ESA VENUS ENTRY PROBE STUDY

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ABSTRACT

The Venus Entry Probe is one of ESA's Technology Reference Studies (TRS). The purpose of the Technology Reference Studies is to provide a focus for the development of strategically important technologies that are of likely relevance for future scientific missions. The aim of the Venus Entry Probe TRS is to study approaches for low cost in-situ exploration of Venus and other planetary bodies with a significant atmosphere. In this paper, the mission objectives and an outline of the mission concept of the Venus Entry Probe TRS are presented.

1. INTRODUCTION

The Venus Entry Probe is an ESA Technology Reference Study (TRS) [1]. Technology reference studies are model science-driven mission studies that are, although not part of the ESA science programme, able to provide a focus for future technology requirements. This is accomplished through the study of several technologically demanding and scientifically meaningful mission concepts, which have been strategically chosen to address diverse technological issues.

Key technological objectives for future planetary exploration include the use of small orbiters and in-situ probes with highly miniaturized and highly integrated payload suites. The low resource, and therefore low cost, spacecraft allow for a phased strategic approach to planetary exploration, thus reducing mission risks compared to a single heavy resource mission.

2. VENUS EXPLORATION IN CONTEXT

More than twenty missions have been flown to Venus so far, including fly-bys, orbiters, and in-situ probes. These past missions have provided a basic description of the planet, its atmosphere and ionosphere as well as a complete mapping of the surface by radar. The upcoming comprehensive planetary orbiters, ESA's Venus Express (launch 2005)[2] and Planet-C from ISAS (launch 2007)[3], will further enrich our knowledge of the planet. These satellite observatories will perform an extensive survey of the atmosphere and the plasma environment, thus practically completing the global exploration of Venus from orbit. For the next phase, detailed in-situ exploration will be required, expanding upon the very successful Venera atmospheric and landing probes (1967 - 1981), the Pioneer Venus 2 probes (1978), and the VEGA balloons (1985).

3. MISSION OBJECTIVES

The objective of the Venus Entry Probe Technology Reference Study is to establish a feasible mission profile for a low-cost in-situ exploration of the atmosphere of Venus. An extensive literature survey has been performed in order to identify a typical set of scientific objectives for such a mission. From this survey, the following set of key issues has been derived (with references to review articles):

[SR1] *Origin and evolution of the atmosphere*

A major question is to understand why and how the atmosphere has evolved so differently compared to Earth. This can only be investigated by in-situ measurements of the isotopic ratios of the noble gases [4, 5].

[SR2] *Composition and chemistry of the lower atmosphere*

Accurate measurements of minor atmospheric constituents, particularly water vapour, sulphur dioxide and other sulphur compounds, will improve our knowledge of the runaway greenhouse effect on Venus, atmospheric chemical processes and atmosphere-surface chemistry, and will address the issue of the possible existence of volcanism [4, 5].

[SR3] *Atmospheric dynamics*

Venus has a very complicated atmospheric dynamical system. The driving force behind the zonal supperrotation, the dynamics of the polar vortices and the meridional circulation as well as the cause of temporal and spatial variations of the cloud layer opacity are all rather poorly understood [4, 5, 6].

[SR4] *Aerosols in the cloud layers*

Measurements of the size distribution, temporal and spatial variability as well as the chemical composition of the cloud particles is of interest for better understanding the thermal balance as well as the atmospheric chemistry [4]. Furthermore, it has been suggested that the unidentified large (~ 7 µm diameter) cloud particles might contain microbial life [7, 8].

[SR5] *Geology and tectonics*

Key outstanding questions on the surface of Venus are the mineralogy, the history of resurfacing as well as of volcanism [5]. Resolving the global tectonic structure and (improved) topographical mapping will improve our understanding on these issues.

4. MISSION DESIGN

4.1 Mission requirements

In order to address the science objectives, the following mission requirements have been imposed on the Venus Entry Probe TRS:

[MR1] In-situ scientific exploration at an altitude between 40 and 57 km at all longitudes by means of an aerobot [SR1-4].

[MR2] Vertical profiles of a few physical properties of the lower atmosphere at varying locations across the planet by means of atmospheric microprobes [SR3].

[MR3] Remote atmospheric sensing to provide a regional and global context of the in-situ atmospheric measurements (also concurrent with the aerobot operational phase) [SR2-4].

[MR4] Remote sensing of the polar vortices with a large field of view and a repeat frequency less than 5 hours [SR3].

[MR5] Remote sensing of the Venus atmosphere at all longitudes and latitudes [SR2-4].

[MR6] Remote sensing of the Venus surface by means of a ground penetrating radar and radar altimeter [SR5].

4.2 Mission concept

The mission concept that is able to fulfil all requirements consists of a pair of small-sats and an aerobot, which drops active ballast probes. A two-satellite configuration is required in order to commence

Table 1. Mission baseline scenario.

S/C Module	Measurements	Strawman payload	Requirements
Venus Polar Orbiter (VPO)	- Atmospheric composition - Atmospheric dynamics - Atmospheric structure	- Microwave sounder - Visible-NIR imaging spectrometer - UV spectrometer - IR radiometer	- Large FOV - Resolution ~ 5 km - Operational before aerobot deployment - Aerobot communications
Venus Elliptical Orbiter (VEO)	- Subsurface sounding - Topographical mapping	- Ground penetrating radar - Radar altimeter - Entry probe	- Low periapse (radar) - Entry probe deployment - Data relay to Earth
Aerobot	- Isotopic ratios noble gases - Minor gas constituents - Aerosol analysis - Pressure, temperature etc. - Tracking and localization of microprobes	- Gas chromatograph /Mass spectrometer with aerosol inlet - Nephelometer - IR radiometer - Meteorological package - Radar altimeter	- Long duration (different longitudes) - Microprobe deployment - Altitude 40 - 57 km (aerosols)
Atmospheric microprobes	- Pressure, temperature - Light level (up and down) - Wind velocity	- P/L fully integrated with probe	- Operational down to 10 km or less

the remote sensing atmospheric investigations prior to the aerobot deployment (MR3).

One satellite will be in a polar Venus orbit. The Venus Polar Orbiter (VPO) contains a remote sensing payload suite primarily dedicated to support the in-situ atmospheric measurements by the aerobot and to address the global atmospheric science objectives. The second satellite enters a highly elliptical orbit, deploys the aerobot and subsequently operates as a data relay satellite, while it also performs limited science investigations of the ionosphere and the surface (after lowering the apoapse).

The aerobot consists of a long-duration balloon, which will analyse the scientifically interesting Venusian middle cloud layer. During flight, the balloon deploys a swarm of active ballast probes, which determine vertical profiles of pressure, temperature, flux levels and wind velocity in the lower atmosphere.

The concept of a long-duration balloon with ballast probes is not new and has been proposed before, see e.g. [9, 10, 11]. The focus of the Venus Entry Probe study is to identify the critical technologies associated with such a concept with the aim to successfully support the technology development of a miniaturized aerobot system with atmospheric microprobes.

Table 1 gives an overview of the mission baseline scenario, including a strawman payload suite. Because atmospheric science investigations (large field of view and high polar revisit frequency, see MR4) and surface radar investigations (low periapse) pose different requirements on the operational orbit, the Venus Polar Orbiter will carry the atmospheric remote sensing instrumentation and the Venus Elliptical Orbiter the radar instrumentation. The tentative operational orbits for both spacecraft are listed in Table 2.

4.3 Launch and transfer to Venus

A Soyuz-Fregat 2-1B launch from Kourou has been selected as the baseline for the Venus Entry Probe TRS because it is a cost-efficient and highly reliable launch vehicle. The mass capability for direct escape to Venus is about 1400 kg. The Earth departure phase can be optimized by launching the Soyuz-Fregat into a highly elliptical Earth orbit, with the spacecraft providing the delta-V for Earth escape [12].

Table 2. Operational orbits for the Venus Polar Orbiter and the Venus Elliptical Orbiter spacecraft.

	VPO	VEO
Periapse (km)	2000	250
Apoapse (km)	6000	7500 – 20000
Period (hr)	3.1	3.1 – 6.2
Inclination	~ 90°	~ 75 - 90°

A standard high thrust heliocentric transfer from Earth to Venus is envisaged, because this is the most cost-efficient and flexible option for a mission to Venus. The launch opportunities are primarily driven by the Earth-Venus synodic period of 1.6 years. The 3.4º inclination of Venus' orbit to ecliptic causes a variation in the Earth-Venus distance, so that the delta-V requirements vary at successive optimum launch windows.

The typical transfer time for a half solar revolution transfer is between 120 and 160 days, with a delta-V requirement for Venus orbit insertion (250 km × 66,000 km) typically less than 1.4 km/s [12]. Depending on Earth departure strategy and planetary geometry, a high-thrust chemical propulsion system can typically bring into Venus orbit a spacecraft mass between 900 kg and 1150 kg.

The VPO and VEO spacecraft can travel as a composite or individually. As the composite configuration is more mass and cost-efficient (mission operations), this is currently selected as the baseline, with the VEO providing the propellant for departure and Venus orbit insertion.

4.4 Venus Polar Orbiter spacecraft

The 3-axis stabilized Venus Polar Orbiter spacecraft is based on a thrust tube structural concept, because of its low mass and simplicity of design. The propulsion system consists of a conventional dual mode bipropellant system, using Hydrazine and Nitrogen Tetroxide for high thrust manoeuvres and Hydrazine monopropellant thrusters for low thrust.

Table 3. Venus Polar Orbiter mass budget.

Item	**Mass(kg)**
Science instruments	30
Communications	22
Structure	51
Propulsion	63
ACS	10
OBDH	4
Power	21
Thermal control	14
Subtotal	**215**
System margin (20%)	43
Total dry mass	**258**

Table 3 shows the top level mass budget for the Venus Polar Orbiter. A mass budget of 30 kg (including margins) has been allocated for the remote sensing atmospheric science instruments (see Table 1). The payload instruments will be integrated into a highly integrated payload suite. By merging individual instruments onto one platform and sharing resources on a system architecture level, considerable mass and power reductions can be achieved without sacrificing the scientific performance. The science data obtained by the Venus Polar Orbiter will be relayed to the Venus Elliptical Orbiter through an X-band link.

4.5 Venus Elliptical Orbiter spacecraft

Table 4 lists the top-level mass budget for the Venus Elliptical Orbiter. For cost reduction purposes, the commonality of platform and subsystems between the VPO and VEO will be exploited as much as possible. As a consequence, the VEO spacecraft also uses a similar thrust tube concept and a dual mode propulsion system.

The Venus Elliptical Orbiter will stay in a highly elliptical orbit until deployment of the entry probe, which is initiated after the VPO has reached its final orbit and the instrument calibration phase has been completed. During this first phase, the VEO primarily acts as a relay station to Earth for data from the VPO as well as from the aerobot, possibly via the VPO. The Ka-band has been selected for communications to Earth, whereas X-band communication is the baseline for the inter-satellite communications.

After the operational phase of the aerobot has ended, the VEO will progress to its final low elliptical orbit (250 km × 7,500 – 20,000 km) in order to start the detailed (sub)surface radar investigations. The current preliminary mass budgets allow for an apoapse of 20,000 km using chemical propulsion. Further work is in progress to assess whether aerobraking or spacecraft mass reduction are viable routes towards a lower apoapse, and consequently a larger surface coverage. A mass of 20 kg has been reserved for a ground penetrating radar and a radar altimeter. Possibly a wide field camera will be included as well.

Table 4. Venus Elliptical Orbiter mass budget.

Item	Mass (kg)
Science instruments	20
Entry Probe	85
Communications	32
Structure	65
Propulsion	135
ACS	10
OBDH	4
Power	19
Thermal control	5
Subtotal	**375**
System margin (20%)	75
Total dry mass	**450**

4.6 Entry vehicle

Fig. 1 shows a conceptual drawing of the entry vehicle. The aeroshell has a 45º sphere-cone geometry, which provides a good packaging shape and aerodynamical stability. Most of the volume of the entry probe is taken up by the spherical gas storage tank, which is surrounded by the ring-shaped gondola. For storage of the balloon inflation gas, a conventional gas tank has been baselined, though alternatives such as cold gas generators or chemical storage of hydrogen are being considered.

In Table 5 the tentative top-level mass budget for the Venus entry vehicle is summarized. Because the design study is still in an early phase, a 25% design maturity margin has been added.

4.6.1 Probe release

The entry probe will be released from the VEO spacecraft, while it is in a highly elliptical orbit with an orbital period in excess of 24 hours. To keep the entry vehicle design simple, the VEO spacecraft will provide the required velocity and orientation for the probe entry. After release of the probe, the spacecraft will perform a re-orbit burn.

Deployment from orbit has been chosen as the baseline because direct entry from the interplanetary transfer hyperbola would require a complicated interplanetary transfer trajectory or orbit insertion scenario in order to fulfil the requirement of starting the remote sensing atmospheric science investigations with the VPO prior to aerobot deployment (MR3).

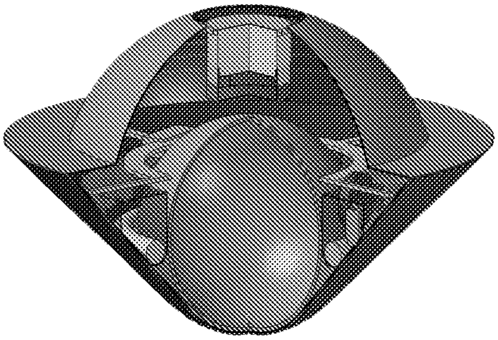

Fig. 1. Conceptual drawing of the entry probe.

4.6.2 Entry, descent and deployment

The probe will enter the dense Venus atmosphere with a velocity of 9.8 km/s and a flight path angle between 30˚ and 40˚, as this scenario yields the best overall system mass. A steep entry angle will cause the probe to penetrate deep within the atmosphere quickly, leading to high accelerations and heat fluxes. However, since the deceleration to subsonic velocities occurs very quickly, the total absorbed heat is relatively low. Additionally, the short entry duration enables a quick release of the aeroshell (~20 seconds), thus minimizing the time for the absorbed heat to soak through the heat shield.

The heat shield material consists of Carbon-Phenolic, which is capable of withstanding very high heat fluxes (~ 300 MW/m^2), much higher than the peak heat flux of ~20 MW/m^2 for a 40˚ entry angle. The maximum entry flight path angle is set by the 200 g acceleration capability of the payload.

The deployment sequence is depicted in figure 2. The 45˚ sphere-cone entry probe is designed to be stable in the hypersonic and supersonic regimes, so that no active control is required. Just above Mach 1.5, a disk-gap-band or a ribbon parachute will be deployed by a pyrotechnic mortar. The parachute stabilizes the probe as it decelerates through the transonic regime. The front aeroshell will be released a few seconds after parachute deployment when the subsonic regime has been reached. To prevent heating from the back cover, the rear aeroshell will be distanced from the aerobot by a tether. At a velocity of ~20 m/s and altitude of ~55 km, the balloon will be deployed. The parachute and rear aeroshell are released and the inflation of the balloon is started. The parachute will be designed with a small amount of glide to ensure lateral separation between the parachute and the balloon. The inflation time of the balloon is a trade between the minimum altitude and the aerodynamic loads on the balloon. Currently, an inflation duration of 20 seconds and a minimum altitude of 54 km is foreseen. The gas storage system will be released after inflation of the balloon, and the aerobot will gradually rise to cruise altitude.

Table 5. Venus entry vehicle mass budget.

Item	Mass (kg)
Gondola in-situ science instruments	4.0
Atmospheric microprobe system	4.0
Aerobot-VEO communications	1.6
Gondola structure and separation system	6.9
Gondola OBDH	0.6
Gondola power	5.6
Gondola environment	0.3
Subtotal (Gondola)	**23.0**
Balloon (including gas, envelope and deployment system)	5.4
Gas storage system	14.9
Entry and descent system	24.8
Total mass entry vehicle	**68.1**
Design maturity margin (25%)	17.0
Mass Entry Vehicle (with margin)	**85.1**

4.6.3 Aerobot

The balloon will stabilize at an altitude of 55 km. At this altitude all the scientific objectives outlined in section 3 can be addressed, while the environment is relatively benign (30 °C and 0.5 bars [13]).

The goal for the aerobot operational mission duration is to travel at least twice around Venus. Taking the average speed of 67.5 m/s from the VEGA balloons that flew at a similar altitude [14], one obtains a minimum flight duration of 14 days.

A light gas balloon with slight overpressure is considered the most suitable candidate for the Venus aerobot, because such a balloon complies best with the operational requirements for a long duration mission. As the gas leaks out of the super pressure balloon, the float altitude will increase until there is insufficient gas for positive buoyancy (and the balloon sinks to the surface). A carefully selected microprobe drop scenario could partially compensate for the loss of balloon gas and thus maximize the operational lifetime. Gas release mechanisms and gas replenishment systems are also being considered in order to compensate for

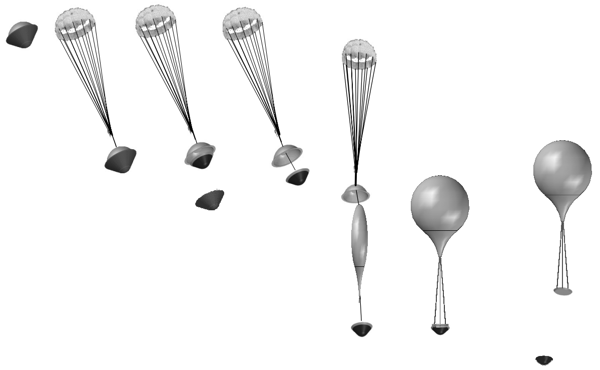

Fig. 2. A schematic of the Venus aerobot deployment.

temperature changes in the balloon gas due to gradients in solar radiation at the day/night and night/day terminators.

Hydrogen has been selected as the baseline for the balloon inflation gas, with helium as a backup option. Though the mass of gas storage systems for hydrogen and helium are similar, the main advantage of hydrogen is that it generally has a lower gas leakage rate compared to helium, which is a monatomic gas. The main disadvantage of using hydrogen is its hazardousness.

The balloon envelope material should have an extremely low leakage rate, possibly requiring welded seams. Additionally, the deployment will have to be carried out in a controlled manner to avoid the slightest damage to the envelope.

4.6.4 Gondola

Figure 3 shows a conceptual drawing of the gondola layout. A strawman payload suite has been defined, which can fulfil the mission objectives. It consists of a gas chromatograph/gas spectrometer (with aerosol inlet), a nephelometer, solar and IR flux radiometers, a meteorological package, a radar altimeter and the atmospheric microprobe system. An assessment study is currently in progress to integrate all instruments, except the atmospheric microprobe system, into two highly integrated payload suites with a total mass of 4 kg and an average power consumption of 5 W.

Electrical power will be provided by amorphous-silicon solar cells, which are mounted on the gondola surfaces, yielding sufficient power during the day. During the night, primary or secondary batteries will be used.

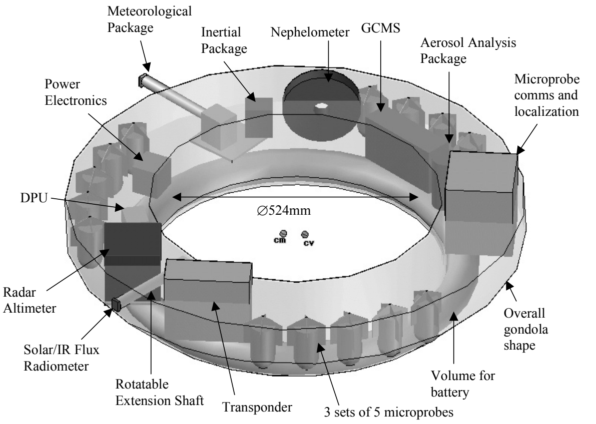

Fig. 3. The layout of the gondola.

Currently, Lithium-thionylchloride primary batteries have been selected as the baseline, as this is the most mass-efficient solution due to their high energy density (~590 Wh/kg). The important drawback of soluble cathode lithium cells is that they are less safe than the more common solid electrolyte Lithium cells. As an alternative, Li-polymer secondary batteries are considered which can be recharged during the day. As the energy density is significantly lower (~170 Wh/kg), the mass penalty for using rechargeable batteries is about 4 kg.

In order to save mass, the payload and communication duty cycles will be substantially lower during the night, resulting in an average night-time power consumption of 5 W, compared to 11 W during the day.

4.6.5 Atmospheric microprobes

The fifteen atmospheric microprobes on board of the aerobot serve a twofold purpose:

- Perform scientific meaningful measurements
- Drop ballast in order to increase the operational lifetime of the aerobot

The atmospheric microprobes measure in-situ vertical profiles of selected properties of the lower atmosphere from the aerobot float altitude down to at least 10 km altitude. Due to the stringent mass limitations of the aerobot, they should be as low-weight as possible. This limits the choice of sensors that can be carried with the microprobes. Currently, the following measurements are foreseen: pressure, temperature, and solar flux levels. The horizontal wind velocity will be deduced from the trajectory of the microprobes. This set of measurements, performed at different longitudes, will provide new insights in the atmospheric dynamics and the heat balance on Venus (see MR2).

In order to investigate both the local weather patterns on Venus as well the global atmospheric dynamics, the 15 microprobes will be dropped in 5 separate drop campaigns, spaced equally over the mission lifetime. The three probes in a drop campaign will be released with an interval of 5 minutes.

Localization and communication of the small microprobes is a challenging task and is therefore subject of a separate technology development activity [15]. A preliminary assessment by Qinetiq indicated a mass of 1.4 kg for the communication and localization system and 104 g for a fully functional microprobe, assuming a 5-year technology development horizon.

5. SUMMARY

The Technology Reference Studies are a tool to identify enabling technologies and to provide a reference for mid-term technology developments that are of relevance for potential future scientific missions. Early development of strategic technologies will reduce mission costs and shorten the mission implementation time. As the enabling technologies mature and mission costs reduce, the scientific community will benefit by an increased capability to perform major science missions possible at an increased frequency.

The Venus Entry Probe Technology Reference Study concentrates on in-situ exploration of Venus and other planetary bodies with a significant atmosphere. The mission profile provides a reference for the development of enabling technologies in the field of atmospheric entry systems, micro-aerobots, atmospheric microprobes and highly integrated miniaturized payload suites.

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