In Proceedings of the 8th ESA Workshop on Advanced Space Technologies for Robotics and Automation
'ASTRA 2004' ESTEC, Noordwijk, The Netherlands, November 2 - 4, 2004

VENUS ORBITER AND ENTRY PROBE: AN ESA TECHNOLOGY REFERENCE STUDY

Andy Phipps, Adrian Woodroffe, Dave Gibbon, Dr Alex Cropp, Mukesh Joshi, Peter Alcindor
Dr. Nadeem Ghafoor, Alex da Silva Curiel, Dr Jeff Ward, Professor Sir Martin Sweeting (SSTL)
John Underwood, Dr. Steve Lingard (Vorticity Ltd)
Dr Marcel van den Berg, Dr Peter Falkner (European Space Agency)

Surrey Space Centre
Surrey Satellite Technology Limited
University of Surrey, Guildford, Surrey. GU2 7XH, UK
Tel: (44) 1483 689278 Fax: (44) 1483 689503
A.Phipps@SSTL.co.uk

Abstract

Traditionally interplanetary spacecraft are expensive, and have development schedules lasting up to 10 years. Being so high cost few concepts reach the manufacture phase. As a result of the infrequency of these missions, more experiments and supporting systems become incorporated, further driving up the cost, and delaying the schedule. Programmes rapidly become unaffordable.

The Venus Entry Probe is one of ESA's 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 which can be adopted. The mission includes a science gathering spacecraft in circular polar Venus orbit, a relay satellite in elliptical Venus orbit, and an atmospheric entry probe delivering a long duration aerobot, which will drop several microprobes during its operational phase.

This paper will focus on the design of the mission, spacecraft and aerobot, with particular emphasis on system level trade-offs. Recognising that resource reduction (mass, power, volume etc.) will be a key requirement to achieving low recurring cost spacecraft, the project has identified a variety of innovative mission enabling and mission enhancing technologies.

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 each specialised for a particular role – one of which deploys an Aerobot. This two-satellite configuration is required in order to commence the remote sensing atmospheric investigations prior to the aerobot deployment.

The Low Venus Orbiter (LVO) enters low Venus orbit 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, deploys the Venus Entry Vehicle (VEV) and subsequently operates as a data relay satellite (and may provide navigational support). After lowering the apoapse it will also perform limited science investigations of the ionosphere and the surface.

The aerobot consists of a long-duration (30 day) balloon that will analyse the Venusian middle cloud layer at an altitude of 55 km, where the environment is relatively benign. The balloon will deploy a swarm of active 'ballast' microprobes, which, once deployed, will determine vertical profiles of the lower atmosphere.

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.

These 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*
5. *Geology and tectonics*

A more detailed description of the scientific rationale is detailed by [van den Berg, 2004].

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 instrument duty cycle utilisation. It will also identify technologies required to develop such a mission.

Mission Design

MISSION REQUIREMENTS

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

- Venus orbiter must be able to perform remote sensing of the Venus atmosphere shortly before, and certainly when, the VEV is deployed in order to provide a global context for the aerobot measurements.
- Support complement of atmospheric and ionospheric payloads
- LVO has an average data requirement of 40 kbps
- VRS has an average data requirement of 10 kbps
- mission launch in 2014 onwards
- A single launch vehicle is mandated for cost reasons
- nominal mission duration: 5 years
- Deploy VEV into 20±5^0 latitude either north or south.
- Planetary protection requirements: None

For the VEV the mission requirements are:

- Support ~8 kg payload suite
- Nominal mission duration: 15 days
- Extended mission duration: to 30 days
- Deploy swarm of fifteen 115 g microprobes

CONSTRAINTS

- European technology (where possible)
- No nuclear technology
- Limit technology development to 5 years
- Launch vehicles 10 year horizon

LAUNCH AND MISSION DELTA-V

Launch is one of the principal cost drivers and opportunities for low cost launches in a 10-year time frame were researched. Despite several promising developments in the pipeline (Dnepr and Rokot upper stage developments) these are not currently funded activities. The lowest cost vehicle available in this timeframe is the Soyuz-Fregat-2B, this being selected for a French Guiana launch. This vehicle offers approximately 1400 kg for direct Earth escape trajectory to Venus and a generous payload fairing envelope diameter of 3.7m x 5.5 m (fairing: S-version) such that volume does not become a design driver. It may be possible to optimise the Earth departure phase by initially launching into a near-Earth escape and utilising the spacecraft's onboard propulsion system to perform escape – this is currently being investigated. Lunar swing-by is not being considered due to the inherent complexity and cost.

The heliocentric transfer to Venus takes between 120-160 days and upon arrival both spacecraft will perform a Venus orbit insertion manoeuvre of around 1.2 kms^{-1} placing the spacecraft into a 24 hour (250 km x 66,000 km) initial capture orbit.

Venus Relay Satellite			
Event	ΔV	Margin	Total ΔV
Earth departure (2015)	0.00	10%	0
Mid course correction	50	10%	55
Venus Orbit Insertion	1,053	10%	1,158
De-orbit burn (VEV release)	21	10%	23
Re-orbit burn (VEV release)	21	10%	23
Modify to operational orbit altitude	1,348	10%	1,483
Orbit maintainance	17	100%	34
Momentum dumping	5	100%	10
TOTAL			2,786
Low Venus Orbiter			
Event	ΔV	Margin	Total ΔV
Earth departure (2015)	0.00	10%	0
Mic course correction	50	10%	55
Venus Orbit Insertion	1,053	10%	1,158
Modify to operational orbit altitude	1,665	10%	1,832
Orbit maintainance	17	100%	34
Momentum dumping	5	100%	10
TOTAL			3,089

Table 1 Spacecraft ΔV

After a period of initial check-out and commissioning LVO reduces its orbit to its final orbit (2,000 x 6,000 km) where it undertakes scientific investigation of the atmosphere prior to VEV deployment. VRS then places the entry vehicle into an intercept trajectory. Both spacecraft perform communications relay and provide navigation support to the Aerobot

After the entry vehicle science-gathering phase is completed VRS enters its final science-gathering orbit of 250 x 7,500-20,000km where it continues to provide communications relay (LVO to Earth). Both spacecraft require a total Δv capability in the region of 2.8 - 3.1kms^{-1}.

Spacecraft Design

PROPULSION

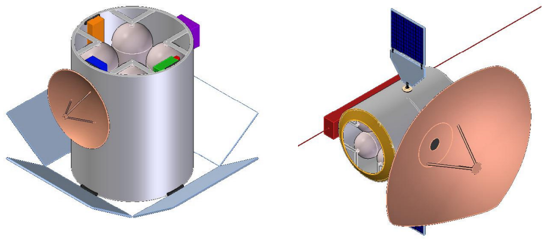
As a result of the high delta-v required both spacecraft would utilise industry-standard chemical propulsion technology. The propulsion system consists of a conventional dual mode bipropellant system, using for high thrust manoeuvres and hydrazine monopropellant thrusters for momentum dumping. A common upper stage (For LVO and VRS) has been investigated but offers no real mass advantage. It also constrains the final orbits significantly.

Solar Thermal Propulsion (STP) is one development that has been considered for this mission. This technology involves focusing sunlight into a fibre optic cable using a mirror, or multiple mirrors. The light can then be piped throughout the spacecraft and guided into a thruster [Kennedy, 02]. STP has advantages over conventional solar electric propulsion (SEP) solutions. Relatively higher thrusts can be achieved, in the order of 1-10 N, (two orders of magnitude above SEP) whilst still operating at a specific impulse of around 400 seconds. This is greater than can be achieved with a conventional bipropellant system. Additionally the sunlight is converted directly into heat giving a direct gain STP system an efficiency of around 89%, compared to a SEP system which may have a light to propulsion energy efficiency of around 10–12%.

However, this technology has a mass overhead of ~15 kg and is yet to be determined if it is compatible with a 5 year development schedule.

STRUCTURE AND CONFIGURATION

The LVO and VRS spacecraft configuration are conceptually very different, reflecting the requirement to keep LVO mostly nadir pointing for science gathering, and VRS Earth pointing for communications relay (see figure below). However, there is a degree of commonality at subsystem level. For simplicity of design and mass efficiency both spacecraft are based upon central thrust tube structural concepts.



Low Venus Orbiter (LVO) Venus Relay Satellite (VRS)

Figure 1 Orbiter configuration

Power generation on LVO is provided by body-mounted arrays at a fixed cant of 30-45 degrees. In the case of VRS two steerable sun tracking (one degree of freedom) arrays provide power. VRS has a fixed Earth pointing high-gain antenna that can be up to 3.5 m in diameter at X-band or 0.8 m at Ka band. The 85 kg VEV is attached with a 3-point separation system. The following figure shows compatibility with the selected launch vehicle.

MASS BUDGET

The following table outlines the tentative top-level mass budget for each spacecraft. The total mass is just under 1400 kg showing compatibility with the Soyuz-Fregat launch vehicle capability. Because the design study is still in an early phase, a total of 25% design maturity margin has been added. The dry mass (including margin) for LVO being around 300 kg and VRS around 220 kg.

Mass Budget	LVO	VRS
Payload	30	10
Entry Probe	0	85
Propulsion (dry)	79	49
Propellant	374	406
Power & Solar Arrays	21	6
Communications	22	32
OBDH	4	4
Environment	18	6
AODCS & Safety	9	9
Structure	67	66
Platform system margin	44	35
TOTAL	669	710

Table 2 Spacecraft mass budget

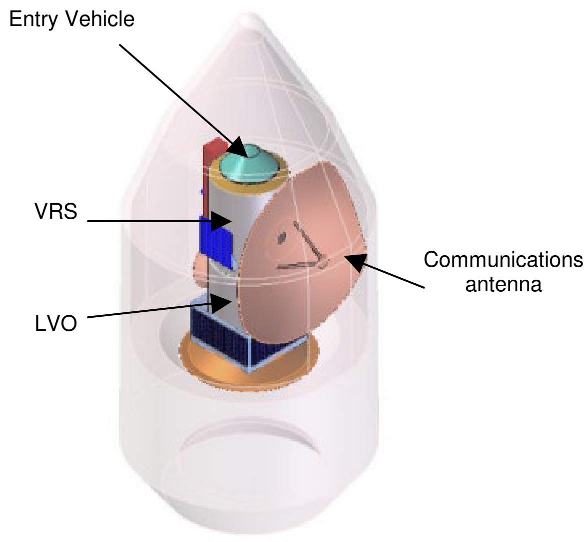


Figure 2 Venus Orbiters and Entry Probe in Soyuz-Fregat S-type fairing (current configuration)

PAYLOADS

The following table outlines the payload resource constraints for LVO, VRS and VEV.

Spacecraft	LVO	VRS	VEV	Units
Mass	30	10	8	Kg
Power	70	25	6.7	W
Data generation	40	10	5	kbps

Table 3 Payload resource constraints

In addition the VRS incorporates two 10m booms and one 3.5 metre axial boom (not shown in illustrations). 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.

ENVIRONMENT

An assessment was made into the radiation and thermal environment the mission will encounter and the applicability of Commercial Off-The-Shelf Technology (COTS). Total dose effects are caused by accumulated charge within the semiconductor material which manifests itself as changes in threshold voltage and consequently increasing leakage current.

A prediction of the radiation environment the spacecraft will encounter was analyzed using ESA's SPacecraft ENVironment Information System (SPENVIS) code. A shielding thickness of 2 mm from sub-system module walls was assumed - leading to an effective thickness of 4 mm when considering the effects of adjacent sub-systems and propellant tanks.

Analysis suggests the expected cumulative mission radiation dose would be in the region of 6.5 krad(Si) over the 5 year mission lifetime. While typical 'soft' COTS technology fails near 5-10krad (Si) suitably selected technology can withstand as much as 100 krad(Si).

The likelihood of SEL occurring within the spacecraft (based upon previous occurrences in LEO) has been estimated as once per spacecraft every three years. This SEL may be destructive, or, in approximately 80% of cases, benign. In many cases, powering down and then powering up the subsystem will eradicate the effects.

The thermal environment for the mission is fairly stable during the transfer phase of the orbit where an ~80% increase in solar flux can be expected as the craft approaches Venus. When in Venus orbit, the spacecraft Thermal Control Subsystem (TCS) will need to be able to cope with an increase in power dissipation (arising from the higher duty cycle of the payloads), and also with the harsh environment of the Venus neighbourhood, particularly the planetary and albedo flux.

The current design approach is to utilise a mainly passive thermal control system for simplicity and cost reasons – the spacecraft being biased cold. Further analysis is required to establish if this is feasible in all operational modes.

PLATFORM AVIONICS

As mass is quite critical high storage efficiency Li-ion cells have been selected - these offer a mass around 25% of a similar capacity NiCd battery. Multiple strings of 1.5Ah cells provide redundancy. Triple junction GaAs based cells have been selected for power generation – the projected performance of these in 5 years time is 35%. A novel power system topology has been proposed. The *Optimised Voltage Power System topology* [Clark, 02] offers good efficiency in both eclipse and sunlight.

Attitude and orbit control is achieved using a conventional set of star sensors, gyros, thrusters and control moment gyroscopes.

The communications system is sized for the worst-case link (VRS to Earth ground station). Assuming the use of a 35 m ground station antenna 6 kbps is achieved at maximum Venus-earth distance. This improves by 16 dBs at minimum distance (~200 kbps). All links including the LVO-VRS inter-satellite link are viable at X-band (7.145GHz), Ka band offering greater capability but for increased cost.

The proposed on-board data handling system is based upon SpaceWire architecture, the on board computer selected being either the PowerPC Quick II CPU, or FPGA based LEON processor. The Venus mission will produce approximately 800Gbytes of data over the proposed five-year mission life. Using currently available COTS hard disk drives, this could be stored on 4-5 disk drives (as 200Gbytes on a single disk is now becoming available). Over the next five years this is likely to at least double with a 1Tbyte disk available in the foreseeable future.

Having this kind of long-term storage onboard opens up the following mission operations possibilities:

- With all the data being stored, the data rate can be varied as the communications link budget varies with the Earth-Venus distance. When the Earth-Venus distance is at a maximum, the data rate could drop below the specified 40Kbps (average) requirement with the difference being stored on the hard disks. When the Earth-Venus distance is near minimum, a more favourable link budget is available and a data rate above the required 40Kbps will be possible
- A second operations mode could be to run remote "software agents" on the satellite to process and analysis the data on board and just return the results. This would dramatically reduce the require link budget. Having the data bulked on the satellite then allows re-analysis of the data should the original agent be faulty or if a new improved version be developed during the mission life.

Venus Entry Vehicle Design

ENTRY AND DEPLOYMENT

The VEV will be released from the VRS spacecraft, while it is in its initial highly elliptical orbit. To reduce the complexity and mass of the VEV the VRS will deliver the entry probe to its planetary intercept trajectory. Deployment from orbit has been chosen 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.

A 45˚ sphere-cone entry probe is baselined as this provides good passive stability in the hypersonic and supersonic regimes. The VEV will enter the dense Venus atmosphere with a velocity of 9.8 kms^{-1} and a flight path angle between 30˚ and 40˚, as this scenario yields the best overall system mass. 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 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 ms^{-1} 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 gas storage system will be released after inflation of the balloon, and the aerobot will gradually rise to its float altitude.

VEV CONCEPT DESIGN

Most of the volume of the entry probe is taken up by the spherical gas storage tank, which is surrounded by a toroidal 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.

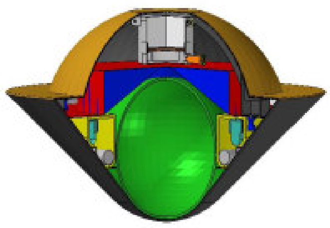


Figure 3 Venus Entry Vehicle (Aerobot stowed)

AEROBOT DESIGN

The following table outlines the relatively benign environment at the aerobot float altitude:

Float Altitude (km)	53	55	62	Tolerance	Units
Temperature (K)	323.2	302.3	254.5	± 4	k
Temperature (C)	50.06	29.16	-18.64	± 4	deg. C
Atmosphere pressure	0.7109	0.5314	0.1659	± 15%	Bar
Zonal wind speed (mean)	60	60	91	± 40	ms-1
VEV planetary rotation rate	7.40	7.40	4.89	n/a	days
Solar downwelling flux (0.4-1 micron)	638			n/a	W/m2
Solar downwelling flux (0.4-1.8 micron)	730			n/a	W/m2
Total upwelling flux	25			n/a	W/m2
Cloud layer	Lower-middle cloud			n/a	n/a
Cloud composition	75% H_2SO_4 * 25% H_2O			n/a	n/a
Electromagnetic radiation	300			n/a	µV/m/sqrt(Hz)

Table 4 Environmental conditions at equilibrium float altitude

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. Rapid updrafts and downdrafts (wind shear) might cause rapid excursions from this altitude. At this altitude the aerobot will experience a varying temperature of between –19 and +50^{0}C. This has a corresponding pressure variation of 0.7 – 0.17 bar.

Due to an effect known as super rotation the aerobot will experience zonal winds that range from 60 to 91 ms^{-1} westwards which implies a day or a night length of between 4.9 and 7.4 (Earth) days. With an uncertainty expected to be as much as ±40ms^{-1} this greatly effects the day and night durations.

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

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

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 (15-30 days). 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 currently under investigation.

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.

GONDOLA DESIGN

The figure below outlines the concept developed for the gondola.

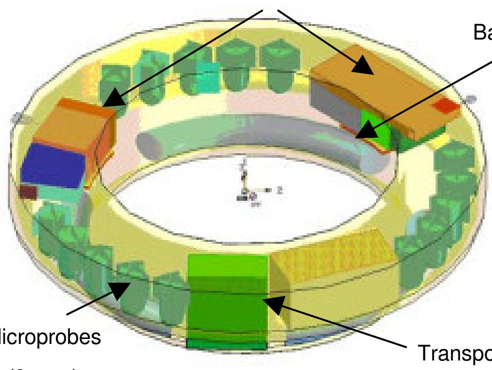


Figure 4 Gondola Internal Configuration

The 4 kg payload suite is incorporated within the VEV primary structure along with 3 'packs' of 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-SiC fiber material is proposed. This reduces the structure mass to <2.0 kg.

Analysis was undertaken using *Satellite Tool Kit* ™ to establish the communications visibility from the LVO and VRS orbiters to an aerobot in near equatorial regions around Venus. The Aerobot was propagated at 25^0 North and 55km altitude for 30 days at a ground speed of 70 ms^{-1} - corresponding to around 5 circumnavigations (see figure below).

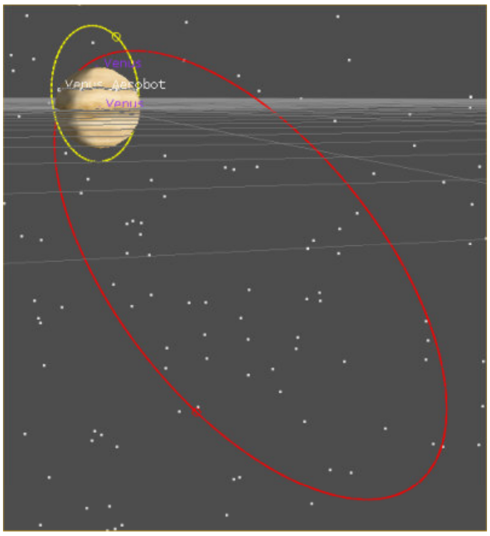


Figure 5 Communications access with aerobot

LVO can maintain a 10.7 kbps link at average viewable distance of 9,514km. VRS can support a 43 kbps link again at average distance of 16,800 km. LVO has 231 accesses with the aerobot over the 30-day mission lifetime. Each occurs with a relatively short duration of 1.25 hours. The total communications duration over the aerobot lifetime is more than 289 hours (or 40% of the time). The VRS, in its highly elliptical polar orbit, has 20 accesses over this time period. Each is considerably longer at 5.3 hours in duration, giving a total communication access time of 106 hours (or 15% of the mission lifetime). The combination of both spacecraft can return over 2.6Mbytes of data, which exceeds the data return requirement. This analysis concludes the uploading of data from the Aerobot to the orbiters is not a significant design driver.

6.7 W of (average) electrical power is required at BOL for the payloads and around 2.6 watts for the platform subsystems (80% being consumed by the transponder). 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 4.8W and 1.1W respectively.

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

1. Primary cells providing power day and night using lithium-thionyl chloride (Li-$SOCl_2$) cells.
2. Primary nighttime operation only. Lithium-thionyl chloride (Li-$SOCl_2$) cells supported by solar cells during day.
3. Secondary power system. Lithium-polymer secondary cells (170 Wh/kg) during night and solar arrays during day.
4. Mini-rotary engine.
5. Hydrazine rotary engine.
6. Micro-turbine.
7. Methanol fuel cell.

Option 1-2 are conventional systems requiring minimal development, option 3 would require the qualification of lithium-polymer cells but this is compatible with a 5 year technology development timeframe. Options 4-7 were studied for viability, development timescales and cost.

A mini and micro-scale rotary engine power source is being developed at the University of California at Berkeley [Lee, Walther]. 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. Typically hydrocarbon fuel has a specific energy (SE) in the region of 11,500 Wh/kg. Assuming 20% of this energy can be converted to useful energy this SE falls to 2,300 Wh/kg. Provision of a separate oxidiser would reduce the effective energy density by around 2/3, to perhaps 800-1000Wh/kg. Berkeley has demonstrated 4W of power generation from a package similar to a 9V PP3 battery (which includes control electronics, valves, fuel but not oxidiser storage and voltage regulation). However, it is at least 5-10 years away from development and its advantages are largely offset by the need to carry oxygen. It is uneconomical to recover oxygen from Venus' CO_2 atmosphere as it requires ~9 times more energy that is generated [Baird, 99].

A hydrazine derivative of the UC Berkeley Wankle 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.

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 [Peirs, 2003], [Epstein, 2003]. 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. These problems are caused by fluid flow and bearing issues associated with getting efficient operation in parts rotating at this rate at such a small scale. Furthermore, for space application the specific fuel consumption, coupled with the need to transport oxidiser, makes it a less than attractive option.

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.

The proposed baseline is option 2 (primary battery supplemented by solar arrays) as this offers the lowest mass system. If the extended mission duration increases to 60 days the secondary power system (option 3) becomes lower mass. Lithium-thionyl chloride (Li-$SOCl_2$) primary cells (at 680Wh/kg) will provide power during the night and electrical power during the day will be provided by amorphous-silicon solar cells, which are mounted on the gondola surfaces (see below). A solar intensity of 600 Wm^{-2} is converted into 70-90W of processed power.

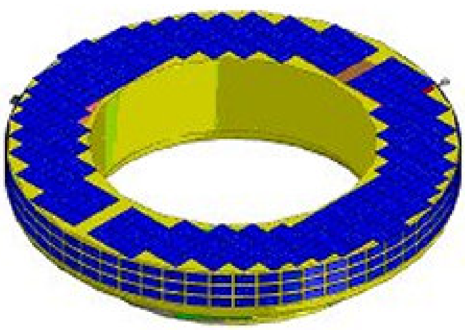


Figure 6 Gondola Solar Power Generator

Higher energy density storage technologies in development include:

- Li-SO_2Cl_2 (Li-sulphuryl chloride), offering 25% more Wh/kg and 50% more Wh/litre than Li-$SOCl_2$),
- Li-NO_2Cl might offer 900Wh/kg

The tables below details the mass budget developed for the gondola - this is sized for 30 days of operational lifetime.

Science	8.1 kg
Communications	1.6 kg
Structure	7.1 kg
OBDH	0.8 kg
POWER	4.9 kg
Balloon	8.6 kg
Gas storage	16.8 kg
Entry System	37.2 kg
Total	**85.1 kg**

Table 5 VEV mass budget

The gondola mass is ~23 kg, with a floating mass of ~32 kg (48 kg with gas storage system), giving an all-up mass of ~85kg.

Enabling Technologies

The following list details mission enabling technologies, or technologies which could increase the science yield

For the orbiter:

- Lithium-polymer cells
- Solar thermal propulsion
- Hard disc drives
- Power system topology
- Low mass controlled moment gyroscopes
- Upper stage development for low cost highly capable launch vehicles such as Dnepr and Rokot

Technology development for the Venus Entry Vehicle and Aerobot are required due to its mass sensitivity.

- low mass (sub kg) European ranging transponder
- Low mass advanced structure technology
- Hydrogen generators and storage technology
- Low leak (acid resistant) balloon technology
- High energy density batteries
- Thin film amorphous silicon solar cells on flexible substrate compatible with space environment

The study has established that the total programme cost around €350 million (FY2004) including platform, operations, payload and launch and overall programme management.

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 enable missions, reduce 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, aerobots, atmospheric microprobes and highly integrated miniaturized payload suites.

Outline both orbiter and VEV concept in brief (get from VEV report

The study has established that the total programme cost around €350 million (FY2004) including platform, operations, payload and launch and overall programme management.

The study concludes in late September 2004, and analysis continues to clarify the thermal and structural design.

Acknowledgments

The authors are indebted to the following for assistance during this study activity: Dr Adam Baker, Dr Jim Clemmet, Craig Clark, Rick Kimber, Dr Tanya Vladimirova, Carlos Lovett Lineares and Stephen Paterson (SSTL). Also Nick Bown (Vorticity Ltd), Joe Moorhouse and Stefan Kraft (Cosine Research) and Julian Harris from Swiss Space Technology.

References

1. M.L. van den Berg, et al. Venus Entry Probe Technology Reference Study. 35th COSPAR Scientific Assembly. July 2004.
2. Kennedy, Maj. Fred. et al. Solar Thermal Propulsion for Microsatellites. *6th Space Propulsion Conference*, Versailles 14-17 May 2002.
3. Clark, C. S. A Universal Power System Architecture: One Topology for Earth and Planetary Orbits, 6th European Space Power Conference, Porto, Portugal May 2002.
4. A.J. Kliore. Venus International Reference Atmosphere - published for COSPAR 1986 ISBN 0-08-034631-6.
5. Lee, C H. Et al. Design and Fabrication of a micro Wankel Engine using MEMS technology.
6. Walther, D. C. Et al. MEMS Rotary Engine Power System: Project Overview and Recent Research Results. Unpublished
7. Baird R S, Sridhar K R, Gottmann M; 2001 Mars In-Situ Oxygen Production Flight Demonstration; AIAA 99-2413, presented at 35th Joint Propulsion Conference, 1999, Los Angeles
8. Peirs, J. et al. Development of a micro Gas Turbine For Electrical Power Generation. 14th MicroMechanics Europe Workshop 2-4 November 2003. Delft, The Netherlands.
9. Epstein A H; Millimeter-scale, MEMS gas turbine engines; GT-2003-38866, paper presented at the ASME Turbo Expo 2003, Atlanta, Georgia, June 2003, pp. 28.