td>
</tr>
<tr>
<td>Back Cover C/SiC</td>
<td>3.6 mm</td>
<td>3.6 mm</td>
<td>9 mm</td>
<td>9 mm (3.07 kg)</td>
<td>9 mm (3.07 kg)</td>
</tr>
<tr>
<td>Back Cover IFI</td>
<td>2.4 mm</td>
<td>2.4 mm</td>
<td>2.4 mm</td>
<td>2.4 mm</td>
<td>2.4 mm</td>
</tr>
</tbody>
</table>

### MASS

<table>
<thead>
<tr>
<th></th>
<th>Venus FPA = -25°</th>
<th>Venus FPA = -50°</th>
<th>Saturn FPA = -25°</th>
<th>Uranus FPA = -45°</th>
<th>Neptune FPA = -55°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front Shield C/SiC+IFI</td>
<td>8.11 kg</td>
<td>8.11 kg</td>
<td>8.11 kg</td>
<td>8.11 kg</td>
<td>8.11 kg</td>
</tr>
<tr>
<td>Back Cover C/SiC+IFI</td>
<td>7.62 kg</td>
<td>7.62 kg</td>
<td>8.62 kg</td>
<td>10.62 kg</td>
<td>10.62 kg</td>
</tr>
<tr>
<td>Total Front Shield (Ablator+C/SiC+IFI)</td>
<td>CP 16.2mm</td>
<td>CP 8.1mm</td>
<td>CP 36.9mm</td>
<td>CP 27.9mm</td>
<td>CP 27.9mm</td>
</tr>
<tr>
<td></td>
<td>Narmco4028 23.4mm (52.80kg)</td>
<td>Narmco4028 13.9mm (33.34kg)</td>
<td>Narmco4028 49.5mm (96.83kg)</td>
<td>Narmco4028 38.7 mm (74.05 kg)</td>
<td>Narmco4028 38.7 mm (74.05 kg)</td>
</tr>
<tr>
<td></td>
<td>FM5055 26.1mm (49.34)</td>
<td>FM5055 11.7mm (22.38kg)</td>
<td>FM5055 54.3mm (105.04 kg)</td>
<td>FM5055 42.3 (80.93 kg)</td>
<td>FM5055 42.3 (80.93 kg)</td>
</tr>
<tr>
<td>Total Back Cover (Ablator+C/SiC+IFI)</td>
<td>PICA-likeCP 3.6mm (8.85kg)</td>
<td>PICA-likeCP 3.6mm (8.85 kg)</td>
<td>PICA-likeCP 9mm (11.03kg)</td>
<td>PICA-likeCP 9mm (13.69kg)</td>
<td>PICA-likeCP 9mm (13.69kg)</td>
</tr>
</tbody>
</table>
**EDS Strategy & Design**

### Venus FPA = -25° A
- **Number of Parachutes:** 2 Parachutes
  - 1 drogue for TPS release
  - 1 main for descent
- **Mach at Parachute Opening:** M = 2
- **Altitude, Pressure at Parachute Opening:** 68 km, 0.11094 bar
- **Descent Timeline:** 60 minutes

### Venus FPA = -25° B
- **Number of Parachutes:** 2 Parachutes
  - 1 drogue for TPS release
  - 1 main for descent
- **Mach at Parachute Opening:** M = 2
- **Altitude, Pressure at Parachute Opening:** 68 km, 0.11094 bar
- **Descent Timeline:** 30 min at 68-45 km
- **Pressure at Parachute Jettisoning:** 0.1-0.5 bar

### Saturn FPA = -25°
- **Number of Parachutes:** 2 Parachutes
  - 1 drogue for TPS release
  - 1 main for descent
- **Mach at Parachute Opening:** M = 1
- **Altitude, Pressure at Parachute Opening:** 68 km, 0.11094 bar
- **Descent Timeline:** 30 min at 68-45 km

### Uranus FPA = -45°
- **Number of Parachutes:** 1 Parachute
  - 1 drogue for TPS release and to meet a given descent time to 10 bars
- **Mach at Parachute Opening:** M = 1
- **Altitude, Pressure at Parachute Opening:** 4 bars
- **Descent Timeline:** 60 minutes

### Neptune FPA = -35°
- **Number of Parachutes:** 1 Parachute
  - 1 drogue for TPS release
  - 1 main for descent
- **Mach at Parachute Opening:** M = 1
- **Altitude, Pressure at Parachute Opening:** 4 bars
- **Descent Timeline:** 60 minutes

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**PEP - Assessment Study**
**PEP – Subsystems Design**

**Communication**
- Telemetry Link: 200 bps during Coast; 2 kbps during descent

**Power**
- **Coast**: On: 86W; Av. 0.5W
- **Entry**: On: 53W; Av. 37W
- **Descent**: On: 416W; Av. 412W

**Payload**
- Ref. Back-up slides for detailed definition

**DHS**
- uC+SCOC3 (MTU, CDMU, uRTU, DPU) – 11.56 kg incl margins

**GNC**
- 3 Timer Units for wake up, 2 g-switch to backup timer units, 1 IMU

**Structure**
- Panel Thicknesses sized to stand 100 bar; max deceleration and max dynamic pressure impact to be further investigated

---

**Summary**

<table>
<thead>
<tr>
<th>Launch Date</th>
<th>Venus FPA = -25°</th>
<th>Venus FPA = -50°</th>
<th>Saturn FPA = -25°</th>
<th>Uranus FPA = -45°</th>
<th>Neptune FPA = -35°</th>
</tr>
</thead>
<tbody>
<tr>
<td>03/11/2020</td>
<td>-340 g</td>
<td>-360 g</td>
<td>532026 vs 542028</td>
<td>2812/29 baseline</td>
<td>2026/09/05</td>
</tr>
<tr>
<td>Transfer Time</td>
<td>0.33 years</td>
<td>8.6 – 9.78 years</td>
<td>18.5 vs 16.4 years</td>
<td>19.3 years</td>
<td></td>
</tr>
<tr>
<td>Inertial Velocity</td>
<td>11.8 km/s</td>
<td>36.0 km/s</td>
<td>21.7 km/s</td>
<td>24.7 km/s</td>
<td></td>
</tr>
<tr>
<td>Inertial FPA</td>
<td>-25° Option 1</td>
<td>-60° Option 2</td>
<td>-25°</td>
<td>-45°</td>
<td>-35°</td>
</tr>
<tr>
<td>Mach at Parachute Opening</td>
<td>M = 2</td>
<td>M = 1</td>
<td>M = 1</td>
<td>M = 1</td>
<td></td>
</tr>
<tr>
<td>Number of Parachutes</td>
<td>1 drogue for TPS Release</td>
<td>1 drogue for TPS Release</td>
<td>1 drogue sized for TPS Release and consequent free fall to 100 bar in ~1 hour</td>
<td>1 drogue sized for TPS Release and to reach 100 bars in ~1 hour</td>
<td></td>
</tr>
<tr>
<td>Parachute Strategy</td>
<td>CASE A: descent from 68 to 92 bar in 60 min</td>
<td>CASE A: descent from 68 to 92 bar in 60 min</td>
<td>CASE B: descent from 65 to 45 km in 30 min, 30 min free fall</td>
<td>1 drogue for TPS Release and consequent free fall to 100 bar in ~1 hour</td>
<td>1 drogue sized for TPS Release and to reach 100 bars in ~1 hour</td>
</tr>
<tr>
<td>Descent Time</td>
<td>60 min (driven by thermal environment)</td>
<td>90 min (driven by available communication link with the carrier (range and elevation optimization))</td>
<td>90 min (driven by available communication link with the carrier (range and elevation optimization))</td>
<td>90 min (driven by available communication link with the carrier (range and elevation optimization))</td>
<td>90 min (driven by available communication link with the carrier (range and elevation optimization))</td>
</tr>
<tr>
<td>Max Deceleration</td>
<td>~250 g</td>
<td>~360 g</td>
<td>~250 g</td>
<td>~300 g</td>
<td>~325 g</td>
</tr>
<tr>
<td>Max Heat Fluxes</td>
<td>59.3 MW/m² at 23.5 s from entry</td>
<td>53.7 MW/m² at 12.9 s from entry</td>
<td>114 MW/m² at 33.0 s from entry</td>
<td>104.04 MW/m² at 30 s from entry</td>
<td>95.08 MW/m² at 37.1 s from entry</td>
</tr>
<tr>
<td>Tot Heat Loads</td>
<td>2.11E+08 J/m²</td>
<td>1.70E+08 J/m²</td>
<td>1.88E+08 J/m²</td>
<td>7.04E+08 J/m²</td>
<td>8.18E+08 J/m²</td>
</tr>
<tr>
<td>Probe Mass</td>
<td>272.71 kg CASE A</td>
<td>254.10 kg CASE A</td>
<td>320.25 kg</td>
<td>312.37 kg</td>
<td>313.34 kg</td>
</tr>
<tr>
<td>Probe Ballistic Coeff</td>
<td>274.87 kg CASE B</td>
<td>203.42 kg CASE B</td>
<td>241.67 kg/m²</td>
<td>231.40 kg/m²</td>
<td>232.54 kg/m²</td>
</tr>
</tbody>
</table>
**Back-up Slides**

**PEP - Assessment Study**

**System - 27**

---

**TPS Mass Fraction**

<table>
<thead>
<tr>
<th>VENUS</th>
<th>VENUS (case B)</th>
<th>VENUS Option 2</th>
<th>SATURN</th>
<th>URANUS</th>
<th>NEPTUNE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal (front shield)</td>
<td>45.85 kg</td>
<td>45.85 kg</td>
<td>27.52 kg</td>
<td>93.92 kg</td>
<td>73.00 kg</td>
</tr>
<tr>
<td>Thermal (backcover)</td>
<td>10.13 kg</td>
<td>10.13 kg</td>
<td>9.86 kg</td>
<td>12.89 kg</td>
<td>15.40 kg</td>
</tr>
<tr>
<td>Launch mass</td>
<td>272.71 kg</td>
<td>274.88 kg</td>
<td>254.10 kg</td>
<td>326.25 kg</td>
<td>312.38 kg</td>
</tr>
<tr>
<td>FS Mass Fraction</td>
<td>16.81%</td>
<td>16.68%</td>
<td>10.83%</td>
<td>28.79%</td>
<td>23.73%</td>
</tr>
<tr>
<td>BC Mass Fraction</td>
<td>3.71%</td>
<td>3.69%</td>
<td>3.88%</td>
<td>3.95%</td>
<td>4.93%</td>
</tr>
<tr>
<td>TPS Mass Fraction</td>
<td>20.53%</td>
<td>20.36%</td>
<td>14.71%</td>
<td>32.74%</td>
<td>28.30%</td>
</tr>
<tr>
<td>Entry Velocity</td>
<td>11.8 km/s</td>
<td>11.8 km/s</td>
<td>11.8 km/s</td>
<td>21.7 km/s</td>
<td>24.7 km/s</td>
</tr>
<tr>
<td>FPA</td>
<td>25 deg</td>
<td>25 deg</td>
<td>50 deg</td>
<td>45 deg</td>
<td>35 deg</td>
</tr>
<tr>
<td>Ballistic Coefficient</td>
<td>202 kg/m²</td>
<td>204 kg/m²</td>
<td>188 kg/m²</td>
<td>242 kg/m²</td>
<td>231 kg/m²</td>
</tr>
</tbody>
</table>

---

<table>
<thead>
<tr>
<th>PIONEER VENUS</th>
<th>MARS Expl. Rovers</th>
<th>HUYGENS (Titan)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FS Mass Fraction</td>
<td>8.83%</td>
<td>9.60%</td>
</tr>
<tr>
<td>BC Mass Fraction</td>
<td>1.52%</td>
<td>2.00%</td>
</tr>
<tr>
<td>TPS Mass Fraction</td>
<td>10.35%</td>
<td>11.60%</td>
</tr>
<tr>
<td>Entry Velocity</td>
<td>11.54 km/s</td>
<td>5.55 km/s</td>
</tr>
<tr>
<td>FPA</td>
<td>32.4 deg</td>
<td>11.5 deg</td>
</tr>
<tr>
<td>Ballistic Coefficient</td>
<td>180 kg/m²</td>
<td>137 kg/m²</td>
</tr>
</tbody>
</table>

---

**PEP - Assessment Study**

**System - 28**
Reconstructing Pioneer-Venus entry: convective heat flux

How to estimate blockage

Park, JTHT Vol. 13,1999

Reconstructing Pioneer-Venus entry: radiative heat flux

How to estimate blockage

Park, JTHT Vol. 13,1999
**PEP Payload Definition**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
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<th></th>
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</thead>
<tbody>
<tr>
<td>ASI/MET</td>
<td>1.25</td>
<td>205x300/50x50</td>
<td>0.16</td>
<td>5900/h</td>
<td>590 compressed</td>
<td>var. cont.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MS</td>
<td>5.0</td>
<td>250x200/100</td>
<td>0.13</td>
<td>4800/h</td>
<td>(6 samples)</td>
<td>1/10'</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>480 compressed</td>
<td></td>
</tr>
<tr>
<td>Doppler Wind</td>
<td>1.5</td>
<td>150x150/118</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>cont.</td>
</tr>
<tr>
<td>Camera</td>
<td>1.2</td>
<td>100x100/200</td>
<td>1.747</td>
<td>75.5 Mb/h</td>
<td>6290 kbit comp.</td>
<td>1/10'</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Photometer</td>
<td>0.3</td>
<td>30x30/80</td>
<td>0.00026</td>
<td>16 bit/minute</td>
<td>0.96 kbit/h</td>
<td>Cont.</td>
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<tr>
<td>DPU and power conv.</td>
<td>1.0</td>
<td>50x50/100</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td><strong>Σ</strong></td>
<td>10.25</td>
<td></td>
<td>2.037</td>
<td>7360.5</td>
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</table>

**PEP Payload Accommodation Requirements**

<table>
<thead>
<tr>
<th>ACOOMMODATION REQUIREMENTS</th>
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</thead>
<tbody>
<tr>
<td>ASI/MET</td>
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<tr>
<td>Close to the center of mass</td>
</tr>
<tr>
<td>1 inlet</td>
</tr>
<tr>
<td>1 inlet</td>
</tr>
<tr>
<td>MS</td>
</tr>
<tr>
<td>2 INLETS</td>
</tr>
<tr>
<td>Doppler Wind</td>
</tr>
<tr>
<td>NONE</td>
</tr>
<tr>
<td>Camera</td>
</tr>
<tr>
<td>Downward looking, 15° field of view</td>
</tr>
<tr>
<td>Photometer</td>
</tr>
<tr>
<td>Upward looking, 30° field of view</td>
</tr>
<tr>
<td>DPU and power conv.</td>
</tr>
<tr>
<td>none</td>
</tr>
</tbody>
</table>

**PEP - Assessment Study**
**Sensitivity Analysis - Venus**

Assumption:
- error in FPA ± 1 degree
- error in ballistic coefficient ± 18.5 kg/ m²

Thickness of TPS varies with:
- 3.75 % for FPA of 25 degrees
- 3.68 % for FPA of 50 degrees.

→ TPS thickness not very sensitive to errors/variation in:

- FPA and ballistic coefficient

**COSPAR Planetary Protection Policy**

Venus, Saturn, Uranus, Neptune: Category II

- **Category II** missions comprise all types of missions to those target bodies where there is significant interest relative to the process of chemical evolution and the origin of life, but where there is only a remote chance that contamination carried by a spacecraft could jeopardize future exploration.

The requirements are for simple documentation only.

Preparation of a short planetary protection plan is required for these flight projects primarily to outline intended or potential impact targets, brief Pre- and Post-launch analyses detailing impact strategies, and a Post-encounter and End-of-Mission Report which will provide the location of impact if such an event occurs.
Telecommands link (carrier to probe) is not required.
Mission Analysis

IFP
ESTEC, 30th June 2010

Prepared by the PEP/CDF* Team

(*) ESTEC Concurrent Design Facility
Contents

• Piggy-back scenario: Laplace
• Dedicated mission:
  – Relay with the carrier
  – DTE

Piggy-back Scenario: JGO launch in 2020

• Launch date: 2020/03/11
• Vinf: 3.38 km/s
• Sequence: VEEGA (only VE represented)
• T1 type transfer to Venus
• Venus GA: 2020/07/01
• Vinf: 6.39 km/s
• Swing by altitude: 21,100 km
**Probe-Carrier Link**

- **Objective:** Max elevation and Min range after a given delay
- **Constraints:**
  - Carrier pericentre $\rightarrow$ 1 degree of freedom of the ODM
  - Elevation of 90 deg after a given delay $\rightarrow$ Along-track component of the ODM
  - Rotation of the atmosphere $\rightarrow$ 1 degree of freedom of the ODM
    $\rightarrow$ ODM fully defined
  - No degree of freedom to have the minimum range after the same delay (the larger the FPA, the larger the difference)
Range-Elevation

Relay with the Carrier

PEP - Assessment Study
Mission Analysis - 7
Mission Analysis - 8
**Sun illumination Probe to Carrier Link**

- **T2 transfers:** The entry is in daylight for all FPA.
- **T1 transfers:**
  - The entry is always in daylight for a FPA of -25 deg.
  - The entry is in daylight for a FPA of -50 deg in 2024 and 2026.
  - The entry is never in daylight for a FPA of -75 deg.

→ A low FPA is recommended.

- In order to have a probe visibility of 60 min, a minimum pericentre altitude of 5000 km is recommended.
• **T2 transfers:** The entry is in daylight and Earth visibility for all FPA
• **T1 transfers:**
  – The entry is in Earth visibility for all FPA
  – The entry is in daylight for a FPA of -25 deg
  – The entry is in daylight for a FPA of -50 deg in 2024 and 2026
  – The entry is never in daylight for a FPA of -75 deg
• An Earth elevation of 90 deg is reached for FPA between 55 and 60 deg
  → A medium FPA is recommended
Comparison

• Commonalities:
  – Transfer time
  – Distance to Earth → Carrier for relay
  – Large radius → Probe to carrier range
  – Fast atmosphere rotation → Entry conditions, modified ODM

• Specificities:
  – Saturn: rings → Adapted strategies
  – Uranus: North pole tilt (but with no impact on mission analysis)
Interplanetary transfer

<table>
<thead>
<tr>
<th>Mission Analysis</th>
</tr>
</thead>
</table>

- Typical transfers are reported (a detailed analysis of possible transfers is subject to an in-going study)
- Possibility of transfers to Uranus via Saturn not analysed, but should be feasible → Double probe
- Fast transfer: Direct Earth to Jupiter. But P/L mass very low (less than 1 ton with AR5 ECB)

### Interplanetary transfer (Cont’d)
Saturn: Entry

EIP altitude: 700 km

Saturn: Entry with FPA = -25 deg

Atmosphere rotation period: 0.44 days
Atmosphere interface velocity: 10 km/s
### Saturn rings

<table>
<thead>
<tr>
<th>Ring or Region</th>
<th>Inner Radius ($r_{in}$) [km]</th>
<th>Outer Radius ($r_{out}$) [km]</th>
<th>Half Thickness ($t_{ring}$) [km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>D Ring</td>
<td>66970</td>
<td>74470</td>
<td>1</td>
</tr>
<tr>
<td>C Ring</td>
<td>74500</td>
<td>92000</td>
<td>1</td>
</tr>
<tr>
<td>B Ring</td>
<td>92000</td>
<td>117400</td>
<td>1</td>
</tr>
<tr>
<td>Cassini Division</td>
<td>117400</td>
<td>122170</td>
<td>–</td>
</tr>
<tr>
<td>A Ring</td>
<td>122170</td>
<td>136780</td>
<td>2</td>
</tr>
<tr>
<td>F Ring</td>
<td>140180</td>
<td>140260</td>
<td>50</td>
</tr>
<tr>
<td>Jan/Ep Debris</td>
<td>149600</td>
<td>153300</td>
<td>900</td>
</tr>
<tr>
<td>G Ring</td>
<td>165000</td>
<td>176000</td>
<td>720</td>
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<tr>
<td>Mimas Debris</td>
<td>181170</td>
<td>189870</td>
<td>4800</td>
</tr>
<tr>
<td>E Ring</td>
<td>180000</td>
<td>300000</td>
<td>10000</td>
</tr>
</tbody>
</table>

### Ascending Node in the Rings

![Graph showing the ascending node in the rings with labeled regions and lines indicating the forbidden area and reference cases.](image-url)
Selection of the Pericentre Radius

- **Objective 1:**
  - Carrier first node farther than the rings or,
  - Carrier first node in the gap between the F and G rings: a la Cassini → HGA used as protection
- **Operations:**
  - Carrier pointing at the probe during descent
  - Carrier pointing at the Earth for data relay → Long enough to reach the second node!
- → **Objective 2:**
  - Carrier second node farther than the rings or,
  - Carrier second node in the gap between the F and G rings: a la Cassini → HGA used as protection
- **Objective 3:**
  - Probe first node farther than the rings or,
  - Probe first node in the gap between the F and G rings: a la Cassini

→ Impact on possible carrier pericentre radius and probe entry latitude

Case 1.1: Carrier out, Probe out
Selection of the Pericentre Radius (Cont’d)

Case 1.2: Carrier out, Probe in

Selection of the Pericentre Radius (Cont’d)

Case 2.1: Carrier in, Probe in
Selection of the Pericentre Radius (Cont’d)

Case 2.2: Carrier in, Probe out

<table>
<thead>
<tr>
<th>Probe</th>
<th>In</th>
<th>Out</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier</td>
<td>ODM=50 m/s</td>
<td>ODM=76 m/s</td>
</tr>
<tr>
<td></td>
<td>rp=1.5 Rs</td>
<td>rp=1.8 Rs</td>
</tr>
<tr>
<td>Carrier</td>
<td>ODM=65 m/s</td>
<td>ODM=90 m/s</td>
</tr>
<tr>
<td></td>
<td>rp=1.7 Rs</td>
<td>rp=2.0 Rs</td>
</tr>
</tbody>
</table>

Carrier shall be protected:

- HGA
- Dedicated shield

PEP - Assessment Study
Mission Analysis - 25

PEP - Assessment Study
Mission Analysis - 26
**Delay: 90 min**

Case 1.1: Carrier out, Probe out

- 90 min
- 60,000 km

Case 1.2: Carrier out, Probe in

- 80 min
- 50,000 km

PEP - Assessment Study

Mission Analysis - 27

PEP - Assessment Study

Mission Analysis - 28
**Delay: 90 min**

**Case 2.1: Carrier in, Probe in**

- Delay: 90 min
- Range: 30,000 km
- Angle: 80 deg

**Case 2.2: Carrier in, Probe out**

- Delay: 90 min
- Range: 40,000 km
- Angle: 90 deg
Uranus: Entry

EIP altitude: 700 km

Uranus: Entry with FPA = -45 deg

Atmosphere rotation period: 0.71 days
Atmosphere interface velocity: 2.7 km/s
**Delay: 90 min**

- Large FPA
- 130 min
- 40,000 km

**Neptune: Entry**

- EIP altitude: 600 km
Neptune: Entry with FPA = -35 deg

Atmosphere rotation period: 0.67 days
Atmosphere interface velocity: 2.7 km/s

Delay: 90 min

100 min
25,000 km

90 min
90 deg

45 deg

Carrier always above the horizon
### ODM: Operations

- Time for OD after ODM: 2 days
- Time for upload of the TCM1 and implementation: 1 day
- Time for propagation and OD after TCM1: 4 days
- Time for upload of the TCM2 and implementation: 1 day
- Time for potential safe mode: 4 days
- Time before safe mode recovery and probe entry: 4 days

→ A reasonable minimum amount of time between probe separation and probe entry is 20 days for all planets.

A larger amount of time may be needed to decrease the ODM down to an acceptable range. This should be traded against the entry accuracy

---

### Summary

<table>
<thead>
<tr>
<th>Planet</th>
<th>Venus1 (1)</th>
<th>Venus2 (1)</th>
<th>Saturn (2)</th>
<th>Uranus</th>
<th>Neptune</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inertial Velocity [km/s]</td>
<td>12</td>
<td>12</td>
<td>35.8</td>
<td>21.7</td>
<td>24.7</td>
</tr>
<tr>
<td>Atmosphere Velocity [km/s]</td>
<td>~0</td>
<td>~0</td>
<td>9.9</td>
<td>2.6</td>
<td>2.7</td>
</tr>
<tr>
<td>Entry latitude (3) [deg]</td>
<td>20</td>
<td>0</td>
<td>15</td>
<td>20</td>
<td>19</td>
</tr>
<tr>
<td>Entry longitude (3) [deg]</td>
<td>-31</td>
<td>-2</td>
<td>176</td>
<td>37</td>
<td>-3</td>
</tr>
<tr>
<td>Relative Velocity [km/s]</td>
<td>12</td>
<td>12</td>
<td>27.4</td>
<td>21.9</td>
<td>22.6</td>
</tr>
<tr>
<td>Relative FPA [deg]</td>
<td>-25</td>
<td>-50</td>
<td>-33.5</td>
<td>-44.5</td>
<td>-38.9</td>
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<tr>
<td>Velocity azimuth [deg]</td>
<td>-61</td>
<td>-55</td>
<td>79</td>
<td>179</td>
<td>83.2</td>
</tr>
<tr>
<td>ODM (4) [m/s]</td>
<td>17</td>
<td>20</td>
<td>76</td>
<td>53</td>
<td>31</td>
</tr>
<tr>
<td>Entry FPA Uncertainty [deg]</td>
<td>0.32</td>
<td>0.32</td>
<td>0.13</td>
<td>0.2</td>
<td>0.3</td>
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<tr>
<td>Entry Epoch Uncertainty [s]</td>
<td>7</td>
<td>7</td>
<td>18</td>
<td>20</td>
<td>18</td>
</tr>
</tbody>
</table>

- (1): Release from JGO S/C for a launch in 2020
- (2): Carrier outside the rings, probe inside the rings
- (3): The choice of entry point affects several parameters: day/night entry, Earth visibility, velocity/atmosphere, FPA/atmosphere. Exception for Saturn: the entry point is fixed because the probe flies through the rings
- (4): All ODM assume a separation 20 days before EIP
Scheme

- Venus
- Saturn
- Uranus
- Neptune

- Assumptions
  - Atmosphere
  - Heat flux correlations
  - Validation

- Entry phase
  - Max heat peak
  - Total heat load
  - Max dynamic pressure
  - Max deceleration

- Descent phase
  - Altitude at drogue chute opening
  - Dynamic pressure at opening
  - Size of parachute to guarantee a requested descent time
Venus

Venus Probe Entry assumption: Atmosphere

Different atmosphere available:
- Rho_min (300 – 100 km)
- Rho_ref (300 – 100 km)
- Rho_max (300 – 100 km)
- Rho_JP1998 (200 – 100 km)
- VIRA (100 – 0 km)
- ESOC (100 – 0 km)
- Seiff (200 – 0 km)
**Venus: heat flux correlations**

- Correlations for the heat fluxes: \( q = c \cdot R_n^A \cdot \rho^B \cdot V^C \)
- Different correlations for the radiative flux:
  - Florence
  - Tauber and Sutton
  - FGE \((A=0.5, B=0.5, C=9)\)
- Different correlations for the convective flux:
  - Zoby
  - Florence \((A=-0.5, B=0.5, C=3)\)

**Changing nose radius: scaling the heat fluxes**

With the chosen correlations

\[
\begin{align*}
q_{c1} &= c \cdot R_1^{-0.5} \cdot \rho^{0.5} \cdot V^3 \\
q_{c2} &= c \cdot R_2^{-0.5} \cdot \rho^{0.5} \cdot V^3
\end{align*}
\]

\[
\begin{align*}
q_{r1} &= c \cdot R_1^{0.5} \cdot \rho^{0.5} \cdot V^9 \\
q_{r2} &= c \cdot R_2^{0.5} \cdot \rho^{0.5} \cdot V^9
\end{align*}
\]

\[
\begin{align*}
q_{c1} &= q_{c2} (R_1/R_2)^{-0.5} \\
q_{r1} &= q_{r2} (R_1/R_2)^{0.5}
\end{align*}
\]
**Venus Probe Entry**

**assumption and code validation:**
reconstructing Pioneer-Venus entry

<table>
<thead>
<tr>
<th>Probe</th>
<th>Mass (base area)</th>
<th>C_d (hyp)</th>
<th>Ball coef</th>
<th>Nose radius</th>
<th>Entry point</th>
<th>Entry Vel</th>
<th>FPA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large &quot;Sounder&quot;</td>
<td>316.48</td>
<td>1.59</td>
<td>1.07</td>
<td>186</td>
<td>0.36</td>
<td>200</td>
<td>11.54</td>
</tr>
<tr>
<td>Small &quot;Day&quot;</td>
<td>91</td>
<td>0.46</td>
<td>1.07</td>
<td>185</td>
<td>0.19</td>
<td>200</td>
<td>11.54</td>
</tr>
<tr>
<td>Small &quot;Night&quot;</td>
<td>91</td>
<td>0.46</td>
<td>1.07</td>
<td>185</td>
<td>0.19</td>
<td>200</td>
<td>11.54</td>
</tr>
<tr>
<td>Small &quot;North&quot;</td>
<td>91</td>
<td>0.46</td>
<td>1.07</td>
<td>185</td>
<td>0.19</td>
<td>200</td>
<td>11.54</td>
</tr>
</tbody>
</table>

**Venus Probe Entry validation:**
reconstructing Pioneer-Venus entry

- Takahashi, AIAA 2002-0909
- Ahn, JTHT Vol. 16, No. 3, 2002
- Park, JTHT Vol. 13, 1999

**Reconstruction altitude**

**Reconstruction velocity**

**Reconstruction convective heat**

**Reconstruction radiative heat**

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**Blockage: what is it?**

![Diagram of blockage](image)

**Venus: entry and descent**

**Problem to address and constraints to fulfill**

- Max heat flux
- Total heat load
- Max deceleration
- Max dynamic pressure
- Altitude at drogue chute opening
- Dynamic pressure at drogue chute opening
- Guarantee front shield separation at drogue chute opening
- Sizing main parachute: 1 hour descent
- Free fall time (Tf) from 45 km to the surface
- Sizing main parachute: 1h-Tf for 68-45 km
Venus: a parametric analysis for the entry phase

- **Assumptions**
  - Given atmospheres: (Seiff)
  - Interface at 200 km altitude (entry conditions provided by mission analysis)
  - Shape is fixed (45 deg half angle blunted cone as Pioneer-Venus/Galileo/JEP..)
  - Cd profile of Galileo is used
  - The nose diameter is fixed (0.36m as Pioneer-Venus but can be rescaled)
  - Chosen correlations (convective flux, radiative flux)

- **Parameters**
  - Entry velocity (10, 11, 12 Km/s)
  - Parachute opening (mach = 1, mach = 2)
  - FPA (5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75)
  - (Hypersonic) ballistic coefficient (100, 150, 200, 250, 300, 350)

- **Constraints**
  - Maximal heat flux?
  - Total heat load?
  - Maximal deceleration (at parachute opening)?
  - Altitude at parachute opening?
  - Maximal dynamic (pressure at parachute opening)?

**Venus example: Entry = 11, Bc = 250, FPA = 25**

- Maximum Deceleration (200 g)
- Maximum Convective Heat flux (32 MW/m²)
- Maximum Radiative Heat flux (19 MW/m²)
- Maximum Total Heat flux (50 MW/m²)
- Total Heat load (210 MJ/m²)
**Venus: maximum deceleration**

**Venus: maximum dynamic pressure**
**Venus: maximum (total) heat flux**

![Diagram](image1)

**Venus: integrated (total) heat load**

![Diagram](image2)
**Venus: Altitude @ mach = 2**

**Venus: Dynamic pressure @ mach = 2**
Venus: feasible domain @ 10 KM/s entry

Deceleration < 450 g
Heat flux < 300 MW/m²

Ballistic coefficient
Altitude at parachute opening > 68km

Venus: feasible domain @ 11 KM/s entry

Deceleration < 450 g
Heat flux < 300 MW/m²

Ballistic coefficient
Altitude at parachute opening > 68km
**Venus: feasible domain @ 12 KM/s entry**

- Deceleration < 450 g
- Heat flux < 300 MW/m²
- Altitude at parachute opening > 68 km

**Base line:**
- $B_c = 202$
- $FPA = -25$

**Base line 2:**
- $B_c = 188$
- $FPA = 50$

**Dyn pre @ M<2 < ?**
**Heat load < 300 MJ/m²**

**Venus: parachute sizing**

- Guarantee front shield separation at drogue chute opening
- Sizing main parachute: 1 hour descent
- Free fall time ($T_f$) from 45 km to the surface
- Sizing main parachute: 1h-$T_f$ for 68-45 km
**Venus: parachute sizing for separation**

\[ B_C^{probe-TPS} \leq 0.7 B_C^{TPS} \]

\[ \frac{M^{probe} - M^{TPS}}{C_D^{drogue} \cdot A^{drogue}} + \frac{C_D^{sphere} \cdot A^{sphere}}{A^{TPS}} \leq 0.7 \frac{M^{TPS}}{C_D^{TPS} \cdot A^{TPS}} \]

\[ A^{drogue} = \frac{1}{0.7} \frac{M^{probe} - M^{TPS}}{M^{TPS}} \frac{C_D^{TPS}}{C_D^{drogue}} A^{TPS} - \frac{C_D^{sphere}}{C_D^{drogue}} A^{sphere} \]

---

**Main parachute opt 1:**

1h between Mach 2 and landing with a parachute guaranteeing \( B_c = 250 \)

Without parachute

With parachute

Descent time (with parachute)
• 1 hour available for the descent
• Free fall from 45 km with just the descent module (fixed mass and dimension) takes ≈ 30 min
• 30 min are left for the parachute to descent from 68 to 45
• Increasing the size of the parachute (decrease the ballistic coefficient) to meet the 30 min of descent
• With a parachute guaranteeing a \( B_c = 10 \) the descent takes 30 min
**Saturn atmospheric profiles**

Different atmosphere models available:
- The Planetary scientist's companion by Lodders, K. Fegley, B.
- Giant Planets of Our Solar System: An Introduction by Patrick Irwin

**Saturn assumption: heat flux correlations**

- Correlations for the heat fluxes: \( q = c \cdot R_n^A \cdot \rho^B \cdot V^C \)
- There are no correlations available in literature for Saturn (Giant planets)
- Due to the close similarity among the Giant planets and a wider literature available for Jupiter, correlations were derived by fitting available (Moss and Simmond AIAA-82-0874) Galileo heat flux data
  - Convective: \( A = -0.5 \), \( B \approx 0.43 \), \( C \approx 3 \)
  - Radiative: \( A = 1 \), \( B \approx 1.33 \), \( C \approx 6.76 \)
- Validation against Galileo data (and Saturn) has been performed
Saturn: entry and descent

Problem to address and constraints to fulfill

- Max heat flux
- Total heat load
- Max deceleration
- Max dynamic pressure
- Pressure at drogue chute opening
- Dynamic pressure at drogue chute opening
- Guarantee front shield separation at drogue chute opening
- Free fall time from 0.1 bar to 100 bar

Saturn: a parametric analysis for the entry phase

- Assumptions
  - Given atmospheres
  - Interface at 700 km altitude (entry conditions provided by mission analysis)
  - Entry velocity (36 Km/s)
  - Shape is fixed (45 deg half angle blunted cone as Pioneer-Venus/Galileo/JEP..)
  - Cd profile of Galileo is used
  - The nose diameter is fixed (0.512m)
  - Chosen correlations (convective flux, radiative flux)

- Parameters
  - Parachute opening (at Mach=1, Mach=2 ?)
  - FPA (5, 10, 15, 20, 25, 30, 35, 40, 45, 50)
  - (Hypersonic) ballistic coefficient (100, 150, 200, 250, 300)

- Constraints
  - Maximal heat flux?
  - Total heat load?
  - Maximal deceleration (at parachute opening)?
  - Pressure (altitude) at parachute opening (Mach=1, mach=2)?
  - Maximal dynamic (pressure at parachute opening)?
Saturn: maximum deceleration and dynamic pressure

Saturn: maximum heat flux
**Saturn: total heat load**

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**Saturn: Parachute opening: Mach = 1, 2?**

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Aerothermodynamics - 33

Aerothermodynamics - 34
**Saturn: feasible domain**

- Deceleration ≤ 250 g
- Heat flux ≤ 300 MW/m²
- Heat load ≤ 1200 MJ/m²
- Base line: 
  - BC = 220
  - FPA = -25

**Saturn: parachute sizing for separation**

\[
B_C^{probe-TPS} \leq 0.7 B_C^{TPS}\\
M_{probe} C_D^{drogue} A_{drogue} + M_{TPS} C_D^{TPS} A_{sphere} \leq 0.7 M_{TPS} C_D^{TPS} A_{TPS}\\
A_{drogue} = \frac{1}{0.7} \frac{M_{probe} - M_{TPS}}{M_{TPS}} C_D^{TPS} A_{TPS} - \frac{C_D^{sphere}}{C_D^{drogue}} A_{sphere}
\]

As for Venus
Saturn: Free fall from pressure = 0.1 bar

- Different entry (hypersonic) ballistic coefficients
- Different FPA
- Fixed ballistic coefficient for the descent phase (pressure vessel mass and dimensions are fixed)
Different atmosphere models available:

- The Planetary scientist's companion by Lodders, K.
- Giant Planets of Our Solar System: An Introduction by Patrick Irwin

**Uranus atmospheric profiles**

- Interface @ 700 km
- Entry phase
- Drogue chute opening
- Front shield release
- Keep parachute for front shield release “as long as possible”
- Opt 1: Drogue chute release, back cover separation, main parachute opening
- Release parachute, free fall
- “Landing”
- -300 km @ 100 bar
- Main scientific interest: 0.1-10 bar
- Reaching 100 bar

**Problem to address and constraints to fulfill**

- Max heat flux
- Total heat load
- Max deceleration
- Max dynamic pressure
- Altitude at drogue chute opening
- Dynamic pressure at drogue chute opening
- Guarantee front shield separation at drogue chute opening
- Flight time of drogue parachute
- Free fall time to 100 bar
Uranus: a parametric analysis for the entry phase

- **Assumptions**
  - Given atmospheres
  - Interface at 700 km altitude (entry conditions provided by mission analysis)
  - Entry velocity (21.7 Km/s)
  - Shape is fixed (45 deg half angle blunted cone as Pioneer-Venus/Galileo/JEP..)
  - Cd profile of Galileo is used
  - The nose diameter is fixed (0.512m)
  - Chosen correlations (convective flux, radiative flux)

- **Parameters**
  - Parachute opening (at Mach = 1, Mach = 2 ?)
  - FPA (5, 10, 15, 20, 25, 30, 35, 40, 45, 50)
  - (Hypersonic) ballistic coefficient (100, 150, 200, 250, 300)

- **Constraints**
  - Maximal heat flux?
  - Total heat load?
  - Maximal deceleration (at parachute opening)?
  - Pressure (altitude) at parachute opening (Mach = 1, mach = 2)?
  - Maximal dynamic (pressure at parachute opening)?

Uranus: maximum deceleration and dynamic pressure
Uranus: Parachute opening: Mach = 1, 2?

Mach = 1

Mach = 2

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Aerothermodynamics - 45

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Aerothermodynamics - 46

Uranus: feasible domain

Pressure at parachute opening > 0.1 bar

Deceleration < 450 g

Heat flux < 300 MW/m²

Base line:

Bc = 220

FPA = -45

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Ballistic coefficient

Aerothermodynamics - 46
Neptune atmospheric profiles

Different atmosphere models available:
- The Planetary scientist's companion by Lodders, K. Fegley, B.
- Giant Planets of Our Solar System: An Introduction by Patrick Irwin

Neptune: entry and descent

Problem to address and constraints to fulfill
- Max heat flux
- Total heat load
- Max deceleration
- Max dynamic pressure
- Altitude at drogue chute opening
- Dynamic pressure at drogue chute opening
- Guarantee front shield separation at drogue chute opening
- Increasing dimensions of drogue parachute
- Free fall time to 100 bar
Neptune: a parametric analysis for the entry phase

• Assumptions
  – Given atmospheres
  – Interface at 600 km altitude (entry conditions provided by mission analysis)
  – Entry velocity (24.7 Km/s)
  – Shape is fixed (45 deg half angle blunted cone as Pioneer-Venus/Galileo/JEP...)
  – Cd profile of Galileo is used
  – The nose diameter is fixed (0.512m)
  – Chosen correlations (convective flux, radiative flux)

• Parameters
  – Parachute opening (at Mach=1, Mach=2 ?)
  – FPA (5, 10, 15, 20, 25, 30, 35, 40, 45, 50)
  – (Hypersonic) ballistic coefficient (100, 150, 200, 250, 300)

• Constraints
  – Maximal heat flux?
  – Total heat load?
  – Maximal deceleration (at parachute opening)?
  – Pressure (altitude) at parachute opening (Mach=1, mach=2)?
  – Maximal dynamic (pressure at parachute opening)?

Neptune: maximum deceleration and dynamic pressure

![Graphs showing maximum deceleration and dynamic pressure](image-url)
Neptune: maximum heat flux

Neptune: total heat load
Neptune: Parachute opening: Mach=1,2?

Mach = 1

Mach = 2

Neptune: feasible domain

Deceleration < 450 g
Heat flux < 300 MW/m²
Pressure at parachute opening > 0.1 bar

Base line:
Bc = 220
FPA = -35

Ballistic coefficient

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Aerothermodynamics - 55

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Aerothermodynamics - 56
**Neptune: sizing the drogue parachute**

- **Entry phase**
- **Drogue chute opening**
- **Front shield release**
- **Increase area of parachute (for front shield release)**

**Main scientific interest**
- 0.1-10 bar

**Release parachute free fall**
- 3200s
- 1.5h = 5400s
- 2200s

**Open at Mach \( \equiv \) keep for 3200s a parachute with an area**

\[ A = k A_{\text{TPS release}} \]

**A = 1.8 A_{\text{TPS release}}**

---

**Extra material**
**Venus: Sizing parachute at separation**

\[
\frac{M_{\text{env}} - M_{\text{env,1}}}{\text{env}} \leq 0.7 \quad \frac{M_{\text{env,1}}}{\text{env,1}}
\]

\[
\frac{M_{\text{env}} - M_{\text{env,2}}}{\text{env}} \leq 0.7 \quad \frac{M_{\text{env,2}}}{\text{env,2}}
\]

\[
\frac{(1 - F_{\text{env}}) M_{\text{env}}}{\text{env}} \leq 0.7 \quad \frac{M_{\text{env}}}{\text{env}}
\]

\[
\beta_{\text{char}} \geq \frac{1}{\sqrt{0.7}}
\]

---

**Main parachute opt2**

---

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Aerothermodynamics - 59

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Aerothermodynamics - 60
**PEP**

**Planetary Entry Probes**

*Thermal*

IFP

ESTEC, 30th June 2010

Prepared by the PEP/ CDF* Team

(*) ESTEC Concurrent Design Facility

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**Venus**
**Assumptions and design drivers**

- Two entry cases for TPS sizing:
  - -25 deg entry angle.
  - -50 deg entry angle.
- Coast and descent analysed for case -25 deg entry angle.
- Entry and descent environments (Fluxes vs. time, atmospheric temperature vs. time) as provided by aerothermodynamics subsystem.
- Coast environment = Planet environment (no direct solar flux and albedo considered => worst cold case).
- Power dissipations vs. time as provided by Power subsystem.
- Units within -20 / +50 C (possibly -40 / +70 C).
- Three high density ablators traded-off for front shield; one low density ablator considered for back cover.
- ESATAN-Ablat and ThermXL software used for computations.

**Aerothermal fluxes and Dynamic pressure -25 deg entry**

Fluxes to be applied on front shield as from aerothermodynamics data but scaled to the probe nose radius => no margin, no blockage on fluxes.
Fluxes to be applied on back cover calculated as \( Q_{\text{tot}} = 0.025 \, Q_{\text{conv_front}} + 0.01 \, Q_{\text{rad_front}} \).
-25 deg entry

- Temperature and Altitude during entry phase

- Release of front shield and back cover once Mach 2 is reached (back cover after front shield) => this occurs at an altitude of about 69.5 km and after 37 sec from entry.

Aerothermal fluxes - 50 deg entry angle

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Considerations for TPS dimensioning

- Front shield: both aerothermal fluxes and max dynamic pressure are not in the range of applicability for low density carbon phenolic => high density carbon phenolic needs to be used.
- Back shield: both aerothermal fluxes and dynamic pressure are in the range of applicability for low density carbon phenolic => a PIC A-like material can be used.
- SEPCORE vs. Normal design traded-off; (SEPCORE baselined).
- 50% uncertainty margin to be used on thickness according to requirements plus 20% maturity margin.
- Both High density carbon phenolic and Pica-like ablators have low TRL.

<table>
<thead>
<tr>
<th>TRL Carbon phenolic</th>
<th>US</th>
<th>EU</th>
</tr>
</thead>
<tbody>
<tr>
<td>≥5 for Launchers</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;5 for Entry probes</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TRL PICA-like</th>
<th>EU</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-4 end 2010</td>
<td></td>
</tr>
</tbody>
</table>

SEPCORE design vs Normal design

- When high fluxes (above ~ 25 MW) and high dynamic pressure (above ~ 1 bar) occur high density carbon-phenolic materials need to be used.
- In the standard design one kind of material is used; part of it ablates, the rest acts as conductive insulator. Typical cold structure temperature limits are 150 – 180 C (250 C pushing the technology).
- In the SEPCORE design the ablator can be used with a reduced thickness because the hot structure underneath can sustain temperatures of up to 1100 – 1200 C. The light weight insulator (with lower thermal conductivity than high density carbon-phenolic material) at its back acts as conductive insulator permitting the cold structure to stay below 150 – 180 C (250 C pushing the technology).
- The SEPCORE design (ablator + hot structure + light weight insulator ) permits to save 20 – 30 % mass compared to the standard design if a high density carbon-phenolic material (~1400 kg/m3) has to be used even if adds complexity to the design.
- It may be convenient also when using low density carbon-phenolic materials.
### TPS dimensioning analysis results -25 deg entry

<table>
<thead>
<tr>
<th>Material Description</th>
<th>Thickness [m]</th>
<th>Area [m²]</th>
<th>Density [kg/m³]</th>
<th>Mass TPS [kg]</th>
<th>Mass of IFI+C/SiC [kg]</th>
<th>TOTmass [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PICA-Like Carbon Phenolic</td>
<td>0.0045</td>
<td>1.640</td>
<td>1400.00</td>
<td>10.50</td>
<td>0.11 5 mm IFI</td>
<td>11.81</td>
</tr>
<tr>
<td>Back Cover</td>
<td>0.002</td>
<td>1.540</td>
<td>266</td>
<td>1.23</td>
<td>7.62 5 mm IFI</td>
<td>8.85</td>
</tr>
</tbody>
</table>

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### TPS dimensioning analysis results -50 deg entry

<table>
<thead>
<tr>
<th>Material Description</th>
<th>Thickness [m]</th>
<th>Area [m²]</th>
<th>Density [kg/m³]</th>
<th>Mass TPS [kg]</th>
<th>Mass of IFI+C/SiC [kg]</th>
<th>TOTmass [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PICA-Like Carbon Phenolic</td>
<td>0.0065</td>
<td>1.640</td>
<td>1400</td>
<td>22.39</td>
<td>0.11 5 mm IFI</td>
<td>22.51</td>
</tr>
</tbody>
</table>

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### TPS dimensioning analysis results -75 deg entry

<table>
<thead>
<tr>
<th>Material Description</th>
<th>Thickness [m]</th>
<th>Area [m²]</th>
<th>Density [kg/m³]</th>
<th>Mass TPS [kg]</th>
<th>Mass of IFI+C/SiC [kg]</th>
<th>TOTmass [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PICA-Like Carbon Phenolic</td>
<td>0.0125</td>
<td>1.640</td>
<td>1400</td>
<td>47.77</td>
<td>0.11 5 mm IFI</td>
<td>48.88</td>
</tr>
</tbody>
</table>

*PEP - Assessment Study*
**Coast Phase Assumptions**

Duration: 20 [days] 480 [hours] 28800 [minutes]

### Power dissipation

<table>
<thead>
<tr>
<th>Component</th>
<th>Power [W]</th>
<th>Duty cycle [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comms</td>
<td>35</td>
<td>0.25%</td>
</tr>
<tr>
<td>DHS</td>
<td>19.73</td>
<td>0.60%</td>
</tr>
<tr>
<td>DHS MTU</td>
<td>0.27</td>
<td>100%</td>
</tr>
<tr>
<td>GNC</td>
<td>15</td>
<td>0.60%</td>
</tr>
</tbody>
</table>

Duration: 20 days = 480 hours = 28800 minutes

- Comms: 35 W for 3.6 minutes every day, 0 W for the rest of the day
- DHS: 19.73 W for 8.64 minutes every day, 0 W for the rest of the day
- DHS MTU: 0.27 W for the whole day
- GNC: 15 W for 8.64 minutes every day, 0 W for the rest of the day

IR flux acting on front shield and back cover MLI

---

**Coast Phase - Analysis Results**

- MLTI with Low emissivity and no Albedo considered
- MLTI with Low emissivity, no Albedo, and 2 W from RHUs

---

![Power dissipation over 1 day](image)

<table>
<thead>
<tr>
<th>Time [sec]</th>
<th>Power [W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.27</td>
</tr>
<tr>
<td>42336</td>
<td>0.27</td>
</tr>
<tr>
<td>43092</td>
<td>0.27</td>
</tr>
<tr>
<td>43092</td>
<td>35</td>
</tr>
<tr>
<td>43092</td>
<td>70</td>
</tr>
<tr>
<td>43308</td>
<td>70</td>
</tr>
<tr>
<td>43308</td>
<td>35</td>
</tr>
<tr>
<td>43459</td>
<td>35</td>
</tr>
<tr>
<td>44064</td>
<td>0.27</td>
</tr>
<tr>
<td>86430</td>
<td>0.27</td>
</tr>
</tbody>
</table>
**Descent Phase Assumptions and Analysis Results**

- Total power dissipated = 280 W (100% DC).
- Descent total duration = 1 hour.

---

**TCS and TPS Design Summary**

- DM dissipative units black painted and mounted on the base plate via fillers;
- Base plate finished with one layer Kapton VDA (low emissivity);
- Base plate connected to DM shell with 3 Titanium brackets (low conductive coupling);
- Internal DM shell insulated with 40 mm Aerogel foam finished with one layer Kapton VDA (low emissivity);
- External DM shell white painted;
- DM shell connected to front shield cold structure with 3 Titanium brackets (low conductive coupling);
- Cold structure internal surface finished with one layer Kapton VDA (low emissivity) (both front shield and back cover);
- Front shield TPS: SEPCORE = 16.2 mm (9 mm + 50% +20% margins) Carbon phenolic Ablator + 2.4 mm C/SiC hot structure + 5 mm IFI Insulation
- Back cover TPS: SEPCORE = 3.6 mm (2 mm + 50% +20% margins) PICA-like Ablator + 2.4 mm C/SiC hot structure + 5 mm IFI Insulation;
- 15 ablation detectors distributed radially and circumferentially on front shield;
- 20 layer MLI on front shield and back cover used during coasting then burned during entry.
- RHU are not baselined due to the larger temperature range of batteries. Temperature will rapidly increase during entry when units will be switched on and high heat fluxes will act on the probe. In case batteries want to be kept above 0°C then 2 RHU (2 W in total) need to be installed on the probe.
**Mass Budget Venus**  
*(baseline case: -25 deg entry angle)*

<table>
<thead>
<tr>
<th>Element</th>
<th>Unit Name</th>
<th>Mass per quantity excl. margin (kg)</th>
<th>Maturity Level</th>
<th>Margin</th>
<th>Total Mass incl. margin (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Front shield ablator (carbon-phenolic)</td>
<td>31.00</td>
<td>To be developed</td>
<td>200</td>
<td>37.20</td>
</tr>
<tr>
<td>2</td>
<td>Backcover ablator (PICA-like)</td>
<td>1.23</td>
<td>To be developed</td>
<td>200</td>
<td>1.47</td>
</tr>
<tr>
<td>3</td>
<td>Front shield and back cover insulation (IFM)</td>
<td>2.07</td>
<td>To be modified</td>
<td>100</td>
<td>2.27</td>
</tr>
<tr>
<td>4</td>
<td>Front shield and back cover hot structure (C/SiC)</td>
<td>11.56</td>
<td>To be modified</td>
<td>100</td>
<td>15.03</td>
</tr>
<tr>
<td>5</td>
<td>Interface yoked to DM (C/SiC)</td>
<td>1.10</td>
<td>To be modified</td>
<td>100</td>
<td>1.21</td>
</tr>
<tr>
<td>6</td>
<td>DM Internal insulation (Arongel)</td>
<td>4.34</td>
<td>To be modified</td>
<td>100</td>
<td>4.78</td>
</tr>
<tr>
<td>7</td>
<td>Space VDA between DM and heat shield / back cover</td>
<td>0.13</td>
<td>To be modified</td>
<td>100</td>
<td>0.15</td>
</tr>
<tr>
<td>8</td>
<td>MLI on front shield and back cover (coast phase)</td>
<td>1.25</td>
<td>To be modified</td>
<td>100</td>
<td>1.45</td>
</tr>
<tr>
<td>9</td>
<td>Ablation detectors</td>
<td>0.10</td>
<td>To be modified</td>
<td>100</td>
<td>0.15</td>
</tr>
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<td>10</td>
<td></td>
<td>0.00</td>
<td>To be developed</td>
<td>200</td>
<td>0.00</td>
</tr>
</tbody>
</table>

**SUBSYSTEM TOTAL:** 9 56.30 15.7 65.15
TPS, TCS design

- Same TPS/TCS design principle as per Venus probe.
- Thicknesses of TPS materials differ due to different aerothermodynamics fluxes and shield release timing (Uranus and Neptune probes are identical).
- Aerothermodynamics fluxes: 100% margin + 20% blockage on both convective and radiative fluxes.
- 3 RHUs (3 W in tot) may be required if batteries want to be kept always above 0 C. (currently not baselined)

<table>
<thead>
<tr>
<th></th>
<th>Saturn</th>
<th>Uranus</th>
<th>Neptune</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front shield release</td>
<td>Mach = 1, T = 76 sec</td>
<td>Mach = 1, T = 65 sec</td>
<td>Mach = 1, T = 60 sec</td>
</tr>
<tr>
<td>Back cover release</td>
<td>Mach &lt; 1, T = 106 sec</td>
<td>T = 1625 sec</td>
<td>T = 3260 sec</td>
</tr>
</tbody>
</table>

Aerothermodynamics fluxes

- Saturn
  - Max Total flux: 114.80 [MW/m²]
  - Tot heat load: 5.66E+08 [J/m²]

- Uranus
  - Max Total flux: 104.64 [MW/m²]
  - Tot heat load: 7.04E+08 [J/m²]

- Neptune
  - Max Total flux: 95.98 [MW/m²]
  - Tot heat load: 8.19E+08 [J/m²]
### TPS dimensioning Saturn

<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>SEPCORE</td>
<td>0.0205</td>
<td>1.640</td>
<td>1400.00</td>
<td>3.07</td>
<td>8.11 5 mm IFI</td>
<td>8.62</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8.62 5 mm IFI</td>
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</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>10.62 20 mm IFI</td>
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<tr>
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<td></td>
<td></td>
<td></td>
<td>13.69</td>
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</tr>
</tbody>
</table>

**Notes:**
- No margin applied yet
- 50% margin applied on thickness

### TPS dimensioning Uranus/Neptune

<table>
<thead>
<tr>
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<tbody>
<tr>
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<td>1400.00</td>
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<td></td>
<td></td>
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<td></td>
<td>8.11 5 mm IFI</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>89.05</td>
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**Notes:**
- No margin applied yet
- 50% margin applied on thickness

### TPS dimensioning Narmco4028

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<td>80.93</td>
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<td></td>
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<td>89.35</td>
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</tr>
</tbody>
</table>

**Notes:**
- No margin applied yet
- 50% margin applied on thickness
- 50%+20% margin applied

---

**PEP - Assessment Study**

**Thermal - 19**
Coast phase assumptions
(common to the 3 outer planets)

Duration 20 [days]
480 [hours]
28800 [minutes]

Power dissipations
Comms 35 [W] => 35 W for 3.024 minutes every day
Duty cycle 0.21% => 0 W for the rest of the day
DHS 19.4 [W] => 19.4 W for 3.024 minutes every day
Duty cycle 0.21% => 0 W for the rest of the day
DHS MTU 0.272 [W] => 0.272 W the all day
Duty cycle 0.21% => 0 W for the rest of the day
GNC 15 [W] => 15 W for 8.64 minutes every day
Duty cycle 0.60% => 0 W for the rest of the day

IR flux acting on front shield and back cover MLI

Coast phase Saturn

Low emissivity MLI, No albedo

Low emissivity MLI, No albedo, 3W heating from RHUs
Coast phase Uranus

Low emissivity MLI, No albedo

Low emissivity MLI, No albedo, 3W heating from RHUs

Coast phase Neptune

Low emissivity MLI, No albedo

Low emissivity MLI, No albedo, 3W heating from RHUs
**Descent phase Saturn**

- Total power dissipated = 310 W (100% DC).
- Descent total duration = 1.5 hour.

**Descent phase Uranus**

- Total power dissipated = 310 W (100% DC).
- Descent total duration = 1.5 hour.
- Back cover kept attached for 1560 sec after front shield release.
Descent phase Neptune

- Total power dissipated = 310 W (100% DC).
- Descent total duration = 1.5 hour.
- Back cover kept attached for 3200 sec after front shield release.

![Descent phase Neptune Graph]

Mass budget Saturn

<table>
<thead>
<tr>
<th>Element 1</th>
<th>0</th>
<th>Unit Name</th>
<th>Part of subsystem</th>
<th>Quantity</th>
<th>Mass per quantity excl. margin</th>
<th>Maturity Level</th>
<th>Margin</th>
<th>Total Mass incl. margin</th>
</tr>
</thead>
<tbody>
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<td>1</td>
<td></td>
<td>Front shield ablator (carbon-phenolic)</td>
<td>1</td>
<td>70.60</td>
<td>To be developed</td>
<td>20</td>
<td>36.72</td>
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<tr>
<td>2</td>
<td></td>
<td>Backcover ablator (PICA-like)</td>
<td>1</td>
<td>3.07</td>
<td>To be developed</td>
<td>20</td>
<td>3.07</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>Front shield and back cover insulation (IFI)</td>
<td>1</td>
<td>3.07</td>
<td>To be modified</td>
<td>10</td>
<td>3.37</td>
<td></td>
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<td>4</td>
<td></td>
<td>Front shield and back cover hot structure (C/SiC)</td>
<td>1</td>
<td>13.86</td>
<td>To be modified</td>
<td>10</td>
<td>15.03</td>
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<tr>
<td>5</td>
<td></td>
<td>Interface yoke to TM (inlet)</td>
<td>1</td>
<td>1.10</td>
<td>To be modified</td>
<td>10</td>
<td>1.21</td>
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<tr>
<td>6</td>
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<td>CM internal insulation (Aerogel)</td>
<td>1</td>
<td>5.15</td>
<td>To be modified</td>
<td>10</td>
<td>5.61</td>
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<td>7</td>
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<td>Upper WM between MM and heat shield / back cover</td>
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<td>0.13</td>
<td>To be modified</td>
<td>10</td>
<td>0.14</td>
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<tr>
<td>8</td>
<td></td>
<td>MLI on front shield and back cover (coast phase)</td>
<td>1</td>
<td>1.22</td>
<td>To be modified</td>
<td>10</td>
<td>1.40</td>
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<tr>
<td>9</td>
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<td>Ablation detector</td>
<td>1</td>
<td>8.10</td>
<td>To be modified</td>
<td>10</td>
<td>8.88</td>
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<tr>
<td>10</td>
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</tbody>
</table>

- Click on button above to insert new unit
- SUBSYSTEM TOTAL: 99.50
- Click on button below to insert new unit
- SUBSYSTEM TOTAL: 99.50
### Mass Budget Uranus/Neptune

<table>
<thead>
<tr>
<th>Element</th>
<th>Unit Name</th>
<th>Part of subsystem</th>
<th>Quantity</th>
<th>Mass per quantity excl. margin</th>
<th>Maturity Level</th>
<th>Margin</th>
<th>Total Mass incl. margin</th>
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<tbody>
<tr>
<td>1</td>
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<td>0 Front shield ablator</td>
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<td>64.08</td>
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<tr>
<td>2</td>
<td>Backcover ablator (PICA-like)</td>
<td>5 Backcover ablator</td>
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<td>To be developed</td>
<td>20</td>
<td>3.89</td>
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<tr>
<td>3</td>
<td>Front shield and back cover insulation (IFI)</td>
<td>3 Front shield and back cover insulation</td>
<td>1</td>
<td>1.00</td>
<td>To be modified</td>
<td>10</td>
<td>1.21</td>
</tr>
<tr>
<td>4</td>
<td>Front shield and back cover for structure (C/SiC)</td>
<td>4 Front shield and back cover</td>
<td>1</td>
<td>1.00</td>
<td>To be modified</td>
<td>10</td>
<td>1.21</td>
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<tr>
<td>5</td>
<td>Interface shield HM (C/SiC)</td>
<td>5 Interface shield</td>
<td>1</td>
<td>1.00</td>
<td>To be modified</td>
<td>10</td>
<td>1.21</td>
</tr>
<tr>
<td>6</td>
<td>DM internal insulation (TYPICAL)</td>
<td>6 DM internal insulation</td>
<td>1</td>
<td>1.00</td>
<td>To be modified</td>
<td>10</td>
<td>1.21</td>
</tr>
<tr>
<td>7</td>
<td>Layer VDA between VM and heat shield / back cover</td>
<td>7 Layer VDA</td>
<td>1</td>
<td>1.00</td>
<td>To be modified</td>
<td>10</td>
<td>1.21</td>
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<tr>
<td>8</td>
<td>MLI on front shield and back cover (coast phase)</td>
<td>8 MLI on front shield and back cover</td>
<td>1</td>
<td>1.00</td>
<td>To be modified</td>
<td>10</td>
<td>1.21</td>
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<tr>
<td>9</td>
<td>Ablation detectors</td>
<td>9 Ablation detectors</td>
<td>15</td>
<td>0.00</td>
<td>To be developed</td>
<td>20</td>
<td>0.00</td>
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**SUBSYSTEM TOTAL**

<p>| | | | | | | | |</p>
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</tbody>
</table>

### TPS Design Summary

**VENUS FPA = -25°**

<table>
<thead>
<tr>
<th>Front Shield Ablator</th>
<th>CP 16.2mm (31.0kg)</th>
<th>Narmco4028 23.4mm (44.77kg)</th>
<th>FM5055 26.1mm (49.94kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front Shield C/SiC</td>
<td>2.4 mm</td>
<td>2.4 mm</td>
<td>2.4 mm</td>
</tr>
<tr>
<td>Back Cover Ablator</td>
<td>3.6 mm</td>
<td>3.6 mm</td>
<td>3.6 mm</td>
</tr>
<tr>
<td>Back Cover C/SiC</td>
<td>2.4 mm</td>
<td>2.4 mm</td>
<td>2.4 mm</td>
</tr>
</tbody>
</table>

**VENUS FPA = -50°**

<table>
<thead>
<tr>
<th>Front Shield Ablator</th>
<th>CP 8.1mm (15.5kg)</th>
<th>Narmco4028 13.9mm (25.83kg)</th>
<th>FM5055 11.7mm (22.38kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front Shield C/SiC</td>
<td>2.4 mm</td>
<td>2.4 mm</td>
<td>2.4 mm</td>
</tr>
<tr>
<td>Back Cover Ablator</td>
<td>3.6 mm</td>
<td>3.6 mm</td>
<td>3.6 mm</td>
</tr>
<tr>
<td>Back Cover C/SiC</td>
<td>2.4 mm</td>
<td>2.4 mm</td>
<td>2.4 mm</td>
</tr>
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</table>

**SATELLITE FPA = -45°**

<table>
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<tr>
<th>Front Shield Ablator</th>
<th>CP 16.2mm (31.0kg)</th>
<th>Narmco4028 23.4mm (44.77kg)</th>
<th>FM5055 26.1mm (49.94kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front Shield C/SiC</td>
<td>2.4 mm</td>
<td>2.4 mm</td>
<td>2.4 mm</td>
</tr>
<tr>
<td>Back Cover Ablator</td>
<td>3.6 mm</td>
<td>3.6 mm</td>
<td>3.6 mm</td>
</tr>
<tr>
<td>Back Cover C/SiC</td>
<td>2.4 mm</td>
<td>2.4 mm</td>
<td>2.4 mm</td>
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</table>

**SATELLITE FPA = -35°**

<table>
<thead>
<tr>
<th>Front Shield Ablator</th>
<th>CP 8.1mm (15.5kg)</th>
<th>Narmco4028 13.9mm (25.83kg)</th>
<th>FM5055 11.7mm (22.38kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front Shield C/SiC</td>
<td>2.4 mm</td>
<td>2.4 mm</td>
<td>2.4 mm</td>
</tr>
<tr>
<td>Back Cover Ablator</td>
<td>3.6 mm</td>
<td>3.6 mm</td>
<td>3.6 mm</td>
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<tr>
<td>Back Cover C/SiC</td>
<td>2.4 mm</td>
<td>2.4 mm</td>
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**NEPTUNE FPA = -35°**

<table>
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<tr>
<th>Front Shield Ablator</th>
<th>CP 9mm (13.69kg)</th>
<th>CP 9mm (11.69kg)</th>
<th>CP 3.6mm (8.85kg)</th>
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<td>Front Shield C/SiC</td>
<td>2.4 mm</td>
<td>2.4 mm</td>
<td>2.4 mm</td>
</tr>
<tr>
<td>Back Cover C/SiC</td>
<td>2.4 mm</td>
<td>2.4 mm</td>
<td>2.4 mm</td>
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**NEPTUNE FPA = -25°**

<table>
<thead>
<tr>
<th>Front Shield Ablator</th>
<th>CP 9mm (13.69kg)</th>
<th>CP 9mm (11.69kg)</th>
<th>CP 3.6mm (8.85kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front Shield C/SiC</td>
<td>2.4 mm</td>
<td>2.4 mm</td>
<td>2.4 mm</td>
</tr>
<tr>
<td>Back Cover C/SiC</td>
<td>2.4 mm</td>
<td>2.4 mm</td>
<td>2.4 mm</td>
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**NEPTUNE FPA = -25°**

<table>
<thead>
<tr>
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<th>CP 9mm (13.69kg)</th>
<th>CP 9mm (11.69kg)</th>
<th>CP 3.6mm (8.85kg)</th>
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</thead>
<tbody>
<tr>
<td>Front Shield C/SiC</td>
<td>2.4 mm</td>
<td>2.4 mm</td>
<td>2.4 mm</td>
</tr>
<tr>
<td>Back Cover C/SiC</td>
<td>2.4 mm</td>
<td>2.4 mm</td>
<td>2.4 mm</td>
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</tbody>
</table>
Back cover

- BC release at ~106s
- BC release at ~1625 s
- BC release at ~3260 s

Front shield

- BC release at ~106s
- BC release at ~1625 s
- BC release at ~3260 s

<table>
<thead>
<tr>
<th>Venus (FPA -25)</th>
<th>Venus (FPA -50)</th>
<th>Saturn</th>
<th>Uranus</th>
<th>Neptune</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.6 mm</td>
<td>3.6 mm</td>
<td>9.0 mm</td>
<td>9.0 mm</td>
<td>9.0 mm</td>
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<tr>
<td>2.4 mm</td>
<td>2.4 mm</td>
<td>2.4 mm</td>
<td>2.4 mm</td>
<td>2.4 mm</td>
</tr>
<tr>
<td>5.0 mm</td>
<td>5.0 mm</td>
<td>10.0 mm</td>
<td>26.0 mm</td>
<td>26.0 mm</td>
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</tbody>
</table>

PEP - Assessment Study

Thermal - 31

High density Carbon-Phenolic Ablator

Low density Carbon-Phenolic Ablator: PICA

IFI: Internal Flexible Insulation
  Made by Al₂O₃-based ceramic microfiber fleeces
PEP

EDLS

IFP

ESTEC, 30-06 2010

Prepared by the PEP/ CDF* Team

(*) ESTEC Concurrent Design Facility

Theory: System Components
Theory: System components

Parachute
Riser
Swivel
3 leg-bridle

Mortar
Bridle (t/3)
Gas generator
Deployment / sabot capture bag containing the parachute and / or capturing the sabot

PEP - Assessment Study
EDLS - 3

Theory: Parachute types

PEP - Assessment Study
EDLS - 4
**Theory: Parachute types**

Conical ribbon parachute:
- Primarily used as drogue or pilot parachutes in space missions
- Excellent supersonic inflation
- Good stability (typical oscillation < 5°)
- Good performance at high dynamic pressures
- High structural integrity
- Deployable above Mach = 2
- Moderate drag
- Very difficult to build scale models

Disc Gap Band parachute:
- Used frequently for Mars missions to decelerate probes before landing or to control descent speed (Huygens).
- Good supersonic, low dynamic pressure inflation
- Easy to build small scale models
- Deployable above Mach = 2 possible
- Higher drag coefficient than Conical Ribbon parachute
- Less stable than Conical Ribbon parachute (typical oscillation < 10°)
- Better performance at low dynamic pressures
Theory: Parachute $C_{DP}$

$$C_{D_{projected}} = \frac{S_0}{S_{projected}} C_{D_0} \quad \text{where} \quad S_0 = \frac{1}{4} \pi D_0^2 \quad \text{and} \quad S_{projected} = \frac{1}{4} \pi D_{projected}^2$$

EDLS - 8
### Theory: Parachute $C_{DP}$

<table>
<thead>
<tr>
<th></th>
<th>Conical Ribbon</th>
<th>Disc Gap Band</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subsonic $C_{D_h}$</td>
<td>0.5-0.55</td>
<td>0.52-0.58</td>
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<tr>
<td>Subsonic $C_{D_{projected}}$</td>
<td>1.12</td>
<td>1.37</td>
</tr>
<tr>
<td>Supersonic $C_{D_{projected}}$</td>
<td>1.02</td>
<td>1.23</td>
</tr>
</tbody>
</table>

\[ \beta_i = \frac{\sum m_j}{\sum (C_{dS})_j} \quad \beta = 0.7 \beta \quad \text{Ballistic coefficient and separation requirement} \]

### Theory: EDLS options
### EDLS sequence Option 1

<table>
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<tr>
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**PEP - Assessment Study**

### EDLS sequence Option 2

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</table>

**PEP - Assessment Study**
VENUS

- Verification of EDLS sequence option 1 and 2
- EDLS options verified for correct ballistic coefficients (proper separation, not flying back into items that were just separated etc.).
- The above is done for:
  - a small parachute that is kept all the way to the Venus surface
  - a large parachute that is jettisoned at about 45 km altitude
    - This measurement range and duration of the free fall in combination with the total available time sizes the large parachute.
  - Now it is shown that with this large jettisonable parachute EDLS option 2 is feasible again and turns out to be the best option, since only a small parachute has to be ejected with the mortar and not a large parachute.
Small main parachute, kept all the way to Venus surface, EDLS option 2

CONCLUSION of the above: No separation since ballistic coefficient of heat shield is smaller than the ballistic coefficient of the sphere– parachute combination.
→ Change to EDLS option 1

Small main parachute, kept all the way to Venus surface, EDLS option 1

CONCLUSION of the above: With EDLS option 1 and drogue parachute dimensioned for heat shield separation.
Large jettisonable main parachute, then free fall to the surface EDLS option 1

**INPUT DATA**

<table>
<thead>
<tr>
<th>Masses</th>
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<tbody>
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<td>Front shield</td>
<td>67.89</td>
</tr>
<tr>
<td>Back cover</td>
<td>31.63</td>
</tr>
<tr>
<td>Sphere</td>
<td>167.83</td>
</tr>
<tr>
<td>Total</td>
<td>267.35</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>[m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front shield</td>
<td>0.99</td>
</tr>
<tr>
<td>Back cover</td>
<td>1.251</td>
</tr>
<tr>
<td>Sphere</td>
<td>0.65</td>
</tr>
<tr>
<td>Drogue parachute</td>
<td>2.63</td>
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<tr>
<td>Main parachute</td>
<td>3.3</td>
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**SUPERsonic drag coefficients**

<table>
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<th>Component</th>
<th>[-]</th>
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<tbody>
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<tr>
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<td>1.26</td>
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<tr>
<td>Sphere</td>
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</tr>
<tr>
<td>Drogue parachute</td>
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<td>Main parachute</td>
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**SUBsonic drag coefficients**

<table>
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<th>Component</th>
<th>[-]</th>
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<tr>
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<td>Back cover</td>
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<tr>
<td>Sphere</td>
<td>0.5</td>
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<tr>
<td>Drogue parachute</td>
<td>1.12</td>
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<tr>
<td>Main parachute</td>
<td>1.27</td>
</tr>
</tbody>
</table>

**CONCLUSION** of the above: With EDLS option 1 as well a large drogue parachute dimensioned for heat shield separation as well as a large main parachute for maintaining height altitude are required. → Change back to EDLS option 2?

---

Large jettisonable main parachute, then free fall to the surface EDLS option 2

**INPUT DATA**

<table>
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<tr>
<th>Masses</th>
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</thead>
<tbody>
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<td>67.89</td>
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<tr>
<td>Back cover</td>
<td>31.63</td>
</tr>
<tr>
<td>Sphere</td>
<td>167.83</td>
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<td>Total</td>
<td>267.35</td>
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<table>
<thead>
<tr>
<th>Dimensions</th>
<th>[m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front shield</td>
<td>0.99</td>
</tr>
<tr>
<td>Back cover</td>
<td>1.251</td>
</tr>
<tr>
<td>Sphere</td>
<td>0.65</td>
</tr>
<tr>
<td>Drogue parachute</td>
<td>0.6</td>
</tr>
<tr>
<td>Main parachute</td>
<td>3.3</td>
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</table>

**SUPERsonic drag coefficients**

<table>
<thead>
<tr>
<th>Component</th>
<th>[-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Whole probe</td>
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<tr>
<td>Front shield</td>
<td>1.26</td>
</tr>
<tr>
<td>Back cover</td>
<td>1.26</td>
</tr>
<tr>
<td>Sphere</td>
<td>1.26</td>
</tr>
<tr>
<td>Drogue parachute</td>
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</tr>
<tr>
<td>Main parachute</td>
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**SUBsonic drag coefficients**

<table>
<thead>
<tr>
<th>Component</th>
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<tbody>
<tr>
<td>Whole probe</td>
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<tr>
<td>Front shield</td>
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<tr>
<td>Back cover</td>
<td>0.47</td>
</tr>
<tr>
<td>Sphere</td>
<td>0.5</td>
</tr>
<tr>
<td>Drogue parachute</td>
<td>1.12</td>
</tr>
<tr>
<td>Main parachute</td>
<td>1.27</td>
</tr>
</tbody>
</table>

**CONCLUSION** of the above: It is possible to change back to EDLS option 2. The ballistic coefficients differ sufficiently and the drogue parachute that shall be jettisoned with the mortar is small. Mortar dimensions fit in this case the current configuration design.
VENUS (and other planets)

- Note: Although not base-lined, a small drag-generating drogue parachute is recommended for stabilization during final free fall.
  - This applies for all free falling probes of the study (Venus, Saturn, Uranus and Neptune)
  - Drogue parachutes are widely and commonly used and are very reliable. Even if they would not properly deploy, the mission has still a large potential to be successful.
- Landing gear

<table>
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<tr>
<th>Unit</th>
<th>Element 1 Unit Name</th>
<th>Quantity</th>
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<th>Margin</th>
<th>Total Mass incl. margin</th>
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<td>1.11</td>
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<td>0.35</td>
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<tr>
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<td>0.10</td>
<td>To be developed</td>
<td>20</td>
<td>0.1</td>
</tr>
<tr>
<td>5</td>
<td>Drogue parachute deployment bag</td>
<td>1</td>
<td>0.10</td>
<td>To be developed</td>
<td>20</td>
<td>0.1</td>
</tr>
<tr>
<td>6</td>
<td>Drogue parachute mortar</td>
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<td>3.92</td>
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<td>4.3</td>
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<td>7</td>
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<tr>
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<tr>
<td>10</td>
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<td>0.1000</td>
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</tr>
<tr>
<td>11</td>
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<td>0.1000</td>
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</tr>
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<tr>
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<td>17</td>
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<tr>
<td>18</td>
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</table>

- Click on button below to insert new unit

**ELEMENT 1 SUBSYSTEM TOTAL**

| Mass reservation for aerodynamic fins and other stabilisation means | 12 | 7.6 | To be developed | 20 | 8.0 |
### VENUS (2)

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**ELEMENT 1 SUBSYSTEM TOTAL**

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### SATURN
SATURN

- Sizing of parachute to separate the front shield
- Free fall of sphere without parachute from the back cover deeper into the Saturn atmosphere.
- Small aerodynamic means to maintain proper attitude are foreseen in the mass budget but no parachute is foreseen for this free fall, since any drag generating device would shorten the free fall and then the penetration depth into Saturn would be less than desirable (1.5 hours is available and it takes 1.5 hours to achieve a depth where the pressure is 100 bar)
- As a NON-BASELINE it might be interesting describe how much a very small parachute would actually "eat up" of the penetration depth. This way, penetration depth (science) is exchanged for greater reliability of the system.

**INPUT DATA**

**Masses**
- Front shield [kg] 116.25
- Back cover [kg] 34.68
- Sphere [kg] 169.95
- Total [kg] 320.88

**Dimensions**
- Front shield [m] 1.251
- Back cover [m] 0.99
- Sphere [m] 0.65
- Drag parachute [m] -

**SUPERsonic drag coefficients**
- Whole probe [-] 1.26
- Front shield [-] 1.26
- Back cover [-] 1.26
- Sphere [-] -
- Drag parachute [-] 1.02
- Main parachute [-] 1.23

**SUBsonic drag coefficients**
- Whole probe [-] 0.47
- Front shield [-] 0.47
- Back cover [-] 0.47
- Sphere [-] 0.33
- Drag parachute [-] 1.12
- Main parachute [-] 1.37

**Conclusion:** 1.9 m (projected diameter) Conical Ribbon parachute

**Conclusion:** 1.9 m (projected diameter) Conical Ribbon parachute

*PEP - Assessment Study*
<table>
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<tr>
<th>Unit</th>
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<tr>
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<td>0.40</td>
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<td>0.5</td>
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<td>0.24</td>
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<td>0.5</td>
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<tr>
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<td>0.10</td>
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<td>0.1</td>
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<tr>
<td>5</td>
<td>Drogue parachute deployment bag</td>
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<td>0.10</td>
<td>To be developed</td>
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<td>0.1</td>
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**Element 1 Subsystem Total**

|                          | 12 | 6.5 | 20.0 | 7.8 |

**PEP - Assessment Study**
URANUS

- Sizing of parachute to separate the front shield
- Back cover is kept and the probe descents on the parachute and back cover till 10 bar would be reached.
- Since this parachute is too large to reach 10 bars in time, the sphere / probe is released and the following options exist:
  - Option 1 second small parachute (not worked out in detail)
  - Option 2 Keep the too large parachute for less time (hence descent only to approximately 4 bar and free fall from there)

Small main parachute, to separate front shield (keep back cover) then free fall.

INPUT DATA

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SUPERsonic drag coefficients

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SUBsonic drag coefficients

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</table>

Click on button below to insert new unit

**ELEMENT 1 SUBSYSTEM TOTAL**: 12 units | 6.5 kg | 18.3 kg | 7.7 kg

---

**NEPTUNE**

**PEP - Assessment Study**

**EDLS - 30**
NEPTUNE

- Size parachute required to separate the front shield AND to increase the stay at the upper layers of the atmosphere
- The parachute size actually required for the descent through the atmosphere is therefore a certain factor greater. The parachute AREA is multiplied by a factor 1.8
- The back cover is kept and the probe descents on the drogue parachute from 0.1 bar to 10 bar for ~ 60 minutes, and is then jettisoned.
- Perhaps (not the baseline) a stabilising drogue would be required for the free fall.

Oversized (1.8 x projected area) drogue parachute to separate front shield (keep back cover) and to maintain longer in the upper atmosphere, then free fall.
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**Element 1 Subsystem Total**

|                         | 12 | 7.2 | 17.8 | 8.4 |

**PEP - Assessment Study**
The payload complement of the entry probe study for Venus and outer planets

PEP

Jens Romstedt
Håkan Svedhem
Jonan Larrañaga

Scientific commonalities for (atmospheric) entry probes

- **Structure, dynamics and meteorology**
  - Temperature, pressure, density, electric field
  - Winds

- **Chemical composition** (abundances & isotopes)
  - main gases
  - trace gases
  - noble gases
  - aerosols

- **Optical properties and features**
  - Surface and atmosphere
Model P/L approach

- Model payload selection is based on scientific themes using payload elements from precursor missions or mission studies
  - Huygens (mission)
  - Venus Express (mission)
  - Jupiter Entry Probes, JEP, (study)
  - Venus Entry Probes, VEP, (study)
  - Tandem (gondola), (study)
- However, the selected P/L is a generic placeholder only providing the resource requirements to the probe and mission design.
- One fits all (Venus, Saturn, Uranus, Neptune)
- Individual P/L elements can be replaced or modified e.g.
  - additional sensors can be added or replaced in the environmental sensor package
  - the chemical analyser can be specifically designed to address relevant chemical species of the respective atmosphere.
  - The imager can be tuned onto the desired wavelength range or replaced by a spectrometer, radiometer, nephelometer etc.

P/L resource budgets

- Realistic resource budgets:
  - Mass, size, power consumption, data volume/rate, operating temperature
  - Duty cycle and accommodation (top level)
- Mass target is ~10kg
- Uniformly a 20% margin is applied, that corresponds to a “to be developed instrument”.
- some resources are reserved for a centralised power supply and DPU
- Uniform operational and non-operational temperatures applied
  - Operational temperature: +50/-40 °C Non-ops. +60/-50 °C
  - Exception: pressure and temperature sensor outside the probe
### Comparison of P/L elements

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*Packaged Definition
Max. Nov. 2005, Int. rev. 2.1

### P/L elements PEP

- **Atmospheric Structure**
  - ASI/MET (Tandem) 1.25 kg
- **Chemical composition and isotopes**
  - MS (Tandem) 5.00 kg
- **Position and Drift**
  - Doppler Wind (Huygens) 1.50 kg
- **Camera incl. UV/VIS/IR photometer**
  - VEx & Huygens 1.50 kg
- **Data, Control and power**
  - this study 1.00 kg

**TOTAL** 10.25 kg

incl. 20% margin 12.30 kg
ASI/MET (multisensor package)

- density, pressure and temperature profile, atmos. electr., acoustic noise, optical depth
- a variety of sensors that needs access through the hull to the environment
  - short studs, valves or other inlets, windows
- Current design relies on central electronics and DPU
- ASI-ACC: 3-axis accelerometer, atmospheric density
- ASI-TEM: Pt-wire resistance thermometer
- ASI-PPI: Kiel probe, pressure measurements
- Other sensors as required (accounted for in resource budget)

Mass Spectrometer (MS)

- aerosol analyzer, chemical composition of minor atmosphere constituents, noble gas abundances and chemical composition
- quadrupole ion trap mass spectrometer with aerosol inlet and pyrolyser
- mass range 10-600 amu
- resolution M/ΔM = 600
- noble gases concentration ppm range (no concentrator)
- 1 inlet each for atmosphere and aerosol samples
- 10 minutes per analysis
Doppler Wind

- measures wind induced motion and spin rate
- precision better than 1 m/s
- makes use of the probe-carrier S/C radio link
- 2 USOs, one on probe - one on orbiter
- account for same mass etc. on orbiter

Camera & photometer

- surface observation (Venus!), atmospheric phenomena, optical density
- e.g. Venus Monitoring Camera (VMC) downward looking
  - 1kx1k CCD
  - split into 4 sectors for observation from UV up to IR
  - compression; 12 bit => 8 bit, factor 8 (approach on Huygens)
- in principle the camera could be replaced by a IR spectrometer providing similar resource budgets
- UV or VIS or IR photometer upward looking
  - the optical unit and sensor is separated, other subsystems are shared.
  - final selection of wavelength range depends on selected science objectives
  - photo diode
External unit to support payload elements

SCOC 3 (spacecraft controller on-a-chip)
- Current ESA development
- LEON 3 processor
- variety of interfaces; SpaceWire, CAN, 1553 MIL and other

Custom designed power conditioner is assumed to part of this unit

P/L resource budget summary

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>ASI/MET</td>
<td>1.25</td>
<td>TEM, PPI 205x300 (outside) ACC 75x95x68 50x50x50 other</td>
<td>1 sby. 5 ave. 10 max.</td>
<td>0.16 CANbus</td>
<td>5900/h 590 compressed</td>
<td>cont.</td>
</tr>
<tr>
<td>MS</td>
<td>5.0</td>
<td>250x200x100</td>
<td>4 sby. 8 ave. 10 max.</td>
<td>0.13 CANbus</td>
<td>4800/h (6 samples) 480 compressed</td>
<td>1/10'</td>
</tr>
<tr>
<td>Doppler Wind</td>
<td>1.5</td>
<td>150x150x118</td>
<td>2 sby. 10 ave. 18 max.</td>
<td>-</td>
<td>-</td>
<td>cont.</td>
</tr>
<tr>
<td>Camera</td>
<td>1.2</td>
<td>100x100x200</td>
<td>4 sby. 8 ave. 10 max.</td>
<td>1.747 Spacewire</td>
<td>75.5 Mb/h 6290 kbit comp.</td>
<td>1/10'</td>
</tr>
<tr>
<td>Photometer</td>
<td>0.3</td>
<td>30x30x80</td>
<td>1 sby. 2 ave. 2 max.</td>
<td>0.00026</td>
<td>16 bit/minute 0.96 kbit/h</td>
<td>cont.</td>
</tr>
<tr>
<td>DPU and power conv.</td>
<td>1.0</td>
<td>50x50x100</td>
<td>3</td>
<td>-</td>
<td>-</td>
<td>cont</td>
</tr>
<tr>
<td>Σ</td>
<td>10.25</td>
<td>35 ave.</td>
<td>2.037</td>
<td>7360.5 comp.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
ACCOMMODATION REQUIREMENTS

<table>
<thead>
<tr>
<th>ASI/MET</th>
<th>ACC</th>
<th>TEM</th>
<th>PPI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Close to the center of mass</td>
<td>Combined with PPI in one external stud</td>
<td>See above</td>
<td></td>
</tr>
<tr>
<td>MS</td>
<td>2 INLETS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Doppler Wind</td>
<td>NONE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Camera</td>
<td>Downward looking, 15° field of view</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Photometer</td>
<td>Upward looking, 30° field of view</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DPU and power conv.</td>
<td>none</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

P/L accommodation II

Some accommodation issues can only be addressed through detailed analysis and design at a later stage.

**Mass Spectrometer**

The inlets need to be opened and closed by a valve.
- the design of the valve is tbd
- the flow of gas and aerosol into and out of the instrument requires detailed analysis

**Camera and Photometer**

Both look through a transparent window (quartz, diamond etc.)
- analysis of optical interferences and transparency for specific wavelength required
- trade-off between scientific objectives, environment and possible instrument design

**ASI/MET**

Some sensors sit outside the probe e.g. pressure and temperature. Connection to main instrument backend through harness and connector into pressurized housing
- no specific challenges identified
## Descent Duration and Profile

<table>
<thead>
<tr>
<th>Planet</th>
<th>Pressure Range (science requirement)</th>
<th>Descent Profile</th>
<th>Freefall Time</th>
<th>Data Collection Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Venus</td>
<td>68 – 45 km, down to surface</td>
<td>CASE A: descent from ~68 to 92 bar in 60 min</td>
<td>~60 minutes of data collection</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(science requirement)</td>
<td>CASE B: descent from 65 to 45 km in 30 min, 30 min free fall</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Saturn</td>
<td>0.1 to 10 bar</td>
<td>Descent from 1 to 100 bar in 90 min</td>
<td>~90 minutes of data collection</td>
<td></td>
</tr>
<tr>
<td>Uranus</td>
<td>0.10 to 100 bar</td>
<td>Descent from 0.06 to 4 bar (drogue chute) in ~26 minutes</td>
<td>~90 minutes of data collection</td>
<td></td>
</tr>
<tr>
<td>Neptune</td>
<td>0.10 to 100 bar</td>
<td>Descent from 0.1 to 10 bar (drogue chute) in ~60 minutes</td>
<td>~90 minutes of data collection</td>
<td></td>
</tr>
</tbody>
</table>

END
Requirement

• Use of the aerodynamic parameter for shape of the Front shield
• Accommodate subsystem units acc. to their requirement such as pointing direction, field of view
• Mounting interfaces shall allow for easy maintenance, mounting and dismounting
• c.o.g. of the probe shall not be higher then the Front shield base
**Design driver 1**

- Aerodynamics parameter:
  - Base diameter = 1250 mm
  - Half-cone angle = 45°
  - Nose radius = 256 mm
  - Corner radius = 12.5 mm
    (taken from shoulder ratio = \( r_c/d_{base} = 0.01 \))

**Design driver 2**

- TPS: Thermal Protection System:

<table>
<thead>
<tr>
<th>FS-thickness in mm</th>
<th>Venus</th>
<th>Saturn</th>
<th>Uranus</th>
<th>Neptune</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ablator</td>
<td>16.2</td>
<td>36.9</td>
<td>27.9</td>
<td>27.9</td>
</tr>
<tr>
<td>C/Sic</td>
<td>2.4</td>
<td>2.4</td>
<td>2.4</td>
<td>2.4</td>
</tr>
<tr>
<td>IFI</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Sandwich</td>
<td>21.8</td>
<td>21.8</td>
<td>21.8</td>
<td>21.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>BC-thickness in mm</th>
<th>Venus</th>
<th>Saturn</th>
<th>Uranus</th>
<th>Neptune</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ablator</td>
<td>3.6</td>
<td>9</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>C/Sic</td>
<td>2.4</td>
<td>2.4</td>
<td>2.4</td>
<td>2.4</td>
</tr>
<tr>
<td>IFI</td>
<td>5</td>
<td>5</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>Sandwich</td>
<td>21.2</td>
<td>21.2</td>
<td>21.2</td>
<td>21.2</td>
</tr>
</tbody>
</table>
**Entry Probe element**

- Patch antenna
- Mortar incl. drogue chute
- Back cover main chute envelope
- DM - upper sphere
- Photometer window
- DM - internal part
- Helix antenna
- Mass spectrometer inlet/outlet
- DM - lower sphere camera window
- Separation ring
- Front shield

**Overall dimension**

- Mass = 261 kg  
  CoG = 456.03 mm  
  Clearance FS-DM = 22.74 mm

- Mass = 323.35 kg  
  CoG = 456.56 mm  
  Clearance FS-DM = 9.15 mm

- Mass = 310 kg  
  CoG = 457.2 mm  
  Clearance FS-DM = 18.15 mm
Requirements - Venus

- Maximum descent Pressure = 92Bar (assume 100Bar).
- Entry deceleration = 200g to 360g (dependant upon FPA).
- Front shield pressure = 300kPa to 700kPa
- Resulting in load of 360kN to 840kN
- Use JEP as starting point:
  - Diameter of Descent Module (DM) = 600mm, 40Bar external pressure, t=2mm
  - Dia DM = 650mm, 100Bar External Pressure, t=4mm
  - Calculation of shell thickness and hence mass did NOT include any safety/qualification factors and were under valued (JEP DM mass = 23kg)
Structure breakdown

- Descent Module
  - Material – Titanium Alloy
  - Diameter = 650mm
  - Shell thickness = 6.81mm (assumed 7mm in Catia)
- Interfaces/stiffeners
  - Material – Titanium Alloy
- Front Shield structure
  - Composite panel assumed, 20mm thick
  - Very High Density core to carry shear loads.
  - DM Connection Ring mounts at 3 separation points – V.High loads
  - DM connection ring would be better interfacing to a monolithic ring attached to Composite front shield.
- Back Cover structure
  - Same approach as for front shell.
- Equipment panel
  - Composite panel assumed
  - Medium Density core assumed
  - Diameter 630mm

Calculation of mass – Descent Module (1)

- Based on uniform pressure applied to a spherical shell.
- From Roark, minimum external pressure, $q'$ is given by:
  \[ q' = \frac{2E_i}{r^2 \sqrt{3(1-\nu^2)}} \] For an ideal case
  \[ q' = \frac{0.365E_i}{r^2} \] Probable actual minimum $q'$
- Knock down factor modified from 0.365 to 0.5 after discussion, to reduce mass by 15kg
**Calculation of mass – Descent Module (2)**

- Equation is rewritten to give t, in terms of $q'$, R and E.
- $q'$ has qualification and buckling factors applied according to ECSS-E-ST-32-10C Rev.1 (2 and 1.25 respectively).
- For Venus requirement of 100Bar external pressure, this becomes 250Bar
- Giving shell thickness $t= 6.81\text{mm} (4.35\text{mm for ideal case})$
- Using the area from the Catia model the mass of the Descent module shell using a Titanium Alloy is 37.42kg

**Calculation of mass – Front Shield**

- 20mm thick composite assumed
- Very High Density core (197kg/m$^3$) used in first estimate to transfer high Shear loads
- 600kN shear load to be distributed
- Assuming insert capability of 10kN, 60 inserts would be required
- For 3 hold down positions, approximately 100kN capability required!
- Conservatism required for mass estimate
- Coupon tests required to confirm insert shear load capability
- Inserts limited by diameter of Descent module
- May need to use monolithic structure
- Mass calculated at 7.5kg
- Back Cover based on this approach for simplicity
Mass breakdown

<table>
<thead>
<tr>
<th>Item</th>
<th>Nr.</th>
<th>Item mass M_struct</th>
<th>Material</th>
<th>Maturity</th>
<th>Unit Margin [%]</th>
<th>Unit mass with margin [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>FS - cold structure</td>
<td>1</td>
<td>7.495</td>
<td>sandwich</td>
<td>New dev.</td>
<td>20</td>
<td>8.99</td>
</tr>
<tr>
<td>FS - IF bracket</td>
<td>3</td>
<td>1.323</td>
<td>TITANIUM</td>
<td>New dev.</td>
<td>20</td>
<td>1.59</td>
</tr>
<tr>
<td>BS - cold structure</td>
<td>1</td>
<td>4.047</td>
<td>sandwich</td>
<td>New dev.</td>
<td>20</td>
<td>4.86</td>
</tr>
<tr>
<td>BS - DM - IF - bracket</td>
<td>3</td>
<td>1.323</td>
<td>TITANIUM</td>
<td>New dev.</td>
<td>20</td>
<td>1.59</td>
</tr>
<tr>
<td>BS - ribs (mortar support)</td>
<td>3</td>
<td>1.000</td>
<td>TITANIUM</td>
<td>New dev.</td>
<td>20</td>
<td>1.20</td>
</tr>
<tr>
<td>DM - upper shell</td>
<td>1</td>
<td>18.711</td>
<td>TITANIUM</td>
<td>New dev.</td>
<td>20</td>
<td>22.45</td>
</tr>
<tr>
<td>DM - lower shell</td>
<td>1</td>
<td>18.711</td>
<td>TITANIUM</td>
<td>New dev.</td>
<td>20</td>
<td>22.45</td>
</tr>
<tr>
<td>DM - connection ring</td>
<td>1</td>
<td>5.665</td>
<td>TITANIUM</td>
<td>New dev.</td>
<td>20</td>
<td>6.80</td>
</tr>
<tr>
<td>DM - mounting platform</td>
<td>1</td>
<td>1.034</td>
<td>sandwich</td>
<td>New dev.</td>
<td>20</td>
<td>1.24</td>
</tr>
<tr>
<td>DM - main parachute support structure</td>
<td>3</td>
<td>1.679</td>
<td>TITANIUM</td>
<td>New dev.</td>
<td>20</td>
<td>2.01</td>
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<tr>
<td>miscellaneous</td>
<td>1</td>
<td>5.000</td>
<td>TITANIUM</td>
<td>New dev.</td>
<td>20</td>
<td>6.00</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>76.64</td>
<td></td>
<td></td>
<td>20.0</td>
<td>91.97</td>
</tr>
</tbody>
</table>

Requirements – Saturn, Neptune and Uranus

• Requirements in terms of structure have not changed from Venus
• Dimensions and hence mass of components remains unchanged from Venus
Conclusions

- Mass budget needs to remain conservative
- Detailed FEA required to analyse stress concentrations around instrument holes
- Additional stiffeners may be required around instrument holes, increasing mass
- Aeroshell support structure needs detailed FEA to confirm if composite panel can be used.
- Structure is highly loaded at all times.
- Pressurising DM by 10 to 20Bar has minimal effect on mass of structure
Contents

• VEP separation sequence
  • Alternative sequence
• Outer Planets separation sequence
• Why use Mechanisms from Huygens Mission as baseline?
• Mechanisms required for VEP
• Mechanisms required for Outer Planets Probes
• Mass budgets
  • VEP
  • Outer Planets Probes
• Power budgets
  • VEP
  • Outer Planets Probes
VEP EDLS Separation Sequences:

<table>
<thead>
<tr>
<th>Event number</th>
<th>Event</th>
<th>Nr. Of pyms</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>End of entry interface</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>Dragon mortar activation</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Completely inflated dragon parachute</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>Activation of heat shield separation pyro bolts</td>
<td>3</td>
</tr>
<tr>
<td>4a</td>
<td>Activation of Back Cover separation pyro bolts</td>
<td>3</td>
</tr>
<tr>
<td>4b</td>
<td>Extraction of the main parachute</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>Fully inflated main parachute; start of measurements</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>Separation main chute</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>Free fall to the surface</td>
<td>0</td>
</tr>
</tbody>
</table>

VEP Alternative EDLS Separation Sequences:

<table>
<thead>
<tr>
<th>Event number</th>
<th>Event</th>
<th>Nr. Of pyms</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>End of entry interface</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>Dragon mortar activation</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Completely inflated dragon parachute</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>Activation of Back Cover separation pyro bolts</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>Fully inflated main parachute</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>Activation of heat shield separation pyro bolts</td>
<td>3</td>
</tr>
<tr>
<td>6</td>
<td>Start of measurements</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>Separation main chute</td>
<td>1</td>
</tr>
</tbody>
</table>

Alternative sequence has No effect on Mechanism design only timing of pyro actuation.
**Outer Planets EDLS Separation Sequences**

<table>
<thead>
<tr>
<th>Event number</th>
<th>Event</th>
<th>Nr. Of parts</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>End of entry interface</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>Drogue motor activation</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Completely inflated drogue parachute</td>
<td>0</td>
</tr>
<tr>
<td>3a</td>
<td>Activation of front shield umbilical cable cutters</td>
<td>2</td>
</tr>
<tr>
<td>3b</td>
<td>Activation of front shield separation gpm bolts</td>
<td>3</td>
</tr>
<tr>
<td>4a</td>
<td>Activation of Back Cover umbilical cable cutters</td>
<td>2</td>
</tr>
<tr>
<td>4b</td>
<td>Activation of Back Cover separation gpm bolts</td>
<td>3</td>
</tr>
<tr>
<td>5</td>
<td>Free fall to the surface</td>
<td>0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>11</strong></td>
</tr>
</tbody>
</table>

**Why Huygens Mechanisms are adopted**

- Good margin on preload of hold down and release mechanisms (due to larger Huygens mass)
- Guarantee that spring motorization forces are adequate (due to larger Huygens mass)
- Proven Flight Heritage

*PEP - Assessment Study*
**Separation Mechanisms (Huygens)**

Separation Subsystem (SEPS) consist of:

- Spin-up and Ejection Device (SED)
  - Structural fixation to main S/C
  - Deploy probe with required force/direction using springs
  - Separation using pyro-nut
- Back Cover Separation Mech (BCM)
  - Structural fixation to probe
  - Separation using bolt cutters
- Frontshield Separation Mech (FSM)
  - Structural fixation to probe
  - Reduce heat flux to probe
  - Release via spring & bolt cutter

I/F with S/C: 3 struts (8 in total)

**Separation Nodes (Huygens)**
**Spin-up and Ejection Device (SED) Example: Huygens-Cassini**

- Reliability of probe separation: $\geq 0.996$
- axial velocity: $v_x = -0.3 \text{ m/s, } +25\%/-10\%$
- spin: $5 \leq \omega_x \leq 10 \text{ rpm}$
- lateral velocity: $|v_t| < 25 \text{ mm/s (3$\sigma$)}$

**Back Cover (BCM) and Front Shield (FSM) Separation Mechanisms Example: Huygens-Cassini**
**Parachute Jettison Mechanism (PJM) and Main Parachute Swivel (MPS)**

Example: Huygens-Cassini

**PJM:**
- 3 mechs, one per each bridle leg
- fully redundant rod cutters

**MPS:**
- Redundant main thrust bearings
- Redundant preload bearings
- MoS₂ Coating on races
- TiC and MoS₂ coating on balls

---

**VEP Mass budget and list of equipments**

Resizing of Huygens-Cassini mechanisms
Taking into account:
- HUY mass 325 kg > VEP mass 235 kg
- HUY Probe Ø 1.9 m (FS Ø 2.7 m) > VEP FS Ø 1.25 m

<table>
<thead>
<tr>
<th>Element 1</th>
<th>Unit Name</th>
<th>Part of custom subsystem</th>
<th>Quantity</th>
<th>Mass per quantity excl. margin</th>
<th>Maturity Level</th>
<th>Margin</th>
<th>Total Mass incl. margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Probe, incl. SED, FSM &amp; BC IF</td>
<td></td>
<td>3</td>
<td>1.3</td>
<td>To be modified</td>
<td>10</td>
<td>4.3</td>
</tr>
<tr>
<td>2</td>
<td>Front shield separation</td>
<td></td>
<td>3</td>
<td>0.8</td>
<td>To be modified</td>
<td>10</td>
<td>2.6</td>
</tr>
<tr>
<td>3</td>
<td>Back cover separation</td>
<td></td>
<td>3</td>
<td>0.3</td>
<td>To be modified</td>
<td>10</td>
<td>1.1</td>
</tr>
<tr>
<td>4</td>
<td>Parachute Jettison mech's</td>
<td></td>
<td>3</td>
<td>0.3</td>
<td>To be modified</td>
<td>10</td>
<td>0.8</td>
</tr>
<tr>
<td>5</td>
<td>Cable cutter</td>
<td></td>
<td>4</td>
<td>0.3</td>
<td>To be modified</td>
<td>10</td>
<td>1.1</td>
</tr>
<tr>
<td>6</td>
<td>Main parachute swivel</td>
<td></td>
<td>1</td>
<td>0.5</td>
<td>To be modified</td>
<td>10</td>
<td>0.5</td>
</tr>
<tr>
<td>SUBSYSTEM TOTAL</td>
<td></td>
<td></td>
<td>6</td>
<td>9.5</td>
<td></td>
<td>10.0</td>
<td>10.4</td>
</tr>
</tbody>
</table>

N.B: Total mass of the Separation Subsystem is 17 kg.
A mass of 10 kg remains on the Orbiter after separation.

**PEP - Assessment Study**
# SEP Mass budget and list of equipments

<table>
<thead>
<tr>
<th>Unit</th>
<th>Unit Name</th>
<th>Part of custom subsystem</th>
<th>Quantity</th>
<th>Mass per quantity excl. margin</th>
<th>Maturity Level</th>
<th>Margin</th>
<th>Total Mass incl. margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Probe, incl. SED, FSM &amp; BC INF</td>
<td></td>
<td>3</td>
<td>1.3</td>
<td>To be modified</td>
<td>10</td>
<td>4.3</td>
</tr>
<tr>
<td>2</td>
<td>Front shield separation</td>
<td></td>
<td>3</td>
<td>0.6</td>
<td>To be modified</td>
<td>10</td>
<td>2.6</td>
</tr>
<tr>
<td>3</td>
<td>Back cover separation</td>
<td></td>
<td>3</td>
<td>0.3</td>
<td>To be modified</td>
<td>10</td>
<td>1.1</td>
</tr>
<tr>
<td>4</td>
<td>Cable cutters</td>
<td></td>
<td>4</td>
<td>0.3</td>
<td>To be modified</td>
<td>10</td>
<td>1.1</td>
</tr>
</tbody>
</table>

**SUBSYSTEM TOTAL**

| Unit | 4 | 8.3 | 10.0 | 9.1 |

*PEP - Assessment Study*  
Mechanism - 13

# UEP and NEP Mass budget and list of equipments

<table>
<thead>
<tr>
<th>Unit</th>
<th>Unit Name</th>
<th>Part of custom subsystem</th>
<th>Quantity</th>
<th>Mass per quantity excl. margin</th>
<th>Maturity Level</th>
<th>Margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Probe, incl. SED, FSM &amp; BC INF</td>
<td></td>
<td>3</td>
<td>1.3</td>
<td>To be modified</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>Front shield separation</td>
<td></td>
<td>3</td>
<td>0.6</td>
<td>To be modified</td>
<td>10</td>
</tr>
<tr>
<td>3</td>
<td>Back cover separation</td>
<td></td>
<td>3</td>
<td>0.3</td>
<td>To be modified</td>
<td>10</td>
</tr>
<tr>
<td>4</td>
<td>Cable cutters</td>
<td></td>
<td>4</td>
<td>0.3</td>
<td>To be modified</td>
<td>10</td>
</tr>
<tr>
<td>5</td>
<td>Drogue Parachute Swivel</td>
<td></td>
<td>1</td>
<td>0.5</td>
<td>To be modified</td>
<td>10</td>
</tr>
</tbody>
</table>

**SUBSYSTEM TOTAL**

| 5 | 8.7 | 10.0 |

*PEP - Assessment Study*  
Mechanism - 14
### VEP - Power budget

Per ESI (European Standard Initiator) Unit (2x Pyro):

- \( E = 0.15 \text{ J total energy} \)
- \( T = 10 \text{ ms max peak duration} \)
- \( P = \frac{E}{t} = 15\text{W average power} \)
- \( I = 5 \text{ A initiation current} \)

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Nr. Of pyros</th>
<th>Nr. of ESI (2 per Pyro)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drogue Deployment</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Front shield Separation</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Back cover Separation</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Main Parachute Jettison</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>14</strong></td>
<td><strong>28</strong></td>
</tr>
</tbody>
</table>

**N.B:** Separation from the S/C: firing of 3 pyros to be included in Orbiter power budget

---

### Outer Planets - Power budget

Per ESI (European Standard Initiator) Unit (2x Pyro):

- \( E = 0.15 \text{ J total energy} \)
- \( T = 10 \text{ ms max peak duration} \)
- \( P = \frac{E}{t} = 15\text{W average power} \)
- \( I = 5 \text{ A initiation current} \)

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Nr. Of pyros</th>
<th>Nr. of ESI (2 per Pyro)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drogue Deployment</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Front shield Separation</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Back cover Separation</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>11</strong></td>
<td><strong>22</strong></td>
</tr>
</tbody>
</table>

**N.B:** Separation from the S/C: firing of 3 pyros to be included in Orbiter power budget
PEP GNC Results

- Requirements & design drivers
  - Passive attitude control (spin-stabilized Entry, no powered descent)
  - Limited GNC role: triggering events, trajectory reconstruction
  - SED performance & coasting phase duration

- Baseline Design
  - GNC equipment list and trade-offs

- Simulations
  - Probe ejection accuracy (3 DoF)
  - Coasting disturbance analysis (6 DoF)
GNC requirements

- Main Mission Requirements:
  - Detect EIP
  - Provide accurate initialization & triggering of EDS sequence

- Science & Post-flight analysis (Huygens):
  - provided by 2 radial ACC -> (insensitive to sign of spin rate !)
  - extensive a posteriori work to perform the attitude reconstruction. c.f. “Huygens attitude reconstruction based on flight engineering parameters”

- Assumptions
  - Spin Rate measurement is required
  - Attitude a posteriori reconstruction is required

PEP GNC design (1)

- Trade-offs :
  - Radial Accelerometers (Huygens like)
    - (+) radial accelerometers = mass effective (~80 g per accelero)
    - (-) only 1-axis angular rate sensing (spin axis)
    - (-) spin rate sign is unknown
  - IMU (JEP-like)
    - (+) 3-axis attitude and angular rate knowledge during all entry & descent
    - (-) mass : 750g for LN200S
    - (-) power : 12W for LN200S (TBD for European IMU)

- Baseline GNC equipment: IMU
  - LN200-S incl. 3 gyroscopes (1°/hr) & 3 acceleros (300µg, range > 70g). TRL 7.
  - Alternative : European IMU (based on SEA MEMS gyroscope) (10°/hr)– feasibility study on-going (TRP). TRL 3-4.
**PEP GNC design (2)**

- **Mission Critical Tasks**
  - Wake-up probe at EIP – 3 hours (IMU calibration strategy)
  - Enable triggering events (EIP, deployment, release, etc…)

- **Redundancy Approach**
  - 3 Timer Units (= 100mW per timer hot redundancy) for wake up (=Huygens)
  - 2 g-switch to backup the timer units (2*50g, no power) for EIP detection (=Huygens)
  - 1 IMU (Huygens : 3+2 acceleros + 4 g-switches in hot / majority voting) + internal redundancy (1 additional acceler)

- **Option : atmospheric sensor for parachute deployment**
  - Direct measurement of Mach / Pdyn instead of indirect based on acceleration.
  - No such sensor currently exists for planetary applications.

---

**3D Simulations – FPA accuracy @ EIP**

- **Drivers for FPA accuracy @ EIP :**
  - Initial Navigation Error
  - FPA initial error :
    - Initial Attitude Error
    - Separation Accuracy
  - Coasting phase duration
  - Gravity Model accuracy (esp. around giant planets with numerous satellites)
### 3 DoF Simulation – Entry accuracy

- **FPA**
  - Initial Navigation Error
    - $\delta r_0 = [0, 1] \text{ km}$
    - $\delta v_0 = [0, 1] \text{ cm/s}$
  - Nominal Separation Velocity
    - $\delta V_{\text{nom}} = 30 \text{ cm/s}$
  - Initial FPA Error
    - Attitude error: $\delta \theta = [0, 1 \text{ deg}]$ (nominal: $0.3^\circ$, $1\sigma$)
    - Separation Velocity Error $\delta V_{\text{lat}} = [0, 10 \text{ cm/s}]$ (nominal: $1 \text{ cm/s}$, $1\sigma$)

- **Matlab 3 DoF simulations**
  - Results of mini Monte Carlo campaign FPA error @ EIP SED & attitude errors
    - ~$0.1^\circ$ ($3\sigma$, nominal) for 20 d (SED impact > attitude)
  - Worst case NAV error:
    - $0.41^\circ$ ($3\sigma$) for 20 d
    - $0.21^\circ$ ($3\sigma$) for 10 d
6 DoF Simulation (ASTOS) Assumptions

- **SEPARATION MECHANISM**: same SED and errors as Cassini-Huygens.

- **PROBE FEATURES**: Venus MCI from Configuration Epoch, E-20d state vector provided by ESOC.

- **TRAJECTORY**: First phase of the trajectory is sun influence until the probe reach the sphere of influence of Venus (6x10^4 km).

- **SOLAR RADIATION PRESSURE**: main disturbance.

\[
F_{SR} = -p_{SR}c_{SR}A_{\odot}r_{\odot}\]

SED Errors 1

**Errors on the direction of the velocity:**

<table>
<thead>
<tr>
<th>Error contribution</th>
<th>Direction</th>
<th>Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compound spacecraft state vector accuracy at separation time</td>
<td>(\eta = 1.5\text{deg})</td>
<td>(\Delta V_e = 0.001\text{m/s})</td>
</tr>
<tr>
<td>Interface plane between Cassini and Huygens</td>
<td>(\eta = 0.12 + 2.0\text{deg})</td>
<td>(\Delta V_e = 0.012\text{m/s})</td>
</tr>
<tr>
<td>Separation mechanism mis-alignment</td>
<td>(\mu = 0.05\text{deg})</td>
<td>(\Delta V_e = 0.032\text{m/s})</td>
</tr>
</tbody>
</table>
**SED Errors 2**

Bore-sight error angle definition:

![Diagram of bore-sight error angle definition]

Attitude Errors (inaccuracy on bore-sight direction):

<table>
<thead>
<tr>
<th>Error contribution</th>
<th>Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>misalignment of the $I_1$ principal axis of inertia respect to the bore-sight of the probe</td>
<td>$\gamma = 0.5^\circ$</td>
</tr>
<tr>
<td>misalignment of the $I_3$ principal axis of inertia respect to the direction of the angular momentum $H$</td>
<td>$\beta = 9^\circ$</td>
</tr>
<tr>
<td>misalignment of the bore-sight of the probe respect to the local horizon at entry gate and at drag interface</td>
<td>$\tau = 0.5^\circ$</td>
</tr>
</tbody>
</table>

**Main 6 DoF Simulation Results**

Angle of attack – side slip angle definition:

![Diagram of angle of attack and side slip angle]

<table>
<thead>
<tr>
<th></th>
<th>Worst case (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angle of Attack</td>
<td>[-4, 3]</td>
</tr>
<tr>
<td>Side Slip Angle</td>
<td>[-3, 4]</td>
</tr>
<tr>
<td>Total AoA</td>
<td>[-5, 5]</td>
</tr>
</tbody>
</table>
Assumptions (ASTOS Simulator Data)

<table>
<thead>
<tr>
<th>Epoch</th>
<th>Mass [Kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>11 June 2020</td>
<td>238.89</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Initial Angular Velocity [º/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angle rate</td>
</tr>
<tr>
<td>ωx</td>
</tr>
<tr>
<td>ωy</td>
</tr>
<tr>
<td>ωz</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Initial State Vector</th>
</tr>
</thead>
<tbody>
<tr>
<td>EME2000 centred on Venus</td>
</tr>
<tr>
<td>X [km]</td>
</tr>
<tr>
<td>Y [km]</td>
</tr>
<tr>
<td>Z [km]</td>
</tr>
<tr>
<td>Vx [km/s]</td>
</tr>
<tr>
<td>Vy [km/s]</td>
</tr>
<tr>
<td>Vz [km/s]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Moment of Inertia w.r.t. the ASTOS axes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Change x and z from original</td>
</tr>
<tr>
<td>[kgxm²]</td>
</tr>
<tr>
<td>---------</td>
</tr>
<tr>
<td>X</td>
</tr>
<tr>
<td>Y</td>
</tr>
<tr>
<td>Z</td>
</tr>
</tbody>
</table>

AoA evolution

AoA range [°] [-4, 3]
**AoA Detail**

![Graph](image)

**Slide Slip Angle Evolution**

<table>
<thead>
<tr>
<th>Side slip Angle [°]</th>
<th>[-3, 4]</th>
</tr>
</thead>
</table>

![Graph](image)
**Outer planets**

- Same GNC design
- Expected results similar to JEP’s
- 6 DoF Simulator ready
## PEP GNC Model

<table>
<thead>
<tr>
<th>Unit</th>
<th>Unit Name</th>
<th>Part of custom subsystem</th>
<th>Quantity</th>
<th>Mass per quantity excl. margin</th>
<th>Maturity Level</th>
<th>Margin</th>
<th>Total Mass incl. margin</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>inertial Measurement Unit</td>
<td></td>
<td>1</td>
<td>0.750</td>
<td>To be modified</td>
<td>10</td>
<td>0.8</td>
</tr>
<tr>
<td>2</td>
<td>g-switch sensors</td>
<td></td>
<td>2</td>
<td>0.050</td>
<td>Fully developed</td>
<td>5</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>SUBSYSTEM TOTAL</td>
<td></td>
<td>2</td>
<td>0.9</td>
<td></td>
<td></td>
<td>9.4</td>
</tr>
</tbody>
</table>

**Click on button above to insert new unit**

---

**Click on button below to insert new unit**
PEP
Planetary Entry Probes

Power

IFP
ESTEC, 30th June 2010
Prepared by the PEP/ CDF* Team

(*) ESTEC Concurrent Design Facility

Venus

PEP - Assessment Study
**Requirements and Design Drivers. Venus**

- Atmospheric entry probe with:
  - Less than 1 year interplanetary transfer, attached to carrier craft.
  - 20 days post-separation cruise, with power required for timers and for brief periodic wake-up periods.
  - 1 hour entry/descent phase, with power required by platform and payload.

**Electrical Power Source Selection**

- **Solar Power:**
  - Fundamentally not suitable for an entry probe.

- **Radioisotope Power Source (e.g. RTG):**
  - RPS have much greater energy density than chemical batteries over a multi-year mission, but their energy/mass ratio is less impressive over 20 days. They have very low power density compared to batteries, and in this application they must be sized according to (peak) power demand, rather than total energy need.
  - For instance: USA MMRTG: 125W, 44 kg. ASRG: 150W, 20 kg. The cost of radioisotope systems and their associated procedures means that they are generally only considered when they are mission enabling (i.e. there is no reasonable alternative).

- **Secondary batteries**
  - Energy density of newer Li-Ion technology is now closer to that of primary batteries, but requires BCR electronics to charge after interplanetary phase. May be considered in longer missions, where the performance of primary batteries is compromised by self-discharge (see later).

- **Primary batteries**
  - Best solution for this application. Selection of the type depends on the details of the power and energy requirements. ...............
PEP & Energy Budget.  
Venus

### Energy Budget Breakdown by Sub-System

- ~62% (130Wh) of the DHS energy is for the timer units (272mW).
- Timers account for only ~18% of total energy budget.
- ~82% of the energy is required at high power (>300W). This drives the choice of primary cell type.
- JEP study proposed dedicated low-current/high capacity cells for the timers. This approach is not appropriate here. However, the JEP selection of LiSO₂ high-current spiral electrode cells for the PCDU supply can be re-applied for PEP.

PEP - Assessment Study  
Power - 5
**Characteristics of SAFT LO26SHX**

**Electrical characteristics**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal capacity</td>
<td>7.5 Ah</td>
</tr>
<tr>
<td>Open circuit voltage (at +30°C)</td>
<td>3.0 V</td>
</tr>
<tr>
<td>Nominal voltage (at 0.8 A +20°C)</td>
<td>2.8 V</td>
</tr>
<tr>
<td>Maximum recommended continuous current (to avoid over-heating; Higher currents possible, consult SAFT)</td>
<td>4 A</td>
</tr>
<tr>
<td>Pulse capability: Typically up to 15 A. (The voltage readings may vary according to the pulse characteristics, the temperature, and the cell's previous history. Fitting the cell with a capacitor may be recommended in severe conditions. Consult SAFT)</td>
<td></td>
</tr>
<tr>
<td>Storage (recommended) (possible without leakage)</td>
<td>+30°C (+86°F) max</td>
</tr>
<tr>
<td>Operating temperature range (Short excursions up to +65°C possible at currents below 1 A)</td>
<td>-60°C / +70°C (-76°F / +158°F)</td>
</tr>
</tbody>
</table>

**Physical characteristics**

- Diameter (max): 34.2 mm (1.345 in)
- Height (max; finish without radial tabs): 59.3 mm (2.33 in)
- Typical weight: 85 g (3 oz)

**Capacity versus Current and Temperature (continuous discharges - 2.0 V cut off)**

- 6 batteries of 8 cells each gives 1012 Wh at ≤24V (at 20°C).
- Total mass of 4.9kg including a 20% “cells-to-batteries allowance”
- PCDU must implement a depassivation routine to prepare the batteries for use after the interplanetary phase.

**PEP - Assessment Study**

**Power - 8**
**Power System Architecture**

8 cells x 3V = 24V (at open circuit)

**TERMA generic modular “Future Power System” components used to estimate PCDU size & mass.**
- It is assumed that a TERMA BCDR unit can be modified into a dual BDR unit of similar mass

- Mass: 10.6 kg
- Dimensions: 190x270x230 mm

---

**PEP - Assessment Study**

**PCDU**

<table>
<thead>
<tr>
<th>Module/PCD</th>
<th>Capability per Module</th>
<th>Number of modules Required</th>
<th>Weight per module [Kg]</th>
<th>Total Weight [Kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>BDR (2 per board)</td>
<td>225 W</td>
<td>3</td>
<td>0.65</td>
<td>1.65</td>
</tr>
<tr>
<td>Command Module</td>
<td>2 required</td>
<td>2</td>
<td>0.35</td>
<td>0.7</td>
</tr>
<tr>
<td>Distribution Module 1.5A</td>
<td>32 lines 1.5A</td>
<td>1</td>
<td>0.65</td>
<td>0.65</td>
</tr>
<tr>
<td>Distribution Module 5A</td>
<td>16 lines 5A</td>
<td>1</td>
<td>0.65</td>
<td>0.65</td>
</tr>
<tr>
<td>Pyro Control</td>
<td>15 pyro lines</td>
<td>1</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Total modules</td>
<td></td>
<td></td>
<td></td>
<td>3.95</td>
</tr>
<tr>
<td>Structure/Backplane</td>
<td></td>
<td></td>
<td></td>
<td>6.6</td>
</tr>
<tr>
<td>TOTAL PDU</td>
<td></td>
<td></td>
<td></td>
<td>10.6</td>
</tr>
</tbody>
</table>

**PEP - Assessment Study**
# Power sub-system summary

<table>
<thead>
<tr>
<th>Element</th>
<th>Unit Name</th>
<th>Quantity</th>
<th>Mass per unit [kg]</th>
<th>Maturity Level</th>
<th>Margin</th>
<th>Total Mass incl. margin</th>
<th>Dim1 [m]</th>
<th>Dim2 [m]</th>
<th>Dim3 [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>PCDU</td>
<td>1</td>
<td>10.5</td>
<td>To be developed</td>
<td>20</td>
<td>12.7</td>
<td>0.192</td>
<td>0.265</td>
<td>0.330</td>
</tr>
<tr>
<td>2</td>
<td>Battery</td>
<td>6</td>
<td>0.82</td>
<td>To be modified</td>
<td>10</td>
<td>5.39</td>
<td>0.079</td>
<td>0.145</td>
<td>0.063</td>
</tr>
<tr>
<td>-</td>
<td>Click on button above to insert new unit</td>
<td>-</td>
<td>0.0</td>
<td>To be developed</td>
<td>20</td>
<td>0.0</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>SUBSYSTEM TOTAL</strong></td>
<td></td>
<td><strong>2</strong></td>
<td><strong>15.5</strong></td>
<td></td>
<td></td>
<td><strong>18.8</strong></td>
<td><strong>18.1</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

These dimensions are for 1 battery (6 are required in total)

---

**Outer planets**
Requirements and Design Drivers - Saturn

• Main deltas for power:
  – 10 year interplanetary transfer, so battery capacity loss is now significant. 3% per year is assumed for the Li-SO₂ cells, so 74% is remaining after 10 years.
  – 90 minute descent phase is the main driver to increase the energy budget to 916Wh (vs. 712 for Venus).

Power subsystem - Saturn

• Battery – Cell selection logic for Venus remains valid. 12 batteries are proposed, each comprising 7 cells in series. These are packaged and connected to BDRs in pairs.
• PCDU – Same architecture as Venus, 6 BDRs.
• 1/6th of the power system is redundant.
• Long transfer phase means that battery depassivation before probe separation is essential. This should not be a problem – experience from Huygens.
**Requirements and Design Drivers. Uranus and Neptune**

- Main deltas for power:
  - Power budget remains as per Saturn.
  - 16/19 years interplanetary transfer, so battery capacity loss is very significant. 3% per year is assumed for the Li-SO$_2$ cells, so 56% is remaining after 19 years.
  - **Question** – Is it therefore advantageous to use Li-Ion rechargeable batteries? These would be left discharged during the interplanetary phase, and would have to be charged before probe separation.
  - Real data on Li-Ion storage degradation over such long periods is unavailable. Battery experts advise that the value may not be so much different than the 3% per year assumed for the primary cells. There are also the following disadvantages:
    - Secondary cells have a lower energy density at BOL.
    - BCR circuitry would be required.
    - Charging the battery may be a significant problem for the power system of the carrier craft (at the outer planets!)
  - Therefore, we select the same Li-SO$_2$ primary cells.

---

**Power subsystem – Uranus and Neptune**

- Battery –12 batteries are proposed, each comprising 9 cells in series. These are packaged and connected to BDRs in pairs.
- PCDU – Same architecture as Venus, 6 BDRs.
- 1/6$^{th}$ of the power system is redundant.
- Long transfer phase means that battery depassivation before probe separation is essential. This should not be a problem – experience from Huygens

---

**Table: Power subsystem**

<table>
<thead>
<tr>
<th>Element 1</th>
<th>Unit Name</th>
<th>Quantity</th>
<th>Mass per quantity excl. margin [kg]</th>
<th>Maturity Level</th>
<th>Margin</th>
<th>Total Mass incl. margin [kg]</th>
<th>Dim1 Length [m]</th>
<th>Dim2 Width [m]</th>
<th>Dim3 Height [m]</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>PCDU</td>
<td>1</td>
<td>10.6</td>
<td>To be developed</td>
<td>20</td>
<td>12.7</td>
<td>0.192</td>
<td>0.265</td>
<td>0.290</td>
</tr>
<tr>
<td></td>
<td>Battery</td>
<td>6</td>
<td>1.04</td>
<td>To be modified</td>
<td>19</td>
<td>12.12</td>
<td>0.073</td>
<td>0.327</td>
<td>0.063</td>
</tr>
<tr>
<td></td>
<td>SUBSYSTEM TOTAL</td>
<td>2</td>
<td>21.6</td>
<td></td>
<td>20</td>
<td>14.9</td>
<td>24.8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

*PEP - Assessment Study*
**RHU aspects**

- RHUs are not baselined for the PEP design, but we should consider the option and the potential impacts if they are required:
  - **RHU:**
    - USA LWRHU may be available if NASA is a partner. 1W output, 40g, 32 x 26mm.
    - Russian Angel RHU may be purchased – this option was examined for Exomars. 8.5W, 180g, 40 x 60mm.
    - ESA nuclear power roadmap aims to have a European RHU at TRL 6 by 2016.
  - **Mech interface:**
    - Both designs are plain cylinders, and some form of holder(s) needs be included in the spacecraft design. Add 50% of the RHU mass?
    - Spacecraft design can be significantly driven by the requirement for RHU installation on the launchpad.
  - **Launch safety approval:**
    - A major project in itself. If USA LWRHU are used with a USA launch, then the risk is reduced due to prior experience. Likewise for Russian Angel RHU with a Russian launch.
PEP
Planetary Entry Probes

Communications

Internal Final Presentation
ESTEC, 30th June 2010

Prepared by the PEP/ CDF* Team
(*) ESTEC Concurrent Design Facility

Requirements

• **Telecommands link** (carrier to probe) is not required.
• During coast phase the telemetry link shall be available during one hour over 20 days (power ON duty cycle = 0.2%).
• During descent phase the telemetry link shall be able to transmit real time data at **2kbps**.
• The probe shall be able to transmit telemetry at **elevations higher than zero degrees**.
Assumptions: frequency

- Antenna size increases
- More than 30 cm for UHF

- Atmospheric loss increases
- More than 25 dB in Saturn S-band

Selected frequency UHF = 400 MHz
- Patch antenna size allows to be place on the back cover
- Atmospheric loss extrapolated from previous technical studies.
  - Venus = 2 dB
  - Saturn, Neptune and Uranus = 15 dB
- A dedicated study on the planetary atmosphere effect (loss, noise temperature, misspolarization, ...) is needed for an final frequency selection.

Assumptions: antennas

- Circular patch antenna on the back cover
- A design with a hole in the centre allows the parachute release.
- Diameter of the radiating element: 300 mm

- Descent phase antenna:
  - Helix antenna in the probe
  - The helix antenna ensures full link coverage down to 0 degrees elevation.
  - Size of the radiating element 250 mm
Assumptions: atmosphere effect

- Molecular attenuation:
  - **Absorption**: The energy of the photons is taken up by matter.
  - **Scattering**: The electromagnetic wave is deviated from its straight path.
Assumptions: atmosphere effect

• Molecular attenuation:
  – Absorption: The energy of the photons is taken up by matter.
  – Scattering: The electromagnetic wave is deviated from its straight path.
  – Dipole momentum: The energy of the photons is taken up by dipole molecules.

• Atmospheric attenuation: The previous physical principles will attenuate the EM signal when it passes through the atmosphere. The total attenuation in dB will depend on:
  – Atmosphere composition (O₂, CO₂, NH₃, ...), phase of the matter (gas, clouds, ice), pressure, temperature.

• Noise figure: The radiation of the planets mainly caused by moving charged particles can block some frequencies.
• Polarization mismatch shall also be addressed.
**Assumptions: atmosphere effect**

- During this study the impact of the atmosphere effect on the communications have been identified as a key issue.
- There is a lack of knowledge on the atmospheric effects, especially for outer planets.
- The final atmospheric attenuation considered in UHF will be a worst case extrapolated from previous studies:

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Latm (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-band 8 GHz</td>
<td>-2 dB</td>
</tr>
<tr>
<td>S-band 2 GHz</td>
<td>-15 dB</td>
</tr>
<tr>
<td>L-band 1 GHz</td>
<td>-15 dB</td>
</tr>
<tr>
<td>UHF 400 MHz</td>
<td>-15 dB</td>
</tr>
<tr>
<td>VHF 100 MHz</td>
<td>-15 dB</td>
</tr>
</tbody>
</table>

### Communications subsystem design

<table>
<thead>
<tr>
<th>Component</th>
<th>Current TRL</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 patch antenna (on the back shield)</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>1 helix antenna</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>2 RF switches</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>2 SSPA</td>
<td>5</td>
<td>Cold redundancy</td>
</tr>
<tr>
<td>2 Transmitters</td>
<td>5</td>
<td>Cold redundancy</td>
</tr>
<tr>
<td>2 Ultra Stable Osc.</td>
<td>5</td>
<td>Cold redundancy</td>
</tr>
<tr>
<td>Cables and harness</td>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>

| Total mass (excluding margin) | 7.4 kg |
| Total consumption | 315 W / 45 W |
Communications subsystem design

- **TRL 5**: All equipment to be developed in order to resist an extreme environment.
- **Transmitters**: GMSK with Turbo codes and variable data rate.
- **Solid State Power Amplifier**: Variable output power 10 to 100 W
- **Patch antenna**: Released with the back shield and with a hole in the middle for parachute release.
- **Helix antenna**: Omnidirectional with at least 0 dBi at 0 degrees elevation.
- **Ultra Stable oscillator**: low phase noise for DTE carrier recovery link and Doppler wind experiment.

### Link budget telemetry relay

<table>
<thead>
<tr>
<th>Telemetry relay</th>
<th>Data rate [kbps]</th>
<th>RF output power [W]</th>
<th>Atm loss [dB]</th>
<th>Slant range [km]</th>
<th>Rx antenna [m]</th>
<th>Link margin [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Venus</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Start of descent</td>
<td>0.2</td>
<td>10</td>
<td>0</td>
<td>38000</td>
<td>0.2</td>
<td>3.05</td>
</tr>
<tr>
<td>End of descent</td>
<td>2</td>
<td>100</td>
<td>0</td>
<td>38000</td>
<td>2</td>
<td>5.80</td>
</tr>
<tr>
<td>Saturn</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Start of descent</td>
<td>2</td>
<td>10</td>
<td>0</td>
<td>90000</td>
<td>1.5</td>
<td>3.07</td>
</tr>
<tr>
<td>End of descent</td>
<td>2</td>
<td>100</td>
<td>0</td>
<td>90000</td>
<td>15</td>
<td>13.07</td>
</tr>
<tr>
<td>Uranus</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Start of descent</td>
<td>2</td>
<td>10</td>
<td>0</td>
<td>100000</td>
<td>1.5</td>
<td>2.15</td>
</tr>
<tr>
<td>End of descent</td>
<td>2</td>
<td>100</td>
<td>0</td>
<td>100000</td>
<td>15</td>
<td>12.15</td>
</tr>
<tr>
<td>Neptune</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Start of descent</td>
<td>2</td>
<td>10</td>
<td>0</td>
<td>80000</td>
<td>1.5</td>
<td>4.09</td>
</tr>
<tr>
<td>End of descent</td>
<td>2</td>
<td>100</td>
<td>0</td>
<td>80000</td>
<td>15</td>
<td>14.09</td>
</tr>
</tbody>
</table>
### Link budget DTE carrier recovery

<table>
<thead>
<tr>
<th>Carrier Recovery DTE</th>
<th>RF output power [W]</th>
<th>Atm loss [dB]</th>
<th>Slant range [AU]</th>
<th>Rx antenna [m]</th>
<th>Link margin [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Venus</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coast</td>
<td>10</td>
<td>0</td>
<td>0.4</td>
<td>35</td>
<td>6.91</td>
</tr>
<tr>
<td>Start of descent</td>
<td>100</td>
<td>0</td>
<td></td>
<td></td>
<td>16.91</td>
</tr>
<tr>
<td>End of descent</td>
<td>100</td>
<td>2</td>
<td></td>
<td></td>
<td>14.91</td>
</tr>
<tr>
<td>Saturn</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coast</td>
<td>10</td>
<td>0</td>
<td>10</td>
<td>SKA</td>
<td>-5.30</td>
</tr>
<tr>
<td>Start of descent</td>
<td>100</td>
<td>0</td>
<td></td>
<td></td>
<td>4.70</td>
</tr>
<tr>
<td>End of descent</td>
<td>100</td>
<td>15</td>
<td></td>
<td></td>
<td>-10.30</td>
</tr>
<tr>
<td>Uranus</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coast</td>
<td>10</td>
<td>0</td>
<td>20</td>
<td>SKA</td>
<td>-11.35</td>
</tr>
<tr>
<td>Start of descent</td>
<td>100</td>
<td>0</td>
<td></td>
<td></td>
<td>-1.35</td>
</tr>
<tr>
<td>End of descent</td>
<td>100</td>
<td>15</td>
<td></td>
<td></td>
<td>-16.35</td>
</tr>
<tr>
<td>Neptune</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coast</td>
<td>10</td>
<td>0</td>
<td>30</td>
<td>SKA</td>
<td>-15.21</td>
</tr>
<tr>
<td>Start of descent</td>
<td>100</td>
<td>0</td>
<td></td>
<td></td>
<td>-5.21</td>
</tr>
<tr>
<td>End of descent</td>
<td>100</td>
<td>15</td>
<td></td>
<td></td>
<td>-20.21</td>
</tr>
</tbody>
</table>

- Telemetry link also possible for Venus with SKA or VLBI
- 5 – 7 dB can be gained by using VLBI techniques.

### Conclusions

- Atmosphere effect needs to be addressed.
- Subsystem design: Flexible power and data rate to optimise the data return (2 kbps) and power consumption (> 300 W).
- Telemetry and carrier recovery as follows:

<table>
<thead>
<tr>
<th>Telemetry relay</th>
<th>Venus</th>
<th>Saturn</th>
<th>Uranus</th>
<th>Neptune</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier recovery DTE</td>
<td>35 m</td>
<td>OK</td>
<td>NOK</td>
<td>NOK</td>
</tr>
<tr>
<td>Telemetry DTE</td>
<td>SKA</td>
<td>NOK</td>
<td>NOK</td>
<td>NOK</td>
</tr>
</tbody>
</table>
Requirements

- **Pre-separation**
  - Probe DHS shall provide a connection with the Orbiter for periodic health check, DHS and DPU software patches, Mission Timers update

- **Coast**
  - Probe DHS shall be able to periodically wake up Communication system and GNC

- **Entry**
  - Probe DHS shall be in charge to control timing events (Parachute deployment etc.)

- **Descent**
  - Probe DHS shall trigger the initial Payload DPU switch-on
  - Probe DHS shall collect and transmit basic telemetry to the orbiter to indicate probe status and sequence phase
**Assumptions**

- No attitude control is required
- Low data processing capability is required during coast and entry phase
- Mission Timers are active during coast and entry
- Most of the data handling tasks are performed by the Data Processing Unit (DPU) as part of the Payload:
  - Scheduling of experiments
  - Data from Payloads acquisition, storage and transmission to the orbiter
  - Data formatting to transponder (encoding telemetry)

**Design drivers**

- High reliability and availability during entry and descent phase
  - Single point failure free design
  - Hot redundant system
  - Rad-hard design
- Very low power consumption during coast phase
  - Power-off not used functions
- Limited mass
Design summary

- There are three main units: one MTU, two CDMUs and a number of micro Remote Terminal (uRTU)
  - **Mission Timer Unit (MTU)**
    - Three independent hot redundant timer circuits and two hot-redundant voting and command circuits.
    - When at least two out of three time-out are received commands are sent to the PCDU to switch-on both CDMUs
    - During cruise all three timers can be programmed independently from one of the two CDMUs
    - During coast phase only the timers are powered
    - During entry/descend phase MTU is off

Design summary

- Command & Data Management Unit (CDMU)
  - Two hot redundant identical units executing the same functions
  - Each CDMU includes a simple and low power V8uC microcontroller. V8uC is a simplified version of the LEON2 processor with program memory and most of the peripherals on-chip
  - Essential Telemetry (ETM) ASIC is used to collect TM from uRTU during coast and entry and descent phase with no software intervention.
  - No main data connection between CDMU and Payloads
  - Events sequence during entry is software controlled by the CDMU
  - All Payload operations, data processing and delivery are controlled by DPU
**PEP DHS baseline**

- CDMU (uController)
- MTR
- P/L
- Camera
- DPU/Mass Memory
- PTME: Packet TM Encoder FPGA
- ETM: Essential TM ASIC
- V8uC: LEON based microcontroller
- MM: Mass Memory banks
- SCOC3: LEON Controller ASIC

**PEP DHS: option 1**

- JEP-like architecture but with power optimization in CDMU
- CDMU based on low power LEON uController (V8uC)
- Event sequences during entry / descent is software controlled by the CDMU
- Scheduling of experiments under CDMU software control
- Payload data processed by DPU but stored and delivered to the Orbiter by CDMU

**Pros:**
- High CDMU flexibility

**Cons:**
- CDMU hardware and software complexity
PEP DHS: option 1

- CDMU (uController)/Mass Memory
- MTR
- P/L
- Camera

PEP DHS: option 2

- CDMU based on fixed FPGA design, no software running.
- Events sequence during entry / descent is hardware controlled by the CDMU FPGA.
- Instruments operations controlled by DPU
- All Payload data handled, stored and transmitted to orbiter by DPU
- No main data connection CDMU-P/L

- Reduced harness
  - Very low power CDMU
  - Very simple and reliable CDMU

- Low CDMU flexibility
**PEP DHS: option 2**

**PEP DHS baseline budget**

- **Mass**

<table>
<thead>
<tr>
<th>Element</th>
<th>Unit Name</th>
<th>Part of custom subassembly</th>
<th>Quantity</th>
<th>Mass per quantity (kg)</th>
<th>Maturity Level</th>
<th>Margin</th>
<th>Total Mass incl. margin (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CDMU</td>
<td>CDMU</td>
<td>2</td>
<td>2.4</td>
<td>To be modified</td>
<td>10</td>
<td>7.5</td>
</tr>
<tr>
<td>2</td>
<td>MTR</td>
<td>MTR</td>
<td>1</td>
<td>2.3</td>
<td>To be developed</td>
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<td>2.6</td>
</tr>
<tr>
<td>3</td>
<td>LUTU</td>
<td>LUTU</td>
<td>6</td>
<td>0.2</td>
<td>To be modified</td>
<td>10</td>
<td>1.3</td>
</tr>
<tr>
<td><strong>SUBSYSTEM TOTAL</strong></td>
<td></td>
<td></td>
<td><strong>3</strong></td>
<td><strong>10.3</strong></td>
<td></td>
<td><strong>17.7</strong></td>
<td><strong>15.6</strong></td>
</tr>
</tbody>
</table>

- **Power consumption**

<table>
<thead>
<tr>
<th>Element</th>
<th>Unit Name</th>
<th>Part of custom subassembly</th>
<th>Quantity</th>
<th>Power (W)</th>
<th>Maturity Level</th>
<th>Margin</th>
<th>Total Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CDMU</td>
<td>CDMU</td>
<td>2</td>
<td>17.8</td>
<td>0.0</td>
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<td>17.8</td>
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<td>2</td>
<td>MTR</td>
<td>MTR</td>
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<td>0.3</td>
<td>0.0</td>
<td>100.0</td>
<td>0.3</td>
</tr>
<tr>
<td>3</td>
<td>LUTU</td>
<td>LUTU</td>
<td>5</td>
<td>1.6</td>
<td>0.0</td>
<td>100.0</td>
<td>8.6</td>
</tr>
<tr>
<td><strong>SUBSYSTEM TOTAL</strong></td>
<td></td>
<td></td>
<td><strong>3</strong></td>
<td><strong>19.7</strong></td>
<td></td>
<td><strong>100.0</strong></td>
<td><strong>19.7</strong></td>
</tr>
</tbody>
</table>
**Release Sequence from Interplanetary Orbit**

- Confirm and correct targeting  
  (usually 3 manoeuvres over 1 month duration)  
  Problems: Allow for a safe mode => set timing accordingly and use balanced thrusters, provide adequate coverage

- Baseline: Release of probe 20 days before Probe entry.

- Point spacecraft at entry point for Lander.

- Release spacecraft (from turntable): Pointing and release operations: several hours (longer with feedback loops)
**Spacecraft Entry Sequence**

- Typically one combined manoeuvre for heading spacecraft for orbit insertion manoeuvre and phasing for probe coverage.
- Tracking to adapt insertion manoeuvre parameters according to manoeuvre/approach errors.
- Spacecraft approach correction manoeuvre TBD.
- Insert safe mode recovery slots into planning.
- Probe entry under coverage from Earth and spacecraft (see SR-5)

**Release Sequence Drivers (1)**

- Requirement to monitor the landing by the spacecraft (see SR-5)
- Arrival time to be adjusted by ΔV manoeuvre and distance of separation manoeuvre (see SR-7)
- Special spatial relation of spacecraft and landing site required (see SR-7)
- Point spacecraft antenna) at entry point for Lander
- Relaxed sequence (20 days) operationally preferable to 6 days minimum sequence (but see SR-8)
- Safe fuel by early deflection manoeuvre (contradiction to SR-8)
- Do not require permanent coverage during drift phase
Release Sequence from Interplanetary Orbit Drivers (2)

- Relax requirements on $\Delta$DOR
- Relax requirements on safe mode or special modes
- Use redundancy for probe communications (DTE + relay)
- Reduce accuracy of the spacecraft targeting on b-plane

Beagle Release Sequence from Mars Express Spacecraft

- 6 days between Beagle Release and landing
- Targeting manoeuvre on the day after Beagle release
- Possibility of safe mode planned for, last day in fail safe mode with drastically reduced capability set
- Tracking required to adjust orbit insertion manoeuvre
- No tasks for Beagle relay or tracking for Mars Express at Beagle landing
- Sequence only possible with permanent coverage and $\Delta$DORs.

- Very compressed schedule requiring a lot of preparation and many simulations.
- Free choice of SOM would rather have been two weeks, but Beagle timer was only 6 days!
- Fail safe mode was drastic choice, switch off of Mass Memory meant no info on fuel usage (i.e. impact on life time still unknown).
THE HUYGENS PROBE RELEASE
(no Cassini capture into moon orbit)

- Upon Saturn arrival in June 2004, the spacecraft executed a Saturn Orbit Insertion manoeuvre.
- After this manoeuvre, Cassini initial orbital period around Saturn was about 152 days.
- Approximately 76 days after orbit insertion, the spacecraft executed a manoeuvre to raise its orbit periapsis and to target the combined Orbiter and Probe for Titan impact.
- The Probe was released from the Orbiter 20 days before the third Cassini Titan flyby.
- Two days after Probe release, the Orbiter performed an Orbit Deflection manoeuvre to place itself into a trajectory flying over the Probe landing site, to allow collection of Probe descent telemetry data.
- In order to receive relay data from the Probe, the Orbiter pointed its high-gain antenna at the predicted Probe entry point on Titan.

Possible Sequences Overview Table

<table>
<thead>
<tr>
<th>Sequence Type</th>
<th>Tracking Campaigns</th>
<th>Tracking Duration</th>
<th>Manoeuvre after day</th>
<th>Number of manoeuvres (TCR + touch up TBC)</th>
<th>Manoeuvre Duration (incl. pointing/repointing)</th>
<th>Manoeuvre Calculation with tracking info</th>
<th>Wait for Manoeuvre Uplink</th>
<th>Recovery Slot</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probe Release and Descent and Landing Communications</td>
<td>1</td>
<td>7</td>
<td>2</td>
<td>1</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>12</td>
</tr>
<tr>
<td>Probe Release and Descent and Landing Communications Correction Manoeuvre</td>
<td>2</td>
<td>6</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>8</td>
<td>12</td>
<td>3</td>
<td>19</td>
</tr>
</tbody>
</table>

The sequence is driven by the number of manoeuvres, because they require tracking slots in between. A single deterministic manoeuvre is compatible with the accuracy requirements for spacecraft capsule communications during capsule EDL.
**Capsule Housekeeping Data Requirements**

- General Housekeeping Control guideline:
  - Things happen (and change) only if the satellite/spacecraft is doing something
  - Very little change to be expected during cruise
  - Critical event to suddenly shut down communications very unlikely
  - Status report at long intervals proposed
  - Amount of data: few kb (can be negotiated)
  - HK compression proposed, will compress status data to few % or less
  - Send bursts of data every several hours (e.g. 25 kbit twice per day, i.e. 100 b/s for 5 minutes) during cruise
  - Traditional (continuous) housekeeping TM during descent
### Possible Sequences Overview Table

<table>
<thead>
<tr>
<th>Sequence Type</th>
<th>Tracking Campaigns</th>
<th>Tracking Duration</th>
<th>Number of manoeuvres (TOR + touch up TBC + insertion)</th>
<th>Manoeuvre Duration (incl. pointing/repointing)</th>
<th>Manoeuvre Calculation with tracking info</th>
<th>Wait for Manoeuvre Uplink</th>
<th>(Safe Mode) Recovery Slot</th>
<th>Total</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADOR Single Manoeuvre</td>
<td>1</td>
<td>3.5</td>
<td>2</td>
<td>4</td>
<td>8</td>
<td>4</td>
<td>1.5</td>
<td>6.0</td>
<td>very time pressed, permanent coverage</td>
</tr>
<tr>
<td>Doppler Single Manoeuvre</td>
<td>1</td>
<td>7.0</td>
<td>2</td>
<td>4</td>
<td>8</td>
<td>16</td>
<td>3.0</td>
<td>12.0</td>
<td>Feasible, but baseline is operationally preferred</td>
</tr>
<tr>
<td>Doppler Double Manoeuvre</td>
<td>2</td>
<td>7.0</td>
<td>3</td>
<td>4</td>
<td>8</td>
<td>16</td>
<td>3.0</td>
<td>20.2</td>
<td>Baseline, reduces insertion error</td>
</tr>
</tbody>
</table>
Requirements & Design Drivers

- Design a probe for entry and descent to either Venus, Saturn, Uranus or Neptune
  - Hyperbolic deployment of the probe from a carrier
  - Overall probe mass 200 kg to 300 kg
  - RF-link via carrier serving as relay to Earth
- Mission duration
- Environmental conditions
  - Aerothermodynamics phenomena and heat flux
  - Deceleration and temperature gradient during descent
  - Pressure during entry & descent
- Test capabilities
### Comparison of the Four Cases

<table>
<thead>
<tr>
<th>Subject</th>
<th>Venus</th>
<th>Saturn</th>
<th>Uranus</th>
<th>Neptune</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transfer time [year]</td>
<td>0.33-0.5</td>
<td>9</td>
<td>18.5</td>
<td>19.3</td>
</tr>
<tr>
<td>Coast time [days]</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Entry time [minutes]</td>
<td>1.77</td>
<td>1.77</td>
<td>1.77</td>
<td>1.77</td>
</tr>
<tr>
<td>Descent time [min]</td>
<td>60</td>
<td>90</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>Atmosphere</td>
<td>CO</td>
<td>He, H+</td>
<td>He, H+</td>
<td>He, H+</td>
</tr>
<tr>
<td>Entry velocity [km/s]</td>
<td>11.8</td>
<td>36.0</td>
<td>21.7</td>
<td>24.7</td>
</tr>
<tr>
<td>Max. heat flux [MW/m²]</td>
<td>59 (81)²</td>
<td>114</td>
<td>104</td>
<td>109</td>
</tr>
<tr>
<td>Max. deceleration [g]</td>
<td>-250 (-360)²</td>
<td>-200</td>
<td>-300</td>
<td>-325</td>
</tr>
<tr>
<td>Structure T [deg. C]</td>
<td>&lt; 450</td>
<td>&lt; 190</td>
<td>&lt; 50</td>
<td></td>
</tr>
<tr>
<td>Pressure [bar]</td>
<td>92</td>
<td>1 – 100</td>
<td>4 – 100</td>
<td>10 - 100</td>
</tr>
</tbody>
</table>

1) worst scenario assumed    2) flight path angle = -50 instead of -25

### Assumptions & Trade-Offs

- The design of the four probes is similar in general layout, mass, payload
- Differences are in details like TPS thickness, parachute deployment scenario
- “Test as you fly”, as far as possible
- Test requirements are similar, at least for the outer planets
- Lifetime and radiation dose might require special attention
**Payload**

- The payload consists of 5 instruments, based on existing units with high TRL:
  - ASI/MET
  - Mass spectrometer (MS)
  - Doppler Wind
  - Camera
  - Photometer
  - Data processing unit and power converter

- A challenge is the mission duration to the outer planets.

**Options**

- Alternative equipment or components might be developed, providing better performance or reliability e.g.
  - TPS
  - batteries
**Technology Development**

- Most TRL of envisaged subsystem and equipment are 5 or higher
- Exceptions are:
  - GNC IMU  TRL 4-5  (guidance navigation and control – inertial measurement unit)
  - Front heat shield  TRL < 5
  - Back cover  TRL 3-4

**TPS Testing**

- Aerothermodynamics analysis and TPS design will have to rely heavily on modelisation
- Models will have to be validated by testing
- TPS material will have to be qualified at very high heat fluxes
- Aerothermodynamics phenomena and heat flux range generally beyond the capabilities of existing facilities
European available aerothermodynamic facilities

- In Europe, facilities from:
- ALTA (Pisa, Italy);
- ARC (Seibersdorf, Austria);
- ASTRIUM-ST (Aquitaine, France);
- CAEPE (Aquitaine, France);
- CIRA (Capua, Italy);
- CORIA (Rouen, France);
- DLR (Cologne and Göttingen, Germany);
- FOI (Stockholm, Sweden);
- GDL (Farnborough, United-Kingdown);
- HTG (Katlenburg-Lindau, Germany);
- ICARE (Orléans, France);
- IRS (Stuttgart, Germany);
- ISL (Saint-Louis, France & Germany);
- Oxford University (UK);
- IUSTI (Marseille, France);
- LAEPT (Clermont-Ferrand, France);
- Max Planck Institute for Plasma Physics (Garching, Germany);
- ONERA (Toulouse and Modane, France);
- PROMES (Odeillo, France);
- RWTH (Aachen, Germany);
- TNO (Rijswijk, The Netherlands);
- TU Braunschweig (Braunschweig, Germany);
- UMIST (Manchester, United-Kingdown);
- UNINA (Naples, Italy);
- VKI (Brussels, Belgium).
- NLR, Amsterdam, The Netherlands
- DNW, various locations in NL and D
**Future ESA Aerotherm.-facility**

- **Kinetic shock tube** for radiation data base for planetary exploration - (almost) at KO June/July 2010 – end July 2012  
  - TRP: T217-052MP-  
  The focus of the activity is on the construction and acceptance of a shock tube and associated initial instrumentation set  
  - Test evaluated costs – **120 k€/test campaign** (200 shots, 3 months)  
  - Activity focuses on defining, constructing and commissioning a shock tube for the study of high temperature chemical kinetics and radiation. Provides clean high temperature plasmas, at ranges of enthalpies and pressures relevant for Mars, Venus and Earth orbital and hyperbolic entries, for representative gas mixtures.  
  - Additional objectives include:  
    - setting adequate measuring techniques incl. data handling H/W and S/W  
    - studying relaxation after a shock wave  
    - validating chemical models  
    - identifying the main radiative species and transition  
    - measuring heat flux directly  
  - Assessing aero forces and moments on models (needs further develop)

**TPS Testing – Plasma facilities**

Starting point JEP with updated values

- Most powerful (in terms of heat-flux) European TPS facilities:  
  - SCIROCCO (CIRA) - segmented arc heater - 3.8 MW/m²  
  - L3K (DLR) - segmented arc heater - 12 MW/m² @ 1300mbar  
  - Plasmatron (VKI) - available 6.5 MW/m² @ 600mbar  
  - SIMOUN (EADS) – Huels arc heater - 7 MW/m² @ 170-270mbar  
  - COMETE (EADS) – Plasmatron – 7 MW/m²  
  - JP 200 (EADS) - Huels arc heater  
    - 80 MW/m² @ 5-50bar  
    - 5 MW/m² @ 1.5bar & 25 MW/m² @ 9bar  
  - High Pressure (EADS) – Huels arc heater – 150 MW/m² (NOT confirmed from Aerothermodynamic group)  
  - PWK4 (IRS) – Magnetoplasmadynamic generator – 3 MW/m² @ 5kPa  
  - RD5 (IRS) 14 MW/m² @ 50 mbar
TPS Testing – Plasma facilities

- **SCIROCCO (CIRA)** – arc jet test facility for large model testing
  - Available: **3.8 MW/m² @ up to 200mbar**
  - Test campaign ~ 75k/test
  - Future projects: - ESA TRP (Aurora E15) - up-grade SCIROCCO facility to more than **20 MW/m²** at approximately 1 atmosphere for 2.5 cm sample in order to validate the TPS for super-orbital Earth Entries (focuses on flow determination around the capsule in realistic pressure and enthalpy). **Delays. Expected November 2010**
  - **Scirocco does not operate with CO2.** SIMOUN does. Upgrade of SCIROCCO for CO2 feasible to allow CO2 flow, but cost could not be offered by Aurora – estimated to about 1.5MEuros (necessary for Venus).
    - heat fluxes/pressure combinations between **15MW/m² @ 1300mbar** and **6MW/m² @ 350 mbar** investigation of the feasibility to up-grade SCIROCCO Plasma Wind Tunnel to reproduce flows representative of super-orbital Earth entries.
  - * SCIROCCO has a potential of more, but was not tested. From the chart of the AWG meeting 25-26/1/07, there are values up to 10MW/m² indicated.*

- **large size model tests**
  - Test Articles Size: 600 mm from design/ 800 mm tested
  - Test Chamber Size: H=9m, D=5m;
  - Not cooled,
  - Many windows
  - 4 Conical Nozzles available: 900, 150, 1350, 1950 mm
TPS Testing – Plasma facilities

- SCIROCCO (CIRA) – arc jet test facility for large model testing

PERFORMANCES
Test Duration (max) 1800s
Stagnation Pressure 5.0 – 175.0 mbar
Test Gas Dry Air + Argon (1-4%)  
Stagnation Heat flux(1) 125 – 1035 kW/m²
Massflow 0.2 – 3.5 kg/s
Total Enthalpy 2.5 – 45 MJ/kg
Reservoir Pressure 1.0 – 17 bar
Maximum Arc Power 70 MW
Flow Speed 2000 – 7000 m/s

Nozzle A offers 10 MW/m² @20-50 kPa

PEP - Assessment Study

TPS Testing – Plasma facilities

- DLR (Cologne and Göttingen, Germany)
TPS Testing – Plasma facilities

– L3K (DLR)
  • segmented arc heater – small samples (max 40mm in diameter, 40 in height)
  • Available: 11.5 MW/m² @ 1300mbar
  • Test campaign: ~100-200 k
  • Future projects: DLR is considering to upgrade L3K up to 14 MW/m² @. More representative pressure levels (TBC depending on available funding)
  - If ESA-DLR join efforts, the ESA contribution is estimated to about 50k (extension from 4 to 5-pack burner, characterisation tests)

TPS Testing – Plasma facilities

• Plasmatron – VKI –Belgium
  • Available up to 6.5 MW/m²@ 600mbar and tested also at 10 MW/m²
  • Test campaign – ROM cost:?
  • Future projects: 2009-VKI decided to construct and build a newly designed nozzle which accelerates the flow and thus helps to achieve higher heat flux. Using the new nozzle, VKI expects to reach the order of 10MW/m² and dynamic pressures close to 800 mbar. The characterization tests with this nozzle are expected to be finalized end of 2009 (presented at 6-th workshop April 2009)
  • The Plasmatron is a subsonic facility which has to be compared with the MPD RD5/ RD7 facilities of IRS. This facility makes proper simulation of shear forces impossible and puts some question mark concerning the reported pressures (other rules might apply for different situations).
• MPD RD5 (IRS)
  • Available: Demonstrated up to 14 MW/m², but @ < 50 mbar
  • Compliant with high heat fluxes requirement but compromising on flux/pressure combination
    - price equivalent ~ It is mostly the price of PhD or researcher. It is not a real cost. Typical is 50-100 kEuros for a campaign.
TPS Testing – Plasma facilities

– EADS/ST

- SIMOUN facility -heat fluxes close to 7 MW/m² @ 170-270 mbar
  Accumulated heat load during testing was ~170 MJ/m², but other configuration also possible: 5 MW/m² @ 200-500 mbar stagnation point configuration.
- SIMOUN advantage- operates with CO2 flow (necessary for Venus)
- JP 200 facility – 2 configurations can be tested:
  - In the stagnation configuration an axysymmetric nozzle is used to test hemispherical, cylindrical and conical test samples. Maximum cold wall heat fluxes up to 80 MW/m² @ 5-50 bar (dynamic pressures)
  - In the duct configuration a rectangular nozzle exit is used to test parallelepipedic test samples under parallel flow. Heat flux/pressure combinations are between 5 MW/m²/1.5 bar and 25 MW/m²/9 bar.

TPS Testing Approach

1. Build a new facility capable to reproduce as close as possible the aerothermodynamics of the outer planets entry and that can be used for CFD validation and TPS testing
2. Split the testing problem in two:
   - Partial validation of CFD models in existing facilities (with modifications)
   - Testing of TPS at high fluxes generated by e.g. radiative facilities
Deceleration Testing

Galileo experienced 228 g during descent (comparable to our Probe)

Individual probe components on a (small) centrifuge to as high as 350 g

- Fully assembled, the probe was too massive to be spun that high on any centrifuge in the world.
- Fully assembled probe tested at 200 g on large centrifuge at Sandia National Laboratories Centrifuge facility (was already existing)
- This centrifuge can subject test packages weighing up to 7,260 kg to 100 g, or lighter weight packages up to 300 g.
- Such facility does not exist in Europe. Test will probably have to be done in US

Deceleration Testing

- Centrifuges up to 200 g for equipment exist in Europe (DLR, Berlin, Centrifuge Z100 / 200)
  - Max. payload: 200 kg (at 50 g)
  - Max. acceleration: 200 g (with 50 kg)
  - Max. dynamic load: 100 000 N
  - Effective central radius: 1800 mm
- For components even higher levels can probably be achieved in Europe on smaller centrifuges (tbc)
- At probe level test is preferable over analysis because property or workmanship variations can initiate failure under extreme loads, in particular for non-conservative structures, e.g. TPS, EDS
Pressure Testing

• During descent high pressure, up to 100 bar is encountered by the probes.
• Pressure testing up to such pressures is not difficult, but typically high pressure chambers are not used in aeronautical testing.
• Identification of suitable facilities, in particular concerning cleanliness is necessary. Possibly such facility needs to be procured.

Testing Conclusions

• Validation of CFD models is the key issue. More detailed investigation on the existing European facilities is needed to assess limitations
• Faithful reproduction of flow field and associated phenomena will be anyway impossible
• Heat flux computation will be subject to high uncertainty. High margin on TPS design required
• Testing of TPS at the required high fluxes is possible on small samples
• High qualification factors will have to be applied (e.g. factor 2 on heat fluxes)
## Model Philosophy

### Probe Models

<table>
<thead>
<tr>
<th>Sample</th>
<th>SM</th>
<th>EM</th>
<th>QM</th>
<th>Scaled models</th>
<th>FM</th>
</tr>
</thead>
<tbody>
<tr>
<td>TPS</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Entry and Descent System</td>
<td>X</td>
<td>X</td>
<td></td>
<td>Hypersonic testing + high thermal</td>
<td>X</td>
</tr>
<tr>
<td>Parachutes</td>
<td>TBD</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Descent Module</td>
<td></td>
<td>Functional and environ. tests</td>
<td>Functional and environ. tests</td>
<td>Aerodynamics testing</td>
<td>X</td>
</tr>
<tr>
<td>Probe System</td>
<td>Separation, Comm’s etc.</td>
<td>EM+ environm. + ref. ground config.</td>
<td>TBD</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>

### Model Philosophy

<table>
<thead>
<tr>
<th>Description</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SM Structural Model</strong></td>
<td>Pressure tests required on all sealed structures</td>
</tr>
<tr>
<td>Flight standard structures and mechanisms</td>
<td></td>
</tr>
<tr>
<td><strong>EM Engineering Model</strong></td>
<td>Also representative of layout, shapes and interfaces.</td>
</tr>
<tr>
<td>Functional and electrical performances represented. Commercial components.</td>
<td></td>
</tr>
<tr>
<td><strong>QM Qualification Model</strong></td>
<td>Shall include acceleration and pressure tests. Facilities TBD</td>
</tr>
<tr>
<td>Full flight standard with all redundancies.</td>
<td></td>
</tr>
<tr>
<td><strong>Scaled models</strong></td>
<td>Special facilities needed for the higher part of the aero-thermal field</td>
</tr>
<tr>
<td>Representative for aerodynamics / aero-thermal (depending on the test)</td>
<td></td>
</tr>
<tr>
<td><strong>FM Flight Model</strong></td>
<td>Including pressure tests</td>
</tr>
<tr>
<td>Flight vehicles, including spare units and parts</td>
<td></td>
</tr>
<tr>
<td><strong>Samples</strong></td>
<td>Special facilities needed</td>
</tr>
<tr>
<td>Assessing TPS and shield vs. high aero-thermal</td>
<td></td>
</tr>
</tbody>
</table>
**Model Philosophy**

- Environmental test is challenging due to outer planet's and Venus' extreme environment
- In addition to providing adequate facilities, also making representative testing is a hot topic
- i.e. extreme environment conditions could be reached, but not in the proper combination, or not for long enough
- Qualification will anyway have to trust analytical extrapolation on top of correlation
- Thus the extreme environmental conditions will NOT be qualified on a FULL SCALE test model.
- Unit level: acceleration qualification needed
**Schedule Assumptions**

- Only one probe is considered here – building two probes together, even for different planets, will benefit from each other.
- Most of the development on TPS material shall be completed within Phase B.
- TPS material development should begin about 3 years before Probe Phase B K.O. (even by making use of *existing* facilities).
- Combined functional tests with an Orbiter are taken into account in the schedule.
- Combined environmental tests with an Orbiter are taken into account.
- Orbiter development is not included.

---

**Schedule Assumptions**

- Facility needed for qualifying the Probe TPS, should be ready and operational *by the beginning of Phase B*.
- Facility should be kept available *along Phase C/D until QR*, in support of Probe development.
- **NOTE**: EM Probe level functional tests are marked on the schedule as TBD because there is a possibility that they are not needed, in case all functions can be verified at DM EM level.

(Free piston shock tunnel HEG, Picture: Courtesy DLR)
Schedule Assumptions

- Assessment phase starting in 2011, duration 2 years
- Phase A / B1 duration 2 years
- Phase B2 / C / D duration 5 years
Summary & Critical Issues

- TPS qualification and acceptance
- Equipment qualification and acceptance for very high deceleration
- System qualification and acceptance for high pressure
- Long mission duration to outer planets (*Will it still work?*)
- Planetary protection issues?
- Use of RHU has an important impact on programatics

Conclusions

- Provided development starts early 2011, the acceptance review could be foreseen end 2020
- This requires early identification of detailed development and verification approach and ensuring the readiness and availability
**Outline**

- Risk Management Policy
  - Objective
  - Project Goals
  - Severity & Likelihood Categorizations
- Top Risk Log
- Probabilistic Risk Assessment
- Conclusions
**Risk Management Policy: Objective**

- **Maximize** the probability of achieving PEP’s intended goals and to contribute to the projects’ risk management process
- The CDF risk management policy for PEP aims at **handling risks** which may cause serious negative cost, schedule, technical and/or science value impacts on the project
- **Risk Management Process definition:**

  An organized, systematic decision making process that efficiently identifies, analyzes, plans, tracks, controls, communicates, and documents risk to increase the likelihood of achieving the project goals.

**Risk Management Policy: Project Goals**

| SRE          | The Planetary Entry Probe(s) shall investigate the characteristics of the Planetary atmospheres of Venus (VEP), Saturn (SEP), Uranus (UEP) and Neptune (NEP):
|             | - Atmospheric profiles (temperature, pressure, density)
|             | - Chemical composition (abundances & isotopes)
|             | - Optical properties and features (surface and atmosphere)
|             | - Measure wind direction and magnitude |
| Technical    | The Planetary Entry Probe(s) platform shall perform correctly during all mission phases incl. launch, transfer, separation, **coast, entry, and descent.** |
| Schedule     | Mission Timeframe shall be 2020-2035 |
| Cost         | Cost at completion shall be within the M-class mission budget |
## Risk Policy: Severity/Likelihood Categorization & Risk Index

<table>
<thead>
<tr>
<th>Severity</th>
<th>Schedule</th>
<th>Science</th>
<th>Technical (ECSS-Q-30 and ECSS-Q-40)</th>
<th>Cost</th>
<th>Score</th>
<th>Likelihood</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catastrophic</td>
<td>Launch opportunity lost</td>
<td>Failure leading to the impossibility of fulfilling the mission's scientific objectives.</td>
<td>Safety: Loss of system, launcher or launch facilities. Loss of life, life-threatening or permanently disabling injury or occupational illness. Severe detrimental environmental effects.</td>
<td>Cost increase in estimated cost (TBD M€)</td>
<td>E (5)</td>
<td>Maximum</td>
<td>Certain to occur, will occur once or more times per project</td>
</tr>
<tr>
<td>Critical</td>
<td>Critical launch delay (TBD) months</td>
<td>Failure results in a major reduction (70-90%) of the mission's science return.</td>
<td>Dependability: Loss of mission. Safety: Major damage to flight systems, major damage to ground facilities. Major damage to public or private property. Temporarily disabling but not life-threatening injury, or temporary occupational illness. Major detrimental environmental effects.</td>
<td>Critical increase in estimated cost (TBD MK)</td>
<td>D (4)</td>
<td>High</td>
<td>Will occur frequently, about 1 in 10 projects P=0.1 R=0.9</td>
</tr>
<tr>
<td>Major</td>
<td>Major launch delay (TBD) months</td>
<td>Failure results in an important reduction (30-70%) of the mission's science return.</td>
<td>Dependability: Major degradation of the system. Safety: Minor injury, minor disability, minor occupational illness. Minor system or environmental damage.</td>
<td>Major increase in estimated cost (TBD MK)</td>
<td>C (3)</td>
<td>Medium</td>
<td>Will occur sometimes, about 1 in 100 projects P=0.01 R=0.99</td>
</tr>
<tr>
<td>Significant</td>
<td>Significant launch delay (TBD) months</td>
<td>Failure results in a substantial reduction (&lt;30%) of the mission’s science return.</td>
<td>Dependability: Minor degradation of system (e.g., system is still able to control the consequences). Safety: Impact less than minor</td>
<td>Significant increase in estimated cost (TBD K€)</td>
<td>B (2)</td>
<td>Low</td>
<td>Will occur seldom, about 1 in 1000 projects P=0.001 R=0.9999</td>
</tr>
<tr>
<td>Minimum</td>
<td>Minimal consequences</td>
<td></td>
<td></td>
<td></td>
<td>A (1)</td>
<td>Minimum</td>
<td>Will almost never occur, 1 in 10000 projects P=0.0001 R=0.99999</td>
</tr>
</tbody>
</table>

### PEP - Assessment Study

## Top Risk Log

<table>
<thead>
<tr>
<th>Risk Type</th>
<th>Risk Index</th>
<th>Risk scenario</th>
<th>Classification</th>
<th>Cause</th>
<th>Mitigating Action 1</th>
<th>Mitigating Action 2</th>
<th>Mitigating Action 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launcher</td>
<td>5C</td>
<td>Launch window constraints for missions to outer planets (Uranus, Neptune and to a lesser extent Saturn).</td>
<td>Schedule</td>
<td>Very lengthy gap between launch windows. Missing launch opportunity would imply mission cancellation.</td>
<td>Plan schedule accordingly with sufficient risk margins.</td>
<td>At least 6-month margin between FAR and the launch campaign.</td>
<td>Baseline launch date offering 2nd launch opportunity within acceptable timeframe. (e.g. Neptune LD 2030 case)</td>
</tr>
<tr>
<td>Mission</td>
<td>4D</td>
<td>Uncertainties related to planetary atmospheric models (especially in the case of the outer planets Uranus and Neptune) with impact on the TPS materials choice and design.</td>
<td>Technical</td>
<td>Wrong estimates of heat fluxes, heat loads (e.g., of heat fluxes), peak deceleration.</td>
<td>Refine atmospheric models and entry trajectory analyses for the outer planets.</td>
<td>Design including sufficient safety margin.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4C</td>
<td>Critical probe-orbiter tracking, targeting &amp; separation sequence: Heavy impact on spacecraft operations.</td>
<td>Technical</td>
<td>High accuracy of spacecraft targeting. Tracking required. Compressed schedule demands a lot of preparation and many simulations.</td>
<td>Reduced release sequence. Releases at least 20 days ahead of entry (piggy-back case).</td>
<td>Use double double maneuver sequence (pyramidal OPS) which reduces insertion error as compared with single maneuver. DOOR Single Maneuver requires only 6 days rather than 20 days but is very time pressed and requires continuous coverage.</td>
<td>Insert safe mode recovery slabs into planning.</td>
</tr>
</tbody>
</table>

### PEP - Assessment Study

Risk - 5

Risk - 6
### Top Risk Log

<table>
<thead>
<tr>
<th>Risk Type</th>
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<tbody>
<tr>
<td>Mission</td>
<td>4C</td>
<td>Critical planetary entry conditions. Limited entry trajectories satisfying all requirements (sun illumination, Earth visibility (DTE comms) or orbiter visibility (relay comms)). Short probe coverage time throughout descent.</td>
<td>Technical</td>
<td>Sun illumination. Loss of orbiter/Earth visibility before end of nominal science mission.</td>
<td>Optimize entry trajectories to maximize probe coverage throughout descent.</td>
<td>Accept limited entry cases.</td>
<td>Use redundant DTE &amp; relay communication.</td>
</tr>
<tr>
<td></td>
<td>4B</td>
<td>Critical Saturn ring gap crossing. Particle collision risk.</td>
<td>Technical</td>
<td>Higher probability of impact with small size debris (water Ice).</td>
<td>Precisely defined ring regions. Relatively well-known environment.</td>
<td>Low impact probability if passage is at clear gaps (e.g. between the rings F and G rings)</td>
<td>Single ring crossing. Appropriate shielding.</td>
</tr>
<tr>
<td></td>
<td>3D</td>
<td>Planetary protection issues impact technical requirements and schedule.</td>
<td>Schedule/technical</td>
<td>Forward contamination of target celestial bodies. Requirements on documentation, cleanliness standards, and sterilization.</td>
<td>COSPAR PP classification: Category I: Venus. No protection of such bodies is warranted and no planetary protection requirements are imposed by this policy. Category II: Saturn, Uranus, and Neptune.</td>
<td>Plan schedule accordingly with sufficient margins to account for PP related delays.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4D</td>
<td>Low TRL of mid/low density ablative TPS heat shield materials (optimal TPS solution for Venus case instead of heritage Carbon Phenolic). Development risk implications</td>
<td>Schedule/technical</td>
<td>Large number of non-qualified materials or elements at research level only. Development challenges.</td>
<td>Development program to raise the TRL and reduce the risk of ablative TPS materials and heat shield systems.</td>
<td>Invest in technology and testing. Evaluate arc jet and other testing capabilities. Prioritize determination of material properties and failure modes. Certification by combination of testing and analysis.</td>
<td>Development time is considered sufficient given launch date objectives (2020-2035).</td>
</tr>
<tr>
<td></td>
<td>4D</td>
<td>Uncertainties in RF signal atmospheric losses in Venus/Saturn/Uranus/Neptune.</td>
<td>Technical</td>
<td>Atmospheric loss can be significant due to high pressure. Clouds can cause high attenuation at specific frequencies. Plan radiation can also block some frequencies.</td>
<td>An assessment of the atmospheric composition shall give the final exact frequency.</td>
<td>Select appropriate frequency to minimize signal attenuation.</td>
<td>A scenario in which the carrier is directly overhead as the probe goes deep in the atmosphere of the entry planet is suitable.</td>
</tr>
<tr>
<td></td>
<td>4D</td>
<td>Uncertainties in parachute deployment dynamic pressure leading to parachute malfunction, insufficient drag, higher than expected descent velocity.</td>
<td>Science/technical</td>
<td>Uncertainties in the external environment (atmospheric density), deployment Mach number.</td>
<td>Design parachute to operate safely without failure in a wide range of dynamic pressures.</td>
<td>Refine atmospheric models and entry trajectory analyses for the outer planets.</td>
<td></td>
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<tr>
<td>Criticality of 100 bar pressure vessel and associated technologies.</td>
<td>Schedule/technical</td>
<td>No existing European representative testing facilities. PV's represent one of the single largest mass elements in a deep atmospheric probe. Present state of the art PV technologies are not adequate for the mass requirements of these missions.</td>
<td>Appropriate PV design guidelines with adequate margins.</td>
<td>Develop manufacturing engineering plans and obtain prototypes for leading candidate materials. Perform testing on prototypes under representative environmental conditions for temperature and pressure survivability.</td>
<td>Invest in testing facility.</td>
<td></td>
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</tr>
<tr>
<td><strong>4D</strong></td>
<td></td>
<td>Critical planetary entry parachute technology and related control systems.</td>
<td>Schedule/technical</td>
<td>Beagle2 heritage (Lindstrand Technologies Limited UK)</td>
<td>Invest in European technology and testing facilities.</td>
<td>Sub-contract to US manufacturers in case of schedule constraints (e.g. IRVIN Aerospace (USA) was responsible for Huygens' parachutes and the probe's descent control sub-system under contract to Martin-Baker Space Systems UK)</td>
<td></td>
</tr>
<tr>
<td><strong>4C</strong></td>
<td></td>
<td>Critical Planetary Entry Probe separation and entry sequence (incl. carrier separation, parachute deployment/activation, from back shield separation, harness cut)</td>
<td>Single Point Failure Mechanisms</td>
<td>Single actuation and short duration events.</td>
<td>Mechanisms' reliability should be demonstrated to be greater or equal to the reliability goal with at least 95% confidence. Use mechanisms with heritage (e.g. Cassini-Huygens)</td>
<td>All Pyrotechnic devices are equipped with redundant ESA standard actuators.</td>
<td></td>
</tr>
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### PEP - Assessment Study

**Risk** - 9

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</tr>
<tr>
<td><strong>3E</strong></td>
<td></td>
<td>Challenging thermal-structural analysis for ablative materials.</td>
<td>Technical</td>
<td>Statistical material properties do not exist for most TPS materials. Obtaining mechanical properties (highly non-linear) across a wide temp. range is challenging and for TPS materials often produce large variations. Failure modes are poorly understood.</td>
<td>Thermal-structural design and analysis based upon FEM is insufficient – combined environment testing, with thermal gradients and mechanical loads is needed.</td>
<td>Experience/time required to develop a credible and validated series of FEM models for an integrated heat shield to assess various load cases.</td>
<td>Invest time in establishing an acceptable thermal-structural margins policy.</td>
</tr>
<tr>
<td><strong>3E</strong></td>
<td></td>
<td>Heritage carbon phenolic from Pioneer-Venus and Galileo (Venus entry case) no longer manufactured.</td>
<td>Schedule/technical</td>
<td>Very limited supply of heritage CP. Current CP employs carbon cloth derived from new rayon source. Limited are jet tests show performance similar to heritage.</td>
<td>Characterization and qualification is straightforward but will require time and resources. Test in high energy laser facility to demonstrate capability at maximum combined heat flux. Vary absence of failure modes.</td>
<td>Test in CO2 arc jet to demonstrate applicability of theoretical thermochemical ablation models to performance in Venus atmosphere.</td>
<td>Validate/update heritage in-depth thermal response models via arc jet tests of instrumented samples at well-defined conditions. Combine surface ablation and in-depth thermal response models into Venus entry design model for carbon phenolic.</td>
</tr>
</tbody>
</table>

### PEP - Assessment Study

**Risk** - 10
### Top Risk Log

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</tr>
</thead>
<tbody>
<tr>
<td>Platform</td>
<td>3D</td>
<td>Limited capability of ground testing facilities (e.g. arc jet) for TPS ablative materials (e.g. EADS Simoun 6 MW Facility or DLR L2K)</td>
<td>Schedule</td>
<td>Low number of available testing facilities. Even an ideal ground test facility will not fully replicate flight environments forcing difficult ground-to-flight traceability efforts. Prone to high-down time.</td>
<td>Plan schedule accordingly. Insert margins in schedule.</td>
<td>Invest in facilities.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3C</td>
<td>Ablative materials manufacturing complexity</td>
<td>Technical</td>
<td>Restarting the manufacturing of previous TPS materials takes significant time and resources. Significant fabrication experience is required to produce quality and consistency.</td>
<td>Investment required to establish necessary infrastructure.</td>
<td>Selection of experienced TPS manufacturer.</td>
<td></td>
</tr>
</tbody>
</table>

### Risk Index Chart

- High risks are typical of a Pre-Phase A Project. Areas with lack of definition or little previous experience pose a priori more risk to the mission and therefore are the ones with more risk reduction potential.
- Experience shows that all risk items with a critical risk index (red/yellow area) must be analyzed and proposals for risk treatment actions elaborated.
- For the remaining risk items there is an alert with respect to a possible increase of the Risk Index.
- In the end, ideally all risk items should reach a level of justifiable acceptance.
- The risk management process should be further developed during the project definition in order to analyze the entire system, refine the risk identification and classification, and provide evidence that all the risks have been effectively controlled.
• Methodology* based on Event Sequence Diagrams (ESD)
• Modelling capabilities:
  – System hierarchy and mission timeline
  – Each scenario in an ESD consists of a unique sequence of occurrences and non-occurrences of pivotal events leading to an end state, which designates the severity of the outcome of a particular scenario
• Analysis Procedure:
  – Individual EDS’s are resolved, resulting in Boolean expressions for each scenario and state
  – Results of individual ESD’s are aggregated, in order to compute risk at higher levels in the system hierarchy


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**PRA Assumptions**

• Equipment list and redundancy from VEP CDF Model
• Mission timeline begins at t=0 orbiter separation and consists of 3 main phases:
  – Cruise
  – Entry
  – Descent
• Equipment operational intervals and/or actuation times from CDF Model
• Equipment failure rates extracted from in-house database (time based-operational interval)
• Point value estimates for on-demand based events
• No uncertainty considered in input variables
**PRA Results**

- VEP System End State Results:
  - Loss of Mission (LOM) Probability: 19.03%
  - Minor Mission Degradation: 11.98%
- % contribution by S/S to LOM Probability
- # Cut sets leading to LOM considering all mission phases: 90
  - Max Order 2: 53
  - Max Order 3: 36
  - Max Order 4: 1

![% of LOM Probability Chart]

**Conclusions**

- Environment
  - Atmospheric modelling and its impact on TPS, communication, and EDL (parachute deployment)
- Technology Development
  - European low density TPS materials and manufacturing processes
  - European parachute technology
  - 100 bar pressure vessel
- Major Mission Events (Targeting/Separation/Entry/Descent)
  - Minimize SPFs
  - Demonstrate mechanisms/EDL system reliability on-ground
- Long mission duration (lifetime) for outer planets
  - Uranus & Neptune transfer time 18-20 years
PEP
Planetary Entry Probes

Annex I: Atmospheric Models for Outer Planets

IFP
ESTEC, 30th June 2010

Prepared by the PEP/ CDF* Team

(*) ESTEC Concurrent Design Facility
Atmospheric Models for Saturn

- Initial models used in the calculations were derived by ESA technical support and are denoted as Reference [B].
- These models have been compared to the data provided in [RD1: Giant Planets of Our Solar System: Atmospheres, Composition, and Structure; P. Irwin; 2009] and [RD2: The Planetary Scientist's Companion; K. Lodders, B. Fegley Jr, 1998].
- Furthermore, the models have been compared to models kindly provided by Dr. A. Coustenis of the SSEWG: [RD5: Tristan Guillot, published in Guillot, 1999 "A comparison of the interiors of Jupiter and Saturn", Plan. Space Sci. 47, 1183; and Saumon & Guillot, 2004, "Shock Compression of Deuterium and the Interiors of Jupiter and Saturn", ApJ 609, 1170; numerical data via personal communication].

- General remarks about the models:
  - Profiles for simulation are for +700 to -500 km for Saturn. Profiles available through references cover only parts, [RD5] mainly the lower parts from > 1bar. This data does not affect the entry phase but impacts the descent phase.
  - The models from [RD5] differ strongly in the altitude at which they reach 10 bar. Within 2 km there is a 9 bar discrepancy between the models.
  - 1 bar altitude shifted to 0 km to make comparison possible (reference used at CDF).
  - Two models provided: One static homogeneous model without He discontinuity at 1 Mbar (not matching observed J4) and one static model with He discontinuity at 1 Mbar (matching observed J’s).
**Comparison to References - Saturn**

- Red Lines: Model used in study [B]
- Blue dots: RD[1,2]
- Green Line: RD[5], Model w/ He - discontinuity
- Magenta Line: RD[5], static homogeneous Model w/o discontinuity

**Evaluation:**
- Density difference is $<2\%$ between [B] and [RD5] (both models)
- Pressure difference $<15\%$ between [B] and [RD5] (both models)
- Temperature profile differs strongest by $<18\%$ (gradually increasing to that value with depth)
- Good agreement between models in lower parts

*PEP - Assessment Study*
Atmospheric Models for Uranus and Neptune

• Initial models used in the calculations were derived by ESA technical support and denoted as Reference [B]
• These models have been compared to the data provided in [RD1: Giant Planets of Our Solar System: Atmospheres, Composition, and Structure; P.Irwin; 2009] and [RD2: The Planetary Scientist's Companion; K. Lodders, B. Fegley Jr, 1998].
• Furthermore, the models have been compared to models kindly provided by Dr. A. Coustenis of the SSEWG: [RD3: M. Herzig et al., in preparation, obtained via personal communication] and [RD4: Fortney, Ikoma, Nettelmann, Guillot & Marley, submitted to Icarus, via personal communication].

• General remarks about the models:
  – Profiles for simulation are from +700 to -300 km for Uranus and +600 to -225 km for Neptune. Profiles available through references cover only parts, [RD3,4] mainly the lower parts from +20 to -400/500 km. This data does not affect the entry phase but impacts the descent phase.
  – There are relatively large differences between [RD3 and RD4]
  – Differences in the lower part, however, mainly lead to different descent timing and thermal evolution.
  – Taking into account the largest differences, the margin policy applied during the study should be able to cope with these variations during entry and not lead to significant impacts on the design. (cf the sensitivity analysis and margin policy sections)
Comparison to References I - Uranus

- Red Lines: Model used in study [B]
- Blue dots: RD[1,2]
- Magenta Line: RD[3]

Evaluation:
- All profiles in good agreement
- Pressure differences < 5%
- Temperature differences <17%
- Differences in the temperature profile mainly affect the thermal calculation but are small enough to be covered by the study margin

PEP - Assessment Study
Comparison to References II - Neptune

- Red Lines: Model used in study [B]
- Blue dots: RD[1,2]
- Magenta Line: RD[3]

Evaluation:
- Except temperature, profiles in good agreement
- Between [B] and [RD3]: <5% difference in pressure, <20% difference in temperature
- Between [B] and [RD4]: density differs by factor of 2, pressure by factor 2 ½, temperature max. difference is factor 2.
- Between [RD3] and [RD4]: roughly as between [B] and [RD4].
- In general, [RD4] profiles change faster with altitude than [B] and [RD3].