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MISSION AND SYSTEM DESIGN OF A VENUS ENTRY PROBE AND AEROBOT

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1 Abstract

The Venus Entry Probe study is one of the European Space Agency's (ESA) technology reference studies. It aims to identify; the technologies required to develop a low-cost, science-driven mission for in-situ exploration of the atmosphere of Venus, and the philosophy that can be adopted. The mission includes a science gathering spacecraft in an elliptical polar Venus orbit, a relay satellite in highly elliptical Venus orbit, and an atmospheric entry probe delivering a long duration aerobot (aerial robot) which will drop several microprobes during its operational phase.

The atmospheric entry sequence is initiated at 120 km altitude and an entry velocity of 9.8 kms^{-1}. Once the velocity has reduced to 15 ms^{-1} the aerobot is deployed. This consists of a gondola and balloon and has a floating mass of 32 kg (which includes 8 kg of science instruments and microprobes). To avoid Venus' crushing surface pressure and high temperature an equilibrium float altitude of around 55 km has been baselined. The aerobot will circumnavigate Venus several times over a 15-22 lifetime analysing the Venusian middle cloud layer. Science data will be returned at 2.5 kbps over the mission duration. At scientifically interesting locations 15 drop-sondes will be released.

This paper focuses on the final mission design with particular emphasis on system level trade-offs including the balloon and pressurisation system, communications architecture, power system, design for mission lifetime in a hostile and acidic environment. It discusses the system design, design drivers and presents an overview of the innovative mission-enabling and mission-enhancing technologies.

Keywords: Entry Probe, Aerobot, Gondola, Planetary Mission, Balloon.

2 Introduction

The Venus Entry Probe is one of ESA's Technology Reference Studies (TRS). These are model science-driven missions that although not part of the ESA science programme are able to provide focus to future technology requirements. This is accomplished through the study of several technologically demanding and scientifically meaningful mission concepts, which are strategically chosen to address diverse technological issues. The TRSs complement ESA's current mission specific development programme and allow the ESA Science Directorate to strategically plan the development of technologies that will enable potential future scientific missions.

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. These low resource, and therefore potentially low cost, spacecraft allow for a phased strategic approach to planetary exploration, thus reducing mission risks compared to a single heavy resource mission.

The aim of the Venus Entry Probe (VEP) TRS is to study approaches for low cost in-situ exploration of the Venusian atmosphere. The mission profile consists of two minisatellites, one dedicated to atmospheric remote sensing and the other specialised for entry probe deployment as well as data relay [1]. This two-satellite configuration is required in order to commence the remote sensing atmospheric investigations prior to the aerobot deployment. The additional advantage is that through the use of a data relay satellite, the other mini-satellite can practically continuously perform remote sensing investigations of the atmosphere.

The Low Venus Orbiter (LVO) enters low Venus orbit (6000km x 2000km) and contains a highly integrated remote sensing payload suite primarily dedicated to support the in-situ atmospheric measurements of the aerobot and to address the global atmospheric science objectives.

The Venus Relay Satellite (VRS) enters a highly elliptical orbit (215,000 x 250 km), deploys the Venus Entry Vehicle (VEV) and subsequently operates as a data relay satellite (and may provide additional navigational support).

The aerobot consists of a long-duration balloon and gondola (depicted below) that will analyse the Venusian middle cloud layer at an altitude of approximately 55 km, where the environment is relatively benign. The balloon will deploy a swarm of active 'ballast' micro-sondes, which, once deployed, will determine vertical profiles of the lower atmosphere[2].

Figure 1 Venus aerobot mission (gondola and balloon)

3 Mission Objectives

The objective of the Venus Entry Probe TRS is to establish a feasible mission profile for a low-cost in-situ exploration of Venus.

The primary scientific objectives of the mission are to study:

1. *Origin and evolution of the atmosphere*
2. *Composition and chemistry of the lower atmosphere*
3. *Atmospheric dynamics*
4. *Aerosols in the cloud layers*

A more detailed description of the scientific rationale is detailed by [3].

The strategy for this mission development is to meet the science requirements at lowest overall mission cost. The study will determine the mission cost, the system drivers and determine if the instrument duty cycle is viable. It will also identify technologies required to develop such a mission.

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 Vehicle:

- Mission launch in 2014 onwards
- Planetary protection requirements: None
- Support ~4 kg payload suite as well as ~4 kg microprobes, including a ranging and navigation system (DALOMIS-C). This generates science data at a rate of 2.5kbs^{-1} for the duration of the mission
- Deploy swarm of fifteen 115 g drop sondes or microprobes. These will either be deployed individually or in groups of 3 in a drop campaign
- Nominal mission duration: 15 days
- Extended mission duration: to 30 days
- Ballistic or orbital entry is permitted, entry must be 20 ± 5^0 latitude either north or south
- Maximum entry deceleration is ~200 G
- Entry sequencing must be dual redundant
- Aerobot float altitude extremes are 53-62 km. For the first 8 days the balloon must be at an equilibrium float altitude of 55 km

4.2 Constraints

- Total mission cost constraint for the orbiters, entry vehicle and gondola (including design, launch, operations, instrument development) is €300-350 million (FY2004)
- Limit technology development to 5 years, European technology shall be utilised where possible.
- Nuclear technology (RTGs/RHUs) shall be precluded for cost and political reasons.

5 Venus Entry Vehicle Design

5.1 Deployment and Atmospheric Entry

The VEV will be released from the VRS spacecraft from a highly elliptical orbit. To reduce the complexity and mass of the VEV the VRS will deliver the entry probe to $20^0 \pm 5^0$ latitude (either north or south) entry point, this requiring 70ms^{-1} ΔV. From release the coast duration is 60 hours. Deployment from orbit has been selected as the baseline as it allows the opportunity for orbital scientific study of the atmosphere prior to entry as well as during the aerobot operational phase.

Several aeroshell geometries were assessed ranging from 30-70^0 sphere cones. A 45° sphere-cone entry probe (see Figure 2) is baselined as it offers the lowest system mass. It also provides good passive stability in the hypersonic and supersonic regimes and heritage from *Galileo*, *Pioneer Venus* and the *Deep Space-2 Microprobe* missions.

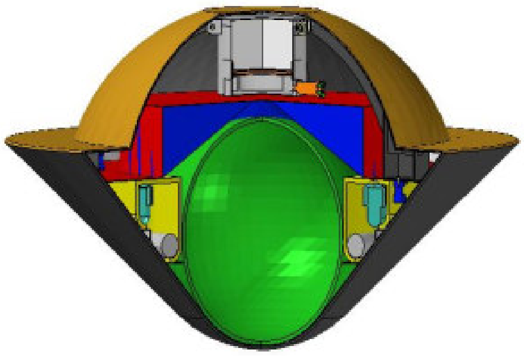

Figure 2 Venus Entry Vehicle (aerobot stowed)

The figure below shows the effect of Flight Path Angle (FPA) upon entry vehicle mass and peak deceleration. The steeper the entry angle the lighter the design becomes, but the greater the entry deceleration becomes. Clearly it is advantageous to minimise both. At 15^0 FPA the peak acceleration during entry is 100 G. At 40^0 FPA 200 G's are reached.

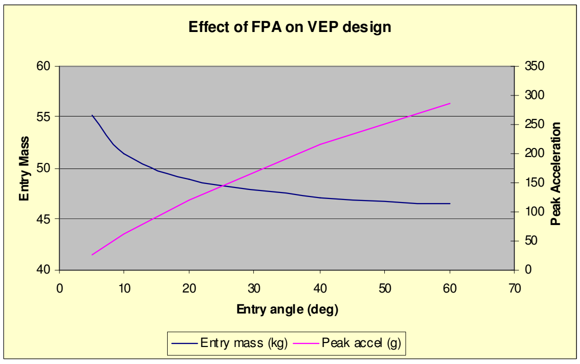

Figure 3 Effect of FPA on VEV Design

A 40^0 FPA was selected as it offers a viable compromise on parameters.

The front aeroshell consists of 7 mm Carbon Phenolic ablative material, the rear aeroshell 3mm of Norcoat Liege. During entry Carbon Phenolic will experience a flux of 17 MW/m^2, this technology can withstand up to 300MW/m^2.

The parachute will be a 3.6 m disc-gap-band design offering good supersonic opening characteristics and stability.

5.2 BALLOON DESIGN

Two general types of balloon may be considered for the Venus aerobot: Montgolfier balloons and light gas (superpressure) balloons. Montgolfier balloons require heated gas at ambient pressure within the balloon envelope to produce buoyancy – this being created due to the lower density with respect to the surrounding atmospheric gas. They tend to be large due to the small density changes achievable. The superpressure balloon being baselined because they do not require a constant thermal energy input, they do, however, require an inflation gas. The balloon diameter is calculated at 3.6 m diameter with a 2 m riser.

The balloon material must be capable of withstanding the temperature at the cruise altitude and surviving exposure to the Venusian atmosphere for the minimum mission lifetime of 15 days (The principal species of concern in the atmosphere is sulphuric acid droplets, which could either condense directly on the balloon or fall onto it in the form of rain).

A variety of candidate materials were considered for the balloon envelope including Polytetrafluoroethylene (PTFE), Polyethelene, Polyethylene terephthalate (PET) and Poly(p-phenylene terephthalamide)-aramid (*Aramica*) (PPTA aramid). Few materials possess both the thermal stability and chemical resistance necessary for a long duration balloon on Venus. PET (polyester) was selected as the baseline material because it offers a good compromise on properties. However, research should be carried out into the potential use of PPTA aramid. It is essential that early research be carried out into the resistance of different types of PET to concentrated acid in order to reduce the mission risk. If PET is found to have insufficient resistance to highly concentrated acid, a coating may have to be considered to improve its characteristics to an acceptable level (a bi-layer of mylar with PTFE protective film could form a back-up solution for the balloon envelope).

Hydrogen, helium and ammonia were considered for the balloon inflation gas. Although helium is inert and far less dangerous than hydrogen the monatomic nature of helium produces a far greater leak rate reducing its efficiency. The trade-off is captured in Table 1. Hydrogen being selected for its overall system mass efficiency.

Inflation gas	Hydrogen	Helium	Ammonia
Relative molecular mass	2	4	20 (includes pyrotechnic products)
Balloon diameter	3.85 m	3.94 m	5.29 m
Gas quantity	1.65 kg	3.55 kg	42.9 kg
Storage system design	Pressure vessel or chemical reagents	Pressure vessel	Hybrid gas generator
Gassing system volume	60 litres	64 litres	~70 litres
Storage system efficiency	10%	20%	50%
Storage system mass (full)	16.6 kg	17.8 kg	85.8 kg
Aerobot mass (inc storage system)	43.2 kg	44.6 kg	116 kg

Table 1 Balloon inflation gas trade-off

This hydrogen must be stored or generated on-board the VEV. Generally speaking a mass efficiency of up to 10% is achievable using a high-pressure storage system or chemical gas generators. Army signal balloons are often filled with hydrogen created from Lithium Hydride reacting with water. A 20 kg system would produce enough hydrogen for this application and occupy 20L of volume. Carbon nanostructures offer storage efficiencies of up to 50% but will not be realised within the technology development timeframe of this mission. The hydrogen high-pressure storage system was baselined as the benefits of moving to a generation system are small relative to the risks involved in these relatively immature technologies. The figure below shows the gondola gas tank within the aeroshell volume - this is the dominant volumetric driver. Fortunately the toroidal shaped gondola packs well around the sphere with little wasted volume. 1.8 kg of hydrogen is required to inflate the balloon, this occupying 66 litres in a 310 bar 16 kg pressurised gas tank.

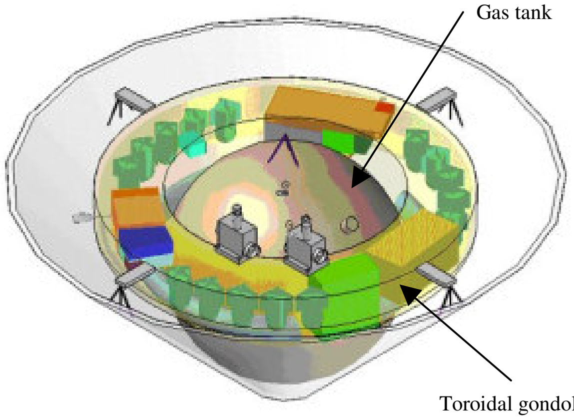

Figure 4 Gondola within Aeroshell

Once the balloon has been pressurised the gas storage system must be released (or the balloon volume must be doubled with a commensurate increase in mass).

As gas pressure will leak from the balloon the gauge pressure of the balloon will decrease slowly over time. A total hole area of 0.04 mm^2 over the 3.6 m balloon (0.0000001% of the surface area) would be sufficient to depressurise the balloon in 2.5 days.

An ammonia gas replenishment system will store 1 kg of ammonia liquid; this is metered out in small quantities to replenish the gas lost through leakage. A 1.7 kg system storing 1 kg of ammonia is baselined, combined with the release of 115 g microprobes at intervals the balloon lifetime could be up to 30 days. Material testing is required to establish if the balloon leak rate can be minimised to this level.

5.3 Entry Sequence

The VEV will enter the dense Venus atmosphere with a velocity of 9.8 kms^{-1} and a flight path angle (FPA) of 40^0. The steep entry angle ensures a short duration entry (9.8kms^{-1} to Mach-1 in under 15 seconds) and allows a quick release of the aeroshell, thus minimizing the time for the absorbed heat soak through the heat shield.

Just above Mach 1.5, a disk-gap-band or a ribbon parachute will be deployed by a pyrotechnic mortar – the initiation being accelerometer activated. The parachute stabilizes the probe as it decelerates through the transonic regime.

Event	Time (s)	Height (km)	Velocity (m/s)	FPA (deg)	Mach	
Atmosphere interface	0	120	9832	-40		
Maximum heat flux	5	88.7	9070	-39.8	43	17 MW/m2
Maximum deceleration	6.7	80.5	5830	-39.8	25.6	216 g
Parachute deployment	15.8	71	359	-43.7	1.5	4650 Pa
Aeroshell release	17.8	70.7	113	-48	0.46	
Balloon deployment	716	54.8	13.7	-90	0.05	
Balloon deployed	736	54.5	13.5	-90		
Balloon inflated	756	54.3	7.8	-90		
Gassing system release	761	54.2	7.5	-90		
Minimum altitude	766	54.2	0			
Cruise altitude	1401	55	0			

Table 2 Entry Timeline (-40 degree FPA)

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 ~15 ms^{-1} and altitude of ~55 km, the balloon will be deployed – this being activated by a barostat or pressure sensor. The parachute and rear aeroshell are released and the inflation of the balloon is started. The gas storage system will be released after inflation of the balloon, and the aerobot will gradually rise to its float altitude.

6 Aerobot

6.1 Environment

The following table outlines the environment at the extremes of aerobot altitude:

Float Altitude (km)	53	55	62	Tolerance	Units	Notes
Temperature	323.2	302.3	254.5	± 4	k	Latitudes below 30 degrees
Atmospheric pressure	0.71	0.53	0.17	± 15%	Bar	Latitudes below 30 degrees
Zonal wind speed (mean)	37-115			n/a	ms-1	Wind westward
VEV planetary circumnavigation time	5-12			n/a	days	Assume 8 day rotation
Solar downwelling flux (0.4-1 micron)	638-730			n/a	W/m2	50-60km (0.4-1 and 0.4-1.8 micron)
Cloud layer	Lower-middle cloud			n/a	n/a	
Cloud composition	75% H2SO4 25% H20 (mode 2 particles)			n/a	n/a	

Table 3 Environmental conditions

The first 8 days of the mission are to stay within the middle cloud layer (55-57 km), the remainder of the mission the float altitude is constrained to 53 to 62 km. Periodic updrafts and downdrafts (wind shear) might cause rapid excursions from this altitude.

Ambient temperature variations for the first 8 days vary between 19º to +39º (internal power dissipation and solar insolation will effect this). Pressure variations are expected to be around 0.45-0.65 bar. For the remainder of the mission the aerobot will experience a varying temperature of between –19 and +50^{0}C. This has a corresponding pressure variation of 0.17 – 0.7 bar.

Although the Venus day is 243 (Earth) days in duration, due to an effect known as super rotation the aerobot will experience zonal winds that range from 37–115 ms^{-1} westwards which implies a day plus night length of between 5 and 12 (Earth) days. For the purposes of this study an 8 day circumnavigation will be assumed.

The total down-welling flux levels during the daytime are in the region of 638-730 W/m^2, whereas the night-time up-welling flux levels are more than an order of magnitude lower and largely appear at infrared wavelengths.

At the desired float altitude the aerobot drifts between dense middle and lower cloud layers. These cloud particles consist of highly concentrated sulphuric acid droplets, and perhaps lower concentrations of hydrochloric and hydrofluoric acid.

6.2 GONDOLA DESIGN

6.2.1 Payload

Table 4 outlines the aerobot payload resource requirements:

Spacecraft	Value	Units	Notes
Mass	8.0	kg	Including support structure
Average power (day/night)	6.5 / 4.8	W	Falls during extended mission
Data generation	2.5	kbps	

Table 4 Payload resource requirements

The 8kg VEV payload mass incorporates both instruments and 3 kg of microprobes, as well as a microprobe deployment and localisation system. The microprobes will provide measurements on the dynamics and thermal balance of the Venus lower atmosphere.

6.2.2 Gondola Structure and Configuration

An unpressurised open shell structure was selected for the gondola for simplicity, mass minimisation and ease of integration and testing. The figure below outlines the concept developed for the gondola.

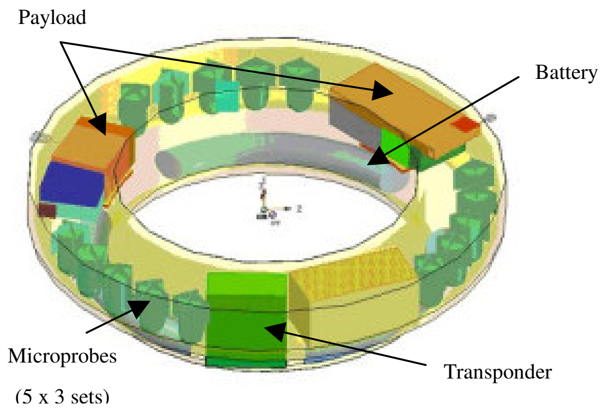

Figure 5 Gondola internal configuration

The payload suite is incorporated within the gondola primary structure as two separate units along with 3 cartridges of 5 microprobes and various support avionics. This provides not only structural support but also protection from the hazardous environment. Aluminum and titanium have been assessed for this material but due to the acute mass sensitivity a Titanium-silicon carbide fiber material is proposed. This reduces the primary structure mass to <2.0 kg.

6.2.3 Communications

The equipment baselined for the aerobot communications system is a 1.5 kg (American technology) ranging transponder with a radio frequency output of 1.5 W. A gondola mounted X-band antenna facilitates uplink and downlink communications with hemispherical coverage. Both LVO and VRS are equipped with 1 m aperture high gain antennas, the 35 m *New Norcia* groundstation being baselined for uplink and direct to Earth downlink communications

Analysis was undertaken using *Satellite Tool Kit* ™ to establish the communications visibility from the aerobot in near equatorial regions around Venus to the two orbiters. LVO is in its operational orbit of 2000 x 6000 km, and VRS is in its initial capture orbit of 215,000 x 250 km. The aerobot was propagated at 25^0 North and 55km altitude for 30 days at a ground speed of 70ms^{-1} (see Figure 6).

The aerobot can maintain an 18.9 kbps datalink with LVO (at average viewable distance of 8,444 km). It has 226 accesses with the aerobot over the 30-day mission lifetime. Each occurs with a relatively short duration of 1.05 hours giving a total communications duration over the aerobot lifetime of 237 hours. Generating data continuously at 2.5 kbps this corresponds to the aerobot requiring 13.5% of the time dedicated to up-link communications. The LVO-aerobot orbit geometry permits co-visibility of 33%. This analysis concludes that uploading of data from the aerobot to LVO is not a significant design driver and can be achieved by daytime communication only.

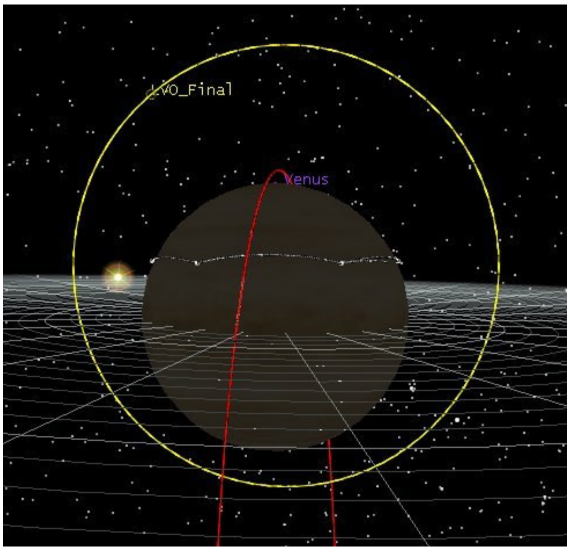

Figure 6 Communications access with aerobot

VRS, in its highly elliptical polar orbit, can only support a 68 bps link with the aerobot (at average distance of 141,059 km). Six VRS-aerobot communication accesses occur over this time period, each more than 22 hours in duration giving a total communication access time of 133 hours (or 18.5% of the mission lifetime). However, this data rate is far too low returning less than 0.03% of all data

During atmospheric entry a data rate of 100 bps can be supported by LVO with 23 dB of total margin (further work is required to establish if communications can be supported through the 15 seconds of atmospheric entry).

Aerobot direct to Earth communications are not viable. Assuming a maximum distance of 258 million km a 1 bps link produces -13.1db margin. Higher output powers, a larger aperture groundstation or an electrically steered aerobot antenna would improve this link.

6.2.4 Power System Technologies

A variety of power storage and generation technologies have been explored as part of this study:

1. Primary cells
2. Secondary cells
3. Mini-rotary engine.
4. Micro-turbine.
5. Hydrazine rotary engine.
6. Methanol fuel cell.

Lithium-Thionyl Chloride ($Li\text{-}SOCl_2$) offers 600-740Wh/kg, but is best for low consumption applications with low nominal discharge rate (< C[Ah]/200[h]). For high current, short duration usage Lithium-Sulfur dioxide ($Li\text{-}SO_2$) at 280Wh/kg offers discharge rates of C/10.

Higher energy density primary storage technologies in development include:

- $Li\text{-}SO_2Cl_2$ (Li-sulphuryl chloride), offering 25% more Wh/kg and 50% more Wh/litre than $Li\text{-}SOCl_2$),
- $Li\text{-}NO_2Cl$ potentially offering up to 900Wh/kg

For secondary cells the polymer lithium ion technology offers superior performance at energy densities up to 170-180Wh/kg. One of the most interesting characteristics of the chemistry is the geometric flexibility of the technology and its ability to be formed into a variety of different shapes and sizes to suit the application.

A mini and micro-scale rotary engine power source is being developed at the University of California at Berkeley [4,5]. The target thermodynamic efficiency for the micro-engine is around 20%, which when coupled with the potential energy density of many hydrocarbon fuels of around 13-15,000Wh/kg gives an energy density of around 2,500-3,000Wh/kg.

Note that this assumes operation in terrestrial atmosphere where oxygen is drawn in from an external source. Provision of a separate oxidiser would reduce the effective energy density by around 2/3, to perhaps 500-1000Wh/kg. Currently this technology is in its early stages of development and only moderate efficiencies have been obtained (typically 2-5%). Work is currently underway to realise efficiency goals in the 10% to 20% range. At the experimental level 4.0 W of power has been demonstrated in the lab – but development will see this rise to 50 W.

The advantages of this technology applied to planetary missions are largely offset by the need to carry both an oxidiser (liquid agents such as hydrogen peroxide and methanol are rational choices) and associated dry mass. It is estimated that such a mini-rotary engine power system requires 5 years of development for terrestrial application. The addition of an oxidiser storage system and (most likely) a change of propellant to a more space storable combination would require between 5-10 years.

However, it is uneconomical to recover oxygen from Venus' CO_2 atmosphere, as it requires ~9 times more energy that is generated [6], and high-pressure storage of gaseous O_2 is mass and volume inefficient.

Miniature gas turbines are under development that can generate electrical energy from fuel, again motivated by the very high energy densities available. These are in effect miniaturized gas turbines, with a compressor sucking in air with a continuous combustion [7,8]. Basic feasibility of this concept has been proven with the lab demonstration of a 10 mm diameter turbine rotating up to 130,000 rpm and producing 50 W of mechanical power. However, it is clear that a number of fundamental performance issues stand in the way of realising this concept. But again the need to transport an oxidiser makes this a less than attractive option.

A hydrazine derivative of the Berkeley Wankel engine has been suggested. However hydrazine, which decomposes over a catalyst to ammonia and nitrogen, has an intrinsically low energy density, (equivalent to 970 to 437Wh/kg). At best, with a 40% efficient electrical conversion rate hydrazine engines could offer around 320Wh/kg. This is half the energy density of Li-$SOCl_2$ cells and so has not been considered further.

Methanol fuel cells are being developed for the consumer markets such as laptops and mobile phones. However, these too suffer from the need to carry oxygen further mitigating their efficiency advantages.

6.2.5 Power System Design

An average of 6.5 W of electrical power is required at BOL for the payloads and around 2.9 watts for the platform subsystems during sunlight. In order to minimise mass, the payload and communication duty cycles will be substantially lower during the night, resulting in an average night-time power consumption falling to 4.8 W and 0.3 W respectively.

Three power system topology options were analysed:

1. Primary cells providing power day and night using lithium-thionyl chloride (Li-$SOCl_2$) cells.
2. Lithium-thionyl chloride (Li-$SOCl_2$) primary cells during night supported by solar cells during day.
3. Secondary power system. Lithium-polymer secondary cells (170 Wh/kg) during night and solar arrays during day.

The following figure details a system mass comparison of the three options:

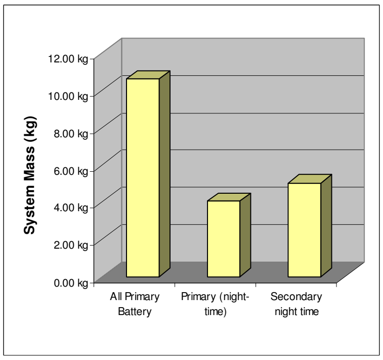

Figure 7 System mass comparison of three alterative topology options for 30-day operational lifetime

The selected baseline power system is the solar power supported primary cell system (option 2: see Figure 8) because of its superior mass performance and adequate utilization of the available gondola surfaces for solar power generation

Due to the inefficiency of lithium-thionyl chloride at high discharge currents lithium sulphur dioxide cells will supply high current users (pyros used during entry and descent).

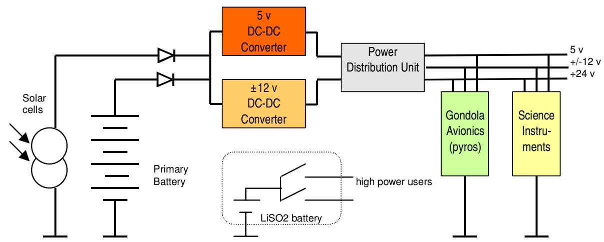

Figure 8 Topology: Primary battery with solar array

Should the extended mission lifetime increase to beyond ~38 days it would be more mass efficient to utilise a secondary storage power system (option 3).

The table below outlines the power generated onboard the gondola for 2 alternative solar cell technologies: Amorphous silicon with reflector and triple junction amorphous silicon cells.

Solar Cell Power Generator			Units	Notes
Intensity	608	608	w/m²	Median between up and down-welling flux (see VIRA model)
Technology	Amorphous silicon with reflector	Triple junction amorphous Silicon	n/a	Unisolar provide amorphous triplejunction cells with 13% efficiency, alternatively single junction amorphous silicon cells with rear reflection
Cell efficiency	4.0%	13.0%	%	28 0 C and 1 AM0 (air mass zero)
Venus atmospheric spectrum enhancement	1.6	1.0	n/a	reduction in spectral bandwidth of 40% on Venus.
cell temperature (worst case)	85.0	85.0	Deg	a-Si cells can survive up to around 120 degrees
Cell temperature coefficient	-13.8%	-13.8%	%	dT=55 degrees @ -2.5% per 10degs for single junction and triple jct a-Si
Solar cell absolute efficiency	5.52%	11.21%	%	
Solar cell surface area	2.030	2.030	m2	
Fill factor	95%	95%		cells are supplied in uncut sheets, laser trimmed to individual cells/strings
Environmental loss factor	93%	93%	n/a	Includes radiation (2%) and cover-glass degredation (estimated at 5%)
Cell total (effective) area	1.93	1.93	m²	
EOL power available	**60.18**	**122.25**	**W**	

Table 5 Solar Cell Power Generated

From the VIRA model[9] the estimated up-welling and down-welling solar fluxes at 55km altitude are 588 Wm^{-2} and 648Wm^{-2} respectively. For the basis of this analysis a figure of 608 Wm^{-2} is assumed.

State of the art efficiencies from the single and triple-junction cells are reported to be 6% and 13% respectively. Single layer cells however are thought to be susceptible to the Staebler-Wronski effect which reduced the efficiency (typically by 30%) after several months of sunlight exposure (from 6% to 4%). This phenomenon is not apparent with the multi-junction cell technology so this is the preferred choice. Amorphous silicon technology is well established for the commercial industry, although advances in the triple junction variety are frequently reported. Amorphous cells are very thin compared to conventional space silicon cells (2µm vs. 160µm). The cell efficiency is expected to reduce above the test temperature of approximately 28°C at a rate of –2.5% per 10°C. At the average working temperature of 85^{0}C a reduction in performance of –13.8% is taken into account. The estimated overall absolute efficiency for the two cells is thus 5.5% for single lay and 11.2 % for triple junction.

Analysis of the locations for cells on the body of the Gondola indicates that approximately 1.9 m^2 of area is available assuming a 95% fill factor (see Figure 9).

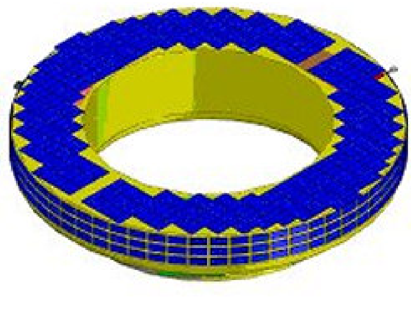

Figure 9 Gondola solar power generator

The usual way of making amorphous silicon is to deposit it on a long strip and then laser cut in parallel lines into as many cells as you require for the voltage. Using this technique extremely high packing factors are expected (95% typical instead of 85% for conventional assemblies).

Radiation loss of 2% considering a well shielded flight to Venus and 5% for cover-glass degradation are also applied.

The estimated power output from the two cell types is thus; 60 W for single layer α-silicon and 122 W for the triple junction.

With sunlight power demand at 68.8 W the triple junction cells provide a viable baseline design.

Cover-glass materials resistant up to 75% sulphuric acid are required. Most cover-glass materials are suitable, but the optical resistance to these environments would need to be determined as well as the physical properties during testing. To limit cell temperature increase it is proposed to baseline a glass based solution because of the known infrared reflective properties.

6.2.6 Thermal Design

During the operational mode the gondola temperature will be driven by the Venus thermal flux environment along with internal power dissipation (largely from power dissipation in the transmitter and DALOMIS-C).

The thermal behavior of the gondola was assessed at the nominal cruise altitude of 55 km. Gondola surface temperature was assessed assuming both a turbulent atmosphere and laminar flow atmosphere.

During daylight the total energy input to the gondola is 608 Wm^{-2} (solar insolation), 528 Wm^{-2} (background thermal environment) and internal power dissipation of 68.8 W (a worst-case figure of 100 W being used). At cruise altitude the ambient temperature is around 300 k. There is a large uncertainly in the thermal flux level at this cruise altitude.

During night time operations the thermal environment consists of 528 Wm^{-2} (background thermal radiation) and internal power dissipation of 47 W. The results for this analysis are presented in Table 6:

Sunlight				
Cylindrical side		Top face		
Turbulent	Laminar	Turbulent	Laminar	
83	76	78	81	Degrees
Night Time				
Cylindrical side		Top face		
Turbulent	Laminar	Turbulent	Laminar	
40	39	39	40	Degrees

Table 6 Gondola thermal analysis results

Considering both a turbulent atmosphere and laminar flow during daylight the temperature varies between 76-83^0. For solar arrays sizing purposes analysis assumes a worst-case temperature of 85^0. During night time the variations are between 39-40^0.

More detailed thermal design and analysis would be able to optimise the solution to reduce the temperatures extremes observed - particularly important for the batteries and payloads. The allowable temperature range of COTS industrial grade components are typically more constrained than high reliability parts (-25 to +85 versus -55 to +125^{0}C). Interestingly the external solar flux and material properties are the dominant thermal drivers, internal power dissipation having little effect.

6.2.7 Mass budgets

The following table outlines the final mass budget for the VEV. The total mass is just over 91 kg.

Gondola	22.7 kg
Balloon envelope, bridle, fill line	5.5 kg
Inflation gas	1.8 kg
Replenishment system	1.7 kg
Gas storage system/fill valve	16.8 kg
Parachute descent system	16.5 kg
Front shield system	25.0 kg
release mechanism/mortar	1.1 kg
TOTAL	91.1 kg

Table 7 VEV mass budget

6.3 OBDH AND CONTROL

A dedicated high reliability (field-programmable gate array based), radiation hard sequencer controls entry and descent. To make maximum use of on-board resources the payload processor undertakes control of payload operations and sequencing of non-critical events (including microprobe deployment) as well as housekeeping/telemetry logging.

Scientific data is generated on-board the gondola at a rate of 2.5 kbps continually for the mission lifetime. On-board telemetry increases this to 2.55 kbps.

6.4 MISSION LIFETIME AND SYSTEM DRIVERS

The balloon envelope material has been chosen to be inert with respect to the Venusian atmosphere. The lifetime of the balloon will be governed by the rate of gas leakage, which will be driven by the material porosity (very low) and any leakage through seams. This can only be quantified by manufacturing test samples from the correct materials. Gas replenishment has been incorporated to mitigate the effects of leakage.

Due to the stringent mass budgets, the primary battery system is sized to provide power for a maximum of 8 (Earth) days, thus limiting the operational lifetime of the aerobot to 15-22 days (depending on local time of entry).

The lifetime of gondola external structure and solar arrays has not been characterised. Further work would be required to characterise the environmental degradation expected.

The VEV and balloon design drivers are:

- Storage volume of hydrogen required to inflate the balloon. This mandates high-pressure storage (>310 bar) tanks (which dominated the VEV volume), but this introduces the requirement to constrain the tank maximum temperature limit to 40 deg. C. The tank mass is significant at ~14 kg.
- Leakage rate of balloon. With the balloon leakage rates assumed a single gas tank filling the balloon will support a mission lifetime of 2 days. A gas replenishment system along with dropping ‘ballast’ (micro-sondes) will support a 30-day balloon lifetime.
- Maintaining the centre of gravity low for a stable VEV design – driving the solution to a spherical gas tank and a toroidal gondola design.
- Night time thermal environment and uncertainly – this effects balloon gas temperature.
- There is large uncertainly in the sulphuric acid condensate environment at the operating altitude (potentially making the balloon heavier), this requires further study.

The gondola design drivers are

- Launch and entry loads
- Thermal environment and uncertainty at cruise altitude (effecting solar array generating power and maximum operating temperature of science instrument and avionics)

- Mass of instruments and DALOMIS-C.
- Structure and harness
- Lifetime of science operations driving the mass of energy storage system.
- Instrument night-time power consumption (sizing the primary power storage system)
- Day time high power subsystems and instruments (high power users demand power from the primary batteries rather than the solar arrays. Efficiency of primary batteries falls rapidly as current rises forcing lower energy density cells to be baselined.
- Integration and testability of gondola. There is a design preference for a 'channel shell' and a breathable bag as a first line of defence against acid droplets ingress. This approach will facilitate removal of avionics and science instruments for testing purposes.

7 Enabling Technologies and Summary

The mission requires critical enabling and enhancing technologies to be developed, these are detailed in Table 8 below:

Critical enabling technologies for the mission (rather than straightforward developments) are: balloon materials, entry probe thermal protection material, and development of acid resistant flexible thin-film triple-junction amorphous silicon solar arrays.

The entry vehicle and balloon have development schedules in the region of 5-6 years.

Technology	Criticality	Schedule	Notes
High density thermal protection material validation	Enabling	2 years	Manufacture and arc-jet testing
carbon carbon structure	Enhancing	2 years +	limited experience in Europe
Mortar cartridge	Enabling	18 months	Build, acceptance test and ship (ITAR item)
Mortar	Enabling	24 months	Design, build, test – requires cartridges for test
Parachute	Enabling	18 months	
TPS sensors	Enhancing	~1-6 months	
Low leak (acid resistant) welded seam balloon	Enabling	12 months	Identification, sample procurement, testing & jointing testing
gas storage systems	Enhancing		large potential mass reduction (~70%)
Develop, test & manufacture		24 months	
Structure	Enhancing	24 + months	Low mass advanced structure technology (Titanium SiC)
FPGA based entry sequencer	Enabling	24 months	Coding 3-6 months, qualification 18 months
Development of a miniaturised PDU and switching unit.	Enhancing	2 months	Heritage circuits/switches. Hybridising required. Package to be qualified.
Solar cell development and qualification (high efficiency and high packing density)	Enabling	~36 months	Driven by environmental qualification (radiation/acid), reduced thermal cycling, vibration test entry shock test
Tests of cover-glass degradation.	Enhancing	9-18 months	Requires simulated Venus environment (for accelerated tests)
Primary cell characterisation and qualification	Enhancing	3-6 months	Capacity characteristics at ~60 mA regions (discharge test over temp extremes, mechanical qualification tests).
Transponder	Enhancing	18 months	low mass (sub kg) European ranging transponder
Hemispherical coverage planar antenna	Enhancing	6-12 months	To demonstrator model being developed
Steerable planar array	Enhancing	6-12 months	+6 dB advantage

Table 8 Enabling and enhancing technology summary

8 Conclusion

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, aerobots, atmospheric microprobes and highly integrated miniaturized payload suites.

This paper details the VEV mission concept including the entry vehicle, a long-lifetime balloon and gondola. The study has found a long duration aerobot can survive 15-22 days in Venus' hostile environment (but recommends a representative environment testing programme) and can be developed in 5-6 years. This lifetime is sufficient for at least two circumnavigations of Venus.

Critical mission enabling technologies are required for the balloon materials, entry probe thermal protection material, and development of acid resistant flexible thin-film triple-junction amorphous silicon solar arrays.

Mission enhancing technologies include gas storage and generation technologies, advanced structural materials, high energy density primary battery technology and a low mass European ranging transponder.

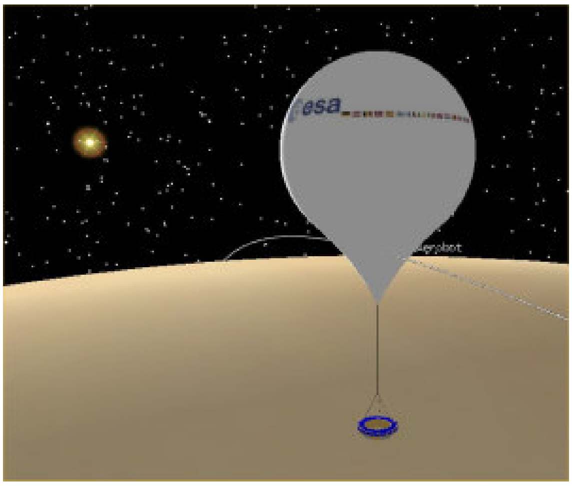

Figure 10 Simulation of gondola flight (Satellite tool kit ™)

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