Venus Sample Return

A Hot Topic ..

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Within the Solar System, Venus presents a set of unique challenges to obtaining samples and returning them to Earth. High temperatures, a thick corrosive atmosphere and poorly characterized terrain are some obvious examples. Our only knowledge of the surface and atmosphere is from Radar images and the data from Soviet probes. A point design now exists for a single launch mission to return Venusian samples massing about 100g. This paper discusses this mission, addressing the science return, how some of Venus' attributes can be used to advantage and what technologies will be needed to make this mission a reality. It also explores possible future directions to make the mission more affordable.

INTRODUCTION

The brilliance of Venus in the morning and evening skies has been the focus of attention of humans throughout time. Observations of Venus during its solar transit in 1761 revealed Venus' albedo as the result of an atmosphere and that Venus was of similar size as Earth; Venus was thought to host a tropical climate, akin to the Earth's Carboniferous period, up to the early twentieth century[REF1]. Telescopic observations of the planet in the 1930s revealed it to have a CO_2 atmosphere[REF2], later ultraviolet telescopic analysis revealed the CO_2 clouds rotated with a period of ~4 days[REF3]. The rotation of the surface was not obtained until ground-based radar observations of the surface yielded a retrograde rotation every 243 Earth days[REF4]. This superrotation of the Venus atmosphere is still a debated topic of atmosphere dynamics.

Spacecraft exploration of Venus began in 1961 with the launch of the Soviet Venera 1 spacecraft (Figure 1), designed to penetrate the atmosphere and land on the surface of the planet. The following year, the U.S. commenced exploration of Venus with Mariner fly-by probes, with the

U.S. and the Soviets taking advantage of the low energy transfer orbit to Venus, which occurred every 19 months. Mariner 2 was the first to successfully encounter Venus, in 1962, taking images and spectra of the planet and confirming Venus' hot, dense CO_2 atmosphere. In 1967, Venera 4 made successful in situ measurements of the atmosphere of 18 bars and 260°C, confirmed by Mariner 5 the same year, recording surface temperatures of ~530°C and ~100 bars. In 1972, Venera 8 reached and recorded data on the surface of Venus, revealing that sunlight did reach the surface of the planet. This resulted in cameras on Veneras 9 and 10 which successfully imaged the surface in 1975 (Figure 2), yielding the first image transmitted from the surface of another planet. Veneras 9 and 10 landed ~2000 km apart, but both reveal a surface with slabby rocks separated by soil. Gamma-ray spectrometers on Veneras 8-10 yielded U, K, Th abundances that were more like the Earth than the Moon[REF5]. These observations were later confirmed by X-ray fluorescence measurements of major elements on Veneras 13 and 14, which are consistent with terrestrial basalts[REF6]. Panoramas from Venera 13 and 14 (Figure 3) also reveal slabby rocks, regoliths and fine materials.

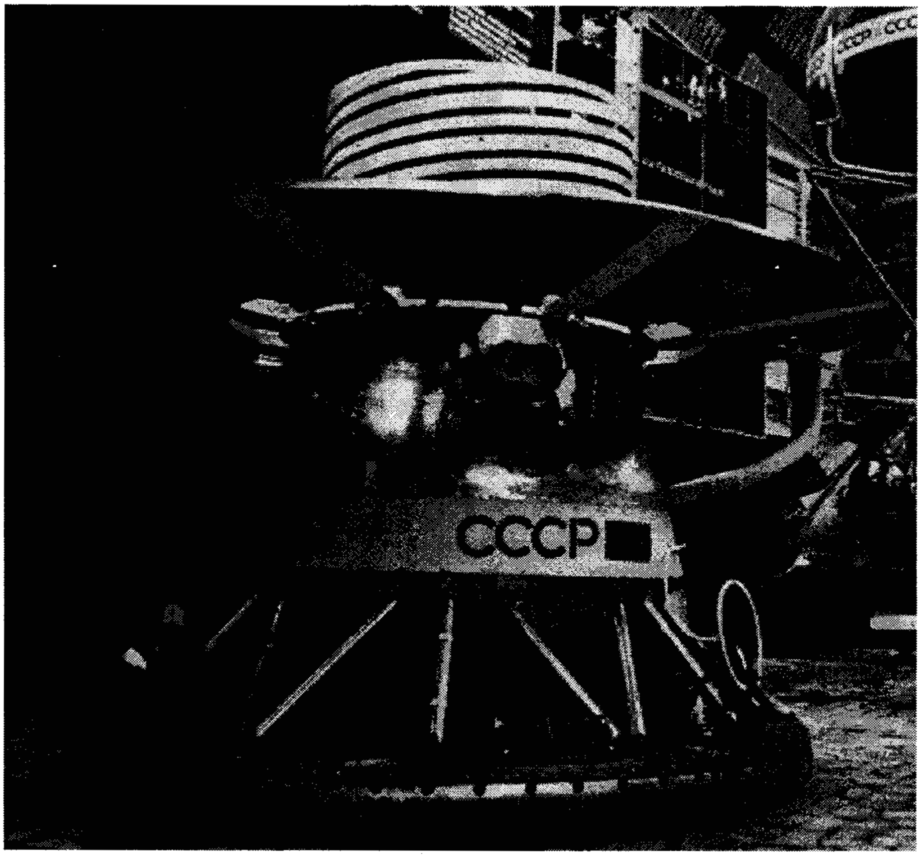
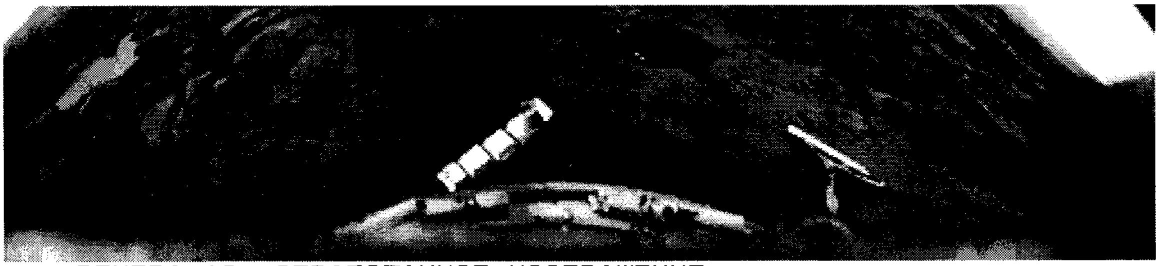


Figure 1. Venera 13. Credit : NASA.

ВЕНЕРА-9 ОБРАБОТАННОЕ ИЗОБРАЖЕНИЕ



ВЕНЕРА-10 ОБРАБОТАННОЕ ИЗОБРАЖЕНИЕ

Figure 2. The surface of Venus as imaged by Venera 9 and 10. The panorama extends from the base of the spacecraft in the center, to the horizon on the edges of the frame. The metallic object on the right is the ~40 cm long. Both images reveal a surface comprising rocks and soil.

Venera 13 color image taken on the surface or Venus

ВЕНЕРА-13 ОБРАБОТКА И СИНТЕЗ ИППИ АН СССР И ЦДКС

ВЕНЕРА-14 ОБРАБОТКА ИППИ АН СССР И ЦДКС

Figure 3. Panoramic images of Venus taken by Venera 13 and 14 in 1982.

The Venera data yielded our first glimpse of what it would be like to stand on the surface of another planet. These data were supplemented by additional measurements of the atmosphere provided by the U.S. Pioneer Venus orbiter and probes which measured composition, temperature and pressure at three entry points. Wind speeds were measured from orbit for over a decade. By the 1980s, the spacecraft had revealed the shrouded Venus to be extremely hot, with a dynamic and oppressive atmosphere. Studies of the atmosphere revealed it to have a runaway greenhouse effect, which illuminated the burgeoning study of global warming on our own planet. The surface of our twin planet has rocks similar to our own, indicating volcanism. But it was not known how these observations fit into a global picture of Venus. This could only be accomplished by mapping the surface, which required radar.

Radar mapping of the surface by Pioneer Venus and Venera orbiters and ground-based radar from Arecibo revealed the surface of Venus as having large (1000s km), contiguous areas of radar-bright (rough) highlands among radar-dark (smooth) lowlands. The Venera landers had imaged these lowlands, suggesting that the lowlands were basaltic in composition. Circular and linear features were discernable, but at such low resolution, it was difficult to assign an origin to the features. This was changed when the Magellan spacecraft was launched in 1983 and began to return images of the surface at 75 m/pixel. Venus is now revealed to be dominated by volcanism: plains, volcanoes both large and small, both viscous and fluid, round volcanic features called coronae that are unique to Venus, and lava flows of many different types. Some of the highlands on Venus are heavily deformed showing evidence of both compressional and extensional tectonics on Venus. While no evidence of terrestrial-type lateral plate tectonics is apparent on Venus, the ~1000 craters on the surface demonstrate that it is relatively young, ~500 Ma, requiring that global-scale volcanic resurfacing occurred at that time. Large volcanoes may represent some of the youngest volcanism on the planet.

The scientific community is now trying to understand how Venus evolved into such a volcanically dominated planet, the nature of the tectonism, and the relationship between the atmosphere and the surface. In addition to further analysis and modeling of the radar data, some fundamental measurements of the surface are required. These include: compositional of the surface, particularly the non-plains terrains, age dating of the surface, in situ measurements of the lowermost 20 km of the atmosphere, and heat flow estimates of the crust. Sample return would provide the opportunity to perform detailed analyses of some of the parameters, such as….

As a result of the landed missions, conducted from 1967 into the mid 1980s, we have an adequate understanding of the conditions at the surface of the planet for engineering purposes.

There is, therefore, a good foundation on which to base our designs. The inhospitable nature of the Venusian surface makes In Situ measurements extremely difficult as most measurements need complex equipmnet and long residence times on the surface. Thus, for Venus, even with the advanced analytical techniques being developed, sample return may remain the most viable option to study the surface of this planet in detail. Some aspects of Venus can be turned to our advantage and this will be discussed, together with the technology advances that will make this mission a reality.

SCIENTIFIC GOALS

The key goals for a Sample Return mission to Venus are:

Marty – how about a list of the "top few" issues … ?

MISSION APPROACH

In outline, the mission can be accomplished using a single Delta III/IV class expendable launch vehicle. This launch vehicle will send the spacecraft on a ballistic transfer to Venus. The spacecraft consists of an orbiter and a lander, where the orbiter also functions to provide transport back to Earth and the lander has on board equipment to; obtain a sample, place the sample in the ascent vehicle, carry the "return to orbit" rocket above the bulk of the atmosphere and finally place the contained sample in Venus orbit for collection by the orbiter. After picking up the sample the orbiter returns to Earth and injects the sample carrier so that it may be picked up at the Utah test range.

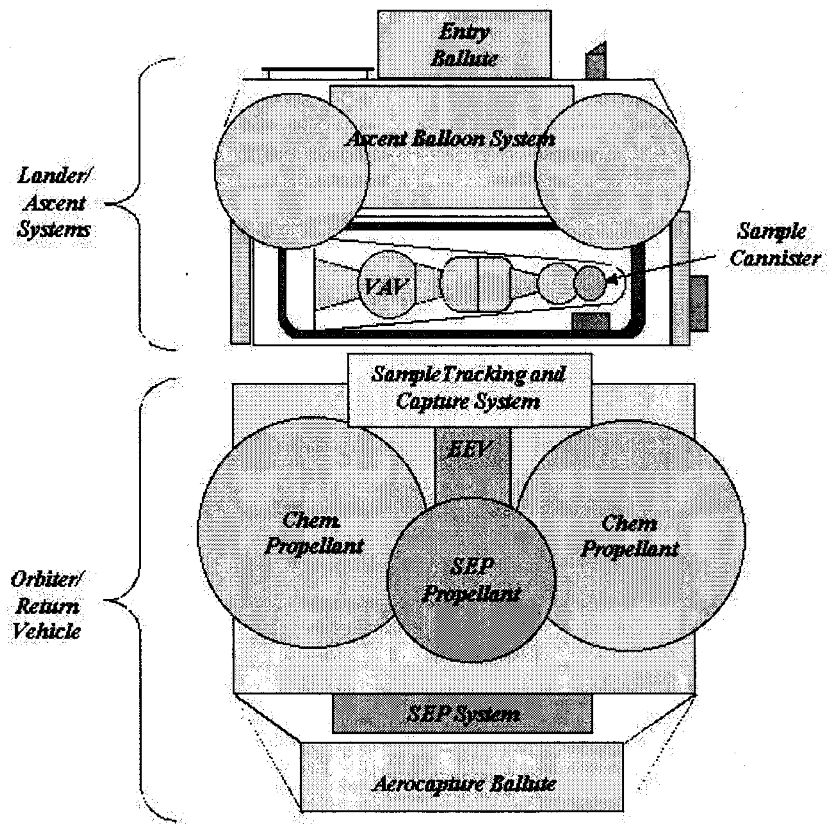


Figure 4 A possible launch configuration for the Venus Surface Sample Return system. The Venus ascent vehicle (VAV) shown in the Lander/Ascent systems is just under 3m long.

Before discussing the mission approach taken in more detail, it is worth identifying the key issues the lander will face at Venus. While the transportation to and from Venus is challenging and must be done effectively the major differences, between this and a mission to another body, lies in the challenges faced by the landed equipment. Venus is a hostile planet with an environment very different from Earth. It presents an environmental challenge as difficult as any in the Solar system for equipment designed for use on Earth or in the relatively benign environment of space. The most challenging aspects of this environment, from the perspective of the landed equipment is the high temperature at the Venusian surface ~ 460°C; the high surface pressure ~ 90 bar (mostly CO_2) and the presence in the atmosphere of highly corrosive species. These include sulfuric acid and *??*. This environment dictates that a lightweight, corrosion resistant and thermally isolated pressure housing be provided for all electronics components. These components provide the control, communications and power functions for the landed equipment. The surface pressure of Venus is sufficiently high that most available semiconductor and integrated circuit components will collapse and be destroyed. The landing gear and sampling system must be made of materials that can withstand the local environment for an extended period of time. The inflation systed for the ascent vehicle must be protected from the thermal environment, to maintain safe pressures in the gas containers, and from exposure to CO_2 as the CO_2 will liquefy at Earth normal temperatures and 90 bar pressures. The balloon need not be protected thermally but the ascent rocket must be isolated from both the thermal and CO_2 environment. The pressure, per se, is not an issue.

Counterbalancing these challenges, are attributes of Venus that make the mission easier and we took advantage of them. The dense atmosphere makes aerocapture of the arriving spacecraft straightforward. We plan to accomplish this using a ballute, high in the Venusian atmosphere. The subsequent capture of the lander and its descent to the surface are made easier by the high atmospheric density. The Soviet lander shown in Fig 1 has a circular structure at the top, which is all that is required to provide a soft, safe landing on the Venusian surface. Surface winds are not an issue as we know from Venera measurements that the wind velocity at the surface is about 1m/sec (~2 mph). The dense atmosphere provides high lift from the He filled balloon lofting the ascent rocket to its ignition altitude. Finally the high solar flux at Venus is used to drive an SEP stage returning the sample from Venus to Earth for analysis. Combining the effects of using these items to our advantage saved over a thousand kilograms – making the mission viable on the desired medium lift launch vehicle. The next section discusses the various phases of the mission in more detail.

A CLOSER LOOK AT THE MISSION

Transfer to Venus

Venus delivery is accomplished by a conventional launch into a direct ballistic transfer trajectory. This transfer is shown in Figure 5 and requires a launch C3 of just over 9 km^2/s^2 for a launch on March 26, 2004 and arrival on September 20, 2004, with the declination of the launch asymptote at 31.3°. The opportunity in 2004 is chosen as representative of the energy demands and arrival geometry of the next several opportunities. It is not meant to imply any programmatic commitment to that date. The actual launch date will be dependent on science priorities and technology development status. Typical trajectory correction maneuvers are planned en route. Solar electric propulsion (SEP) was considered as an alternative and while it does offer some mass advantage (adding perhaps 5% to 10% to the delivered mass), the cost of the SEP system didn't seem worth the mass gain for the Earth – Venus transfer.

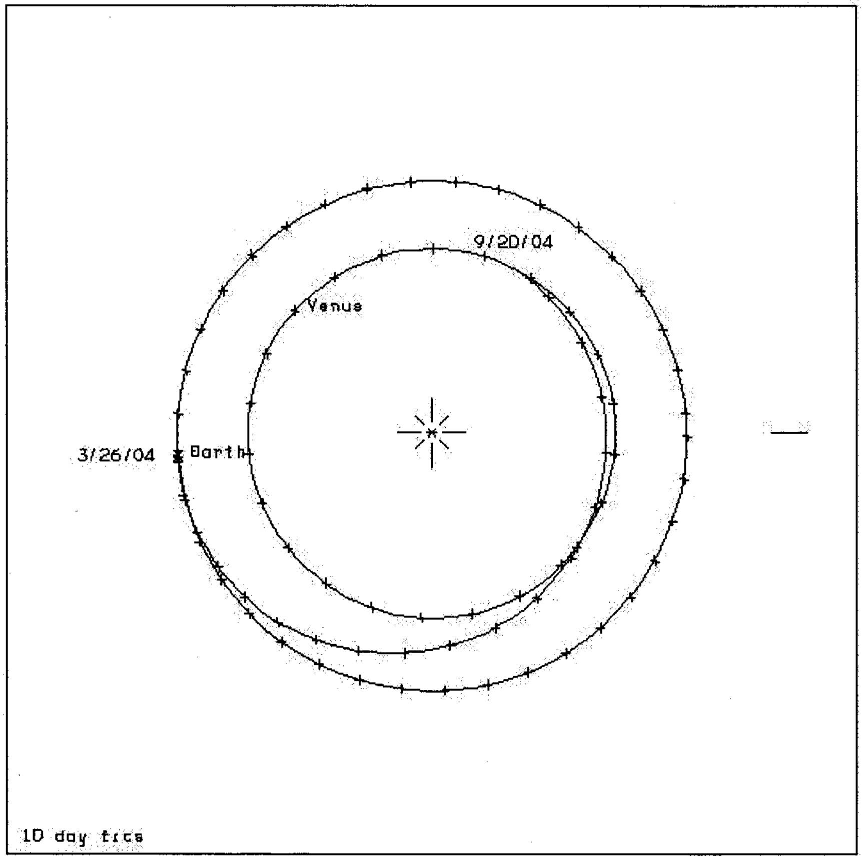


Figure 5. The Earth-Venus transfer orbit. The view is a projection of the ballistic transfer trajectory and Earth's and Venus' orbits into the ecliptic plane as seen from ecliptic north.

Aerocapture at Venus

Aerocapture is done using an inflated hypersonic drag device (also known as a ballute, a hybrid of balloon and parachute). Because of the relatively low ballistic coefficient of the ballute the atmospheric heating is spread over a much larger area and the larger diameter increases the thickness of the boundary layer; both effects make an ablative heat shield unnecessary, offering a significant mass advantage. For the approach velocity of 5.75 km/s, corresponding to an entry velocity of 11.75 km/s, the mass of a conventional heat shield and associated aeroshell structure was estimated to be about 30% of the entry mass; initial estimates of the ballute were that it would be about 14% of the entry mass, which is the value used in mass estimates reported here. Since then, more detailed analysis of the ballute has been done and the mass fraction is reduced from the initial estimate [REF7].

The ballute also offers a much simpler control approach for aerocapture. Given that the ballistic coefficient of the spacecraft is far lower than the ballute, the following approach is feasible. As the ballute enters the upper atmosphere, the deceleration of the combined ballute – spacecraft is measured and then integrated to provide a measurement of the ΔV versus time. From this a time can be computed to release the ballute when sufficient ΔV will have been accumulated. More precisely, when the desired ΔV is predicted based on the experienced drag. This approach eliminates the complex guidance and control systems required by conventional aeroshells to control the errors due to navigation and uncertainty in the atmosphere. The aerocapture reduces the periapse velocity of the vehicle from 11.77 km/s to 10.16 km/s at an altitude of 110 km, a ΔV of 1.61 km/s. This leaves the spacecraft in a 6.8 day elliptical orbit.

Staging Orbit for Lander Deployment

The declination of the arrival asymptote is -24.3° (relative to IAU north, which is toward ecliptic north), so the initial orbit is inclined to Venus' equator, where the entry is aimed so that the apoapse of the ellipse is near a node on Venus' equator. A plane change maneuver at the node near apoapse puts the inclination at 0° relative to Venus's spin axis (180° relative to IAU north); this maneuver also raises the periapse altitude to 130 km. Aerobraking is then used to reduce the apoapse altitude to 300 km, when another maneuver raises periapse to the same altitude. A cartoon showing this arrival strategy is shown in Figure 6.

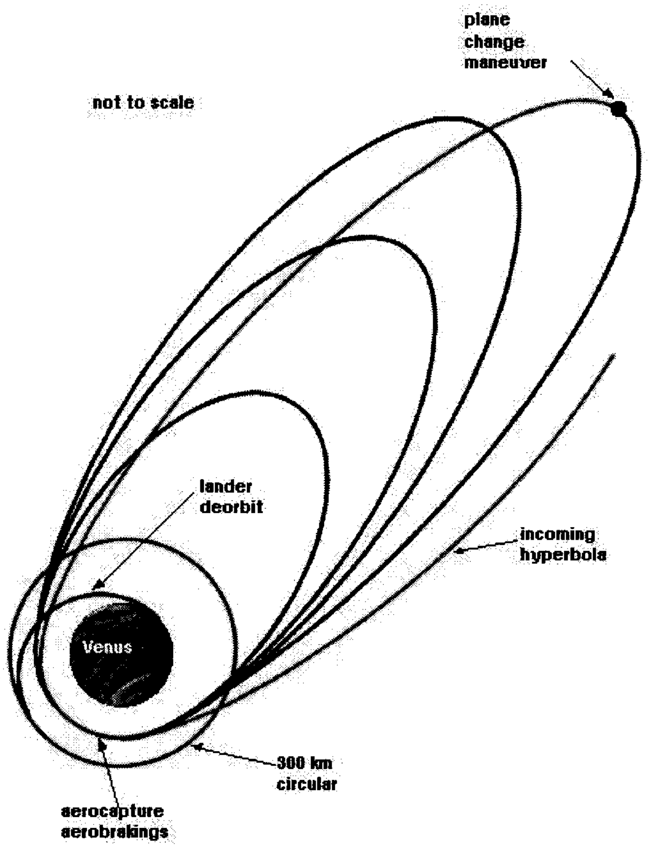


Figure 6. A cartoon of the arrival strategy at Venus. The view is a projection into Venus's equatorial plane as seen from ecliptic north. The orbits are not to scale.

The resulting final orbit is equatorial and circular. This was selected as it provides both access to all longitudes and for science and keeps the orbiter coplanar with the ascent vehicle after sample acquisition. This latter fact greatly simplifies the rendezvous and recovery strategy for the orbital sample . This is acceptable from a science perspective since the equator crosses all types of Venusian terrain. Note that Venus rotates very slowly and has little J2 so that orbits precess very slowly, so at first thought a given landing site would stay on a ground track for a reasonable mission lifetime. But because of the density of the atmosphere a significant amount of time is spent during descent and ascent where high altitude winds are equivalent to a four-day rotation period, so the location of a lander and returning sample would move away from the plane of a non-equatorial orbit. A low circular orbit also minimizes the entry velocity for the lander and improves communications between the lander systems and the orbiter.

Landing

Descent to the surface must be as quick as practical to minimize exposure to the extreme atmosphere. After separation from the orbiter, the landing package uses a small solid rocket motor (about the size of a Star 17) to lower its periapse into the atmosphere. Another hypersonic drag device (possibly with the same inflation hardware as was used by the first one for aerocapture) is deployed to remove the entry velocity for landing and then released to allow the lander to fall as quickly as possible. One and a half hours is estimated for the descent. Because of the high atmospheric density near the surface, the terminal velocity at landing will be as low as a few meters per second; a small parachute (cf. the Venera drag shield visible at the top of the lander in Fig 1) may be deployed near the surface to reduce the velocity further and to provide stable orientation for landing. Like Viking and Pathfinder, this mission accepts the risk of landing "in the blind," though pictures will be taken during the descent to the landing site for later transmission to the orbiter. This led to the selection of volcanic highlands for the landing site, because the tesserae are too rugged to assure a safe landing without terminal hazard avoidance. Equipment which carries a significant mass penalty.

The VAV is thermally isolated within an insulated bag, which is maintained at ambient pressure through the descent, landing, and balloon ascent. The initial concept used the local atmosphere to fill the bag during the descent but this doesn't work—carbon dioxide liquifies at the surface pressure at the temperature desired for the VAV. Either a separate gas tank must be brought for pressurizing the VAV container during descent or some of the balloon helium can be used. The use of helium presents its own problems since helium is a good thermal conductor; this would imply the presence of a double insulation layer on the VAV container with only the outer layer using the atmospheric CO_2 as the insulating gas. On the other hand, clever plumbing would allow the helium in the VAV container to be vented into the balloon during ascent so that no extra helium would need to be brought to Venus.

Landed Operations

Sampling must be done quickly but with limited power. Ultrasonic coring has been demonstrated at JPL [REF8]. This technique can drill at high speed by exciting the drill tip into resonance with the rock. The rock disintegrates and rapid drilling occurs. This technique is at an early stage of development but a device based on this approach appears to have the best prospect for rapid sample acquisition. A hollow tube is used as the drill to enable collection of a 10-20 cm core. A mechanism to deploy and control the drill and transfer the sample to a canister was designed, by the study group to operate at Venus ambient conditions. Imaging would be done before and during drilling to provide selection and context for the sample. There may only be time to collect one core sample to the desired depth of 10 to 20 cm, depending on the surface properties. A cartoon of the lander on the surface is shown in Figure 7.

The orbiter will pass over the lander every 93 minutes, which enables a 9-minute telecommunications pass. The link from the landed elements to the orbiter consists of a single MCAS UHF transmitter, a 5-W UHF SSPA, a UHF diplexer, and a UHF wide-beam patch antenna; the equipment on the orbiter side of the link is the same except for a 1- W SSPA and a narrower beam antenna (8 dBi). The timeline for the operations has been designed so that the link will be active at the beginning and end of landed operations, i.e., at landing and at the beginning of ascent. Communications to Earth from the orbiter will be done at X-band with the space transponding modem now being developed, redundant 10- W X-band SSPAs, and a 0.25-m X-band high gain antenna.

Thermal and pressure protection would be provided to telecom and other electronics by a pressure vessel. Thermal capacity of the system elements would be supplemented by a phase change material to provide temperature control. Power for the electronics would be provided by primary $LiSOCl_2$ batteries, with a small thermal battery on the lander platform to provide supplementary power for pyrotechnic events. While the electronics would be part of the mass lifted by the balloon, the primary batteries would be sized so that one (with 1038 Watt.hr capacity) could stay behind on the lander and only the minimum necessary (with 824 Watt.hr capacity) would need to be lifted

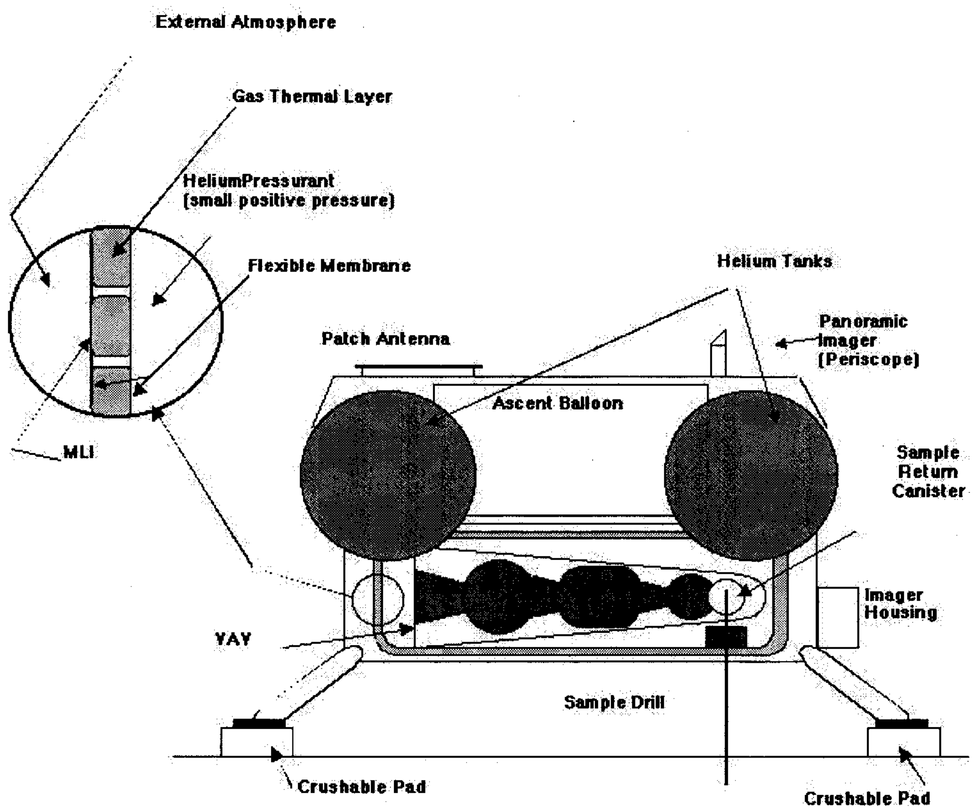


Figure 7. The landed system collects a Venus surface sample.

Balloon Ascent

An ascent to an altitude of 66 km offers the opportunity to rocket the sample into orbit; a lower altitude would require a larger rocket, a higher altitude a larger balloon — the minimum total is achieved somewhere around 66 km, depending on the detailed characteristics of the balloon and the VAV. The balloon would be of the "zero-pressure" variety but would still need to survive the harsh environment. One candidate material is polybenzoxazole (PBO) for strength at high temperature. The PBO would have a Teflon coating for protection against sulfuric acid. Another coating over the teflon may be needed to prevent the balloon from sticking together while it's packed up and under the high Venusian pressure. The balloon would be inflated from helium tanks, which stay on the lander.

The electronics package (including telecom) would be carried up with the balloon to provide communications to the orbiter for three or four passes during the ascent. This would allow transmission of data stored during operations on the surface as well as provide engineering data on the ascent itself. When more Earth-like atmospheric conditions are reached at an altitude of 50 km or so, the bag protecting the VAV would be opened and the core sample transfered to the container which will be ultimately placed in orbit.

Rocketing to Orbit

Venus Ascent Vehicle designs were simulated with a variety of stage combinations and guidance schemes. A successful rocket ascent was simulated for a three-stage combination of off-the-shelf solid rockets, a Star 24C, a Star 17A, and a Star 13A. The VAV would use inertial guidance and control (which need to be developed) to steer the first two stages and to orient and spin up the third stage to do the final insertion burn at altitude. A cartoon of the VAV and ascent design is given in Figure 8.

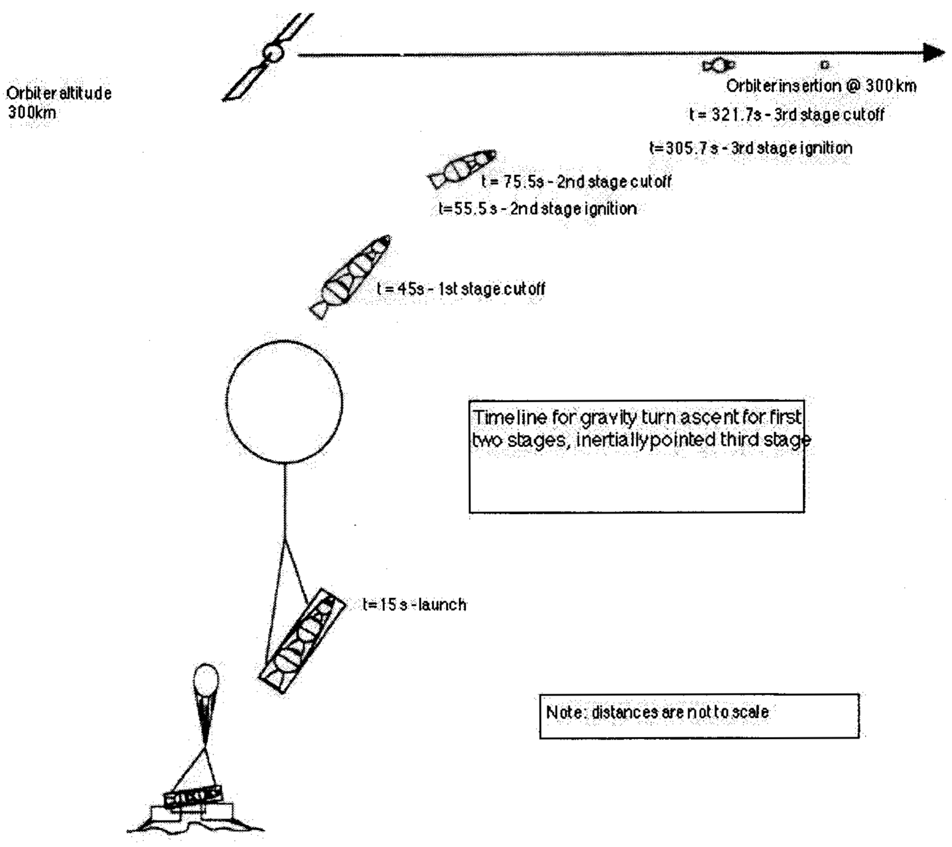


Figure 8. The Venus ascent vehicle (VAV) puts the surface sample into orbit.

Rendezvous and Capture

The technology needed for this phase of the mission, both hardware and techniques [REF9], is being developed in the Mars Surveyor Program for sample return from Mars. Then the orbiter would change its orbit plane to match that of the orbited sample, which would typically be slightly dispersed from the nominal equatorial orbit plane. Then, using the Mars Surveyor strategy, the orbiter would maneuver to match the orbit size and shape, but with a slight difference in semi-major axis so that the orbiter would gradually approach the sample carrier. On-board guidance would control the terminal phase of the rendezvous using both visual and radio beacon data to determine the relative positions of the orbiter and sample container.

Return to Earth

Trans-Earth injection is very demanding because of Venus' size. A comparison between conventional chemical propulsion and solar electric propulsion (SEP) showed a large mass advantage to SEP — more than a 30% reduction in total system mass leaving Earth at the beginning of the mission. This does not include the difference in the mass of the aerocapture ballute. In contrast to the use of SEP for the delivery of the spacecraft to Venus, the use of SEP for the return trip takes advantage of the closer proximity of the Sun and the lower mass of the returning vehicle, which both imply a smaller, less costly SEP system. The SEP system designed here consists of one advanced NSTAR thruster (under development) and a 2.5 kW GaAs solar array (capacity measured at 1 AU, end of life).

The SEP system would spiral the orbiter out of Venus orbit into heliocentric space over the course of 437 days beginning on September 29, 2005. Arrival at Earth would occur on September 29, 2008 after a heliocentric transfer taking 536 days and with a final hyperbolic approach velocity of 3.2 km/s. Figure 9 shows the heliocentric transfer using SEP.

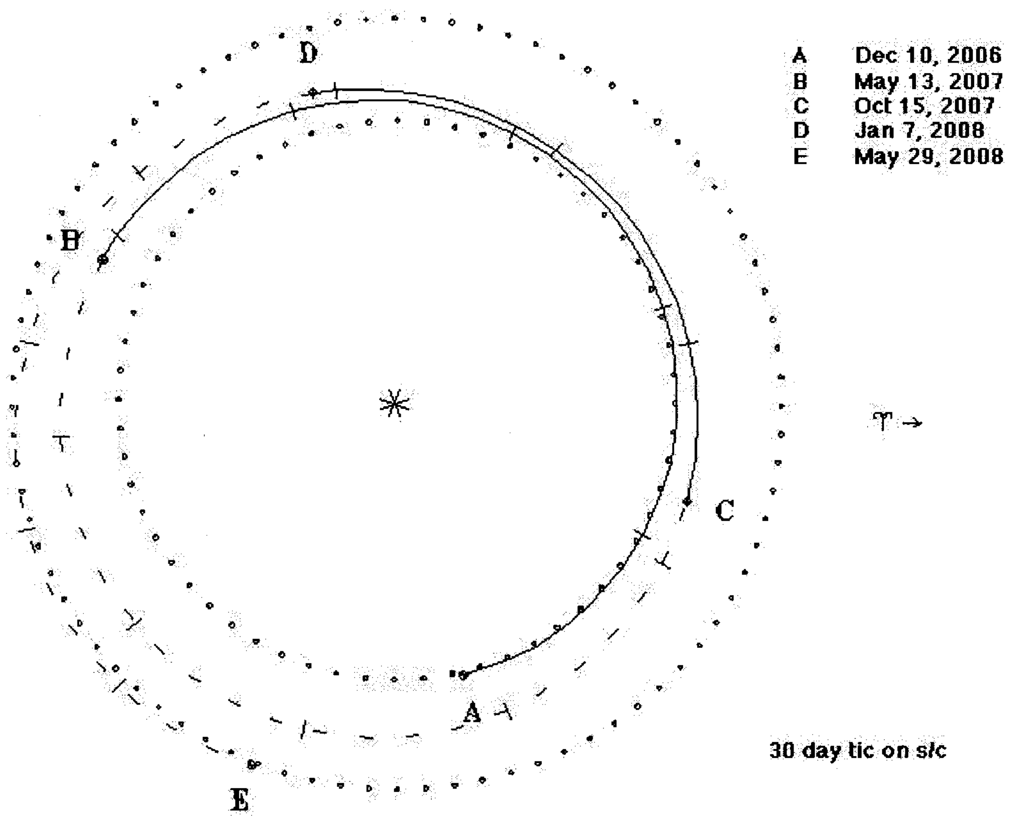


Figure 9. The SEP return trajectory from Venus to Earth. The view is a projection of the trajectory and Earth's and Venus's orbits into the ecliptic plane, seen from ecliptic north. The part of the transfer trajectory shown with a solid line is when the solar electric propulsion (SEP) is on.

SYSTEMS OVERVIEW

Mass and ΔV summaries for this mission are given in Tables 1 and 2. The orbiter propulsion system is a bi-prop chemical system with an I sp of 328 s, somewhat advanced over today's technology. The total mass estimated includes a 30% contingency, which is appropriate for this early stage of the design, except for the orbited sample container, which is aggressively allocated at 2 kg. All interstage adapters and other supporting structures have also been included. Further refinements of the mass for the sample container and the VAV which puts it into orbit will benefit from development of the Mars Ascent Vehicle being proposed for the Mars Sample Return program.

MISSION ALTERNATIVES

The multitude of mission phases and relatively large number of system elements make for a large number of engineering trades which must be considered. Table 3 shows the main trades considered and gives the reason for making the baseline choice for each trade. In particular, the mission architecture baselined here depends on the ability of solid rocket motors to withstand the pressure at the surface (they will be protected from the heat). An alternative approach also studied in some detail would be to keep the VAV suspended by a powered blimp at a high altitude and use smaller balloons to acquire a sample from the surface and bring it back to altitude where the blimp would rendezvous with it and transfer the sample to the VAV.

Table 1: Mission ΔV Budget in m/s

	Event	**ΔV**
Orbiter	Earth-Venus TCM	50
	Plane change to equatorial	122
	Aerobraking control	100
	Circularize 300-km orbit	50
	Orbiter Subtotal	322
Lander	Deorbit from 300-km orbit	120
VAV	Ascent (three-stage solid)	8375
Orbiter	Rendezvous with sample	225
Orbiter (SEP return)	Venus escape and Venus-Earth transfer requires 208 kg of xenon	9312

Table 2: System Mass Budget in kg

Venus Ascent Vehicle		**476 kg**
Stage 1 dry (based on Star24C)	53 kg	
Stage 1 propellant	220 kg	
Stage 2 dry (based on Star17A	49 kg	
Stage 3 dry (based on Star13A)	7 kg	
Stage 3 propellant	33 kg	
Payload	2 kg	
Lander Mass (besides VAV)		**931 kg**
Balloon	86 kg	

Pressurant	78 kg	
Other lifted mass	30 kg	
Drill and instruments	16 kg	
Other landed dry mass	533 kg	
Deorbit propellant	66 kg	
Entry ballute	122 kg	
Orbiter		**1186 kg**
Earth Entry Vehicle	20 kg	
Dry mass	680 kg	
Chemical Propellant	270 kg	
Xenon propellant for SEP	216 kg	
Aerocapture Ballute		**420 kg**
Total launch mass		**3013 kg**

Table 3: Engineering trades considered and made.

Mission Trade	**Baseline**	**Alternatives**	**Reason**
Launch	single	multiple	cost
Transfer to Venus	chemical ballistic	SEP, solar sail	cost, simplicity
Capture at Venus	ballute	conic aeroshell, biconic aeroshell, propulsive	mass
Initial Venus orbit	ellipse	circular	ΔV, mass
Lander entry orbit	circular equatorial	ellipse, direct entry	site selection
Entry technolog y	ballute	conic aeroshell, biconic aeroshell	mass

Sampler element	full lander	tether from floating platform, freeflyer from platform	risk, simplicity
VAV handling	take to surface	hold at floating platform	risk, simplicity
Sample selection	random	selected, rover	cost, simplicity
VAV configuration	"thin" cylinder	toroidal	cost
VAV avionics	IMU on second stage	radio beacon, horizon sensors, sun sensor, star tracker,gyros	mass, simplicity
VAV control	3-axis 1st & 2nd stages, spin 3rd stage	multiple possible combinations	cost, simplicity
Rendezvous tech.	radio beacon+visual	visual only	risk
Rendezvous prop.	chemical	SEP	risk, simplicity
Transfer to Earth	SEP	chemical ballistic, solar sail	mass
Earth entry	capsule aeroshell	ballute	risk, cost

CONCLUSION

Venus surface sample return missions have been studied for over thirty years. The initial studies showed immediately that the use of a return rocket launching directly from the surface of Venus was impractical[REF10]. All subsequent studies have assumed the use of balloon technology to put a launch platform high in the atmosphere[REF1-14]. For all these studies, the total system mass injected from Earth was 10,000 kg or more. Such a large injected mass mandates multiple launches from Earth and may also require on-orbit assembly in low Earth orbit. This study, conducted at the Jet Propulsion Laboratory, is the first to identify a Venus surface sample return with an injected mass sufficiently low that only a single Earth launch is required.

The technologies that provided the greatest advantages in reducing the total system mass for this mission were: the use of hypersonic drag devices (ballutes) instead of aeroshells; the use of advanced SEP for the return from Venus to Earth and a hardware system for controlling the direction of the VAV's first two solid stages. This latter is accomplished by a small self-contained inertial measurements unit (IMU) initialized from the landed package. The ballute technology not only saves mass but provides a far simpler and more robust approach to controlling the spacecraft during aerocapture. The advanced SEP, using next generation NSTAR thrusters now under development, takes advantage of the solar energy available at Venus to reduce the mass requirements by over 1000 kg.

A number of other technology developments are more obviously necessary, including high temperature balloon systems, thermal control systems, pressure-tolerant rockets, drilling and sample handling systems, rendezvous and capture systems, and low mass avionics. Some of these technologies will be developed for the Mars Sample Return mission, but Venus surface sample return remains a technology driver for space exploration and the associated technology efforts.

There are some technologies that were not addressed by the study but that could provide leverage to ease the mission constraints. Two examples, based on DoD technologies, are the use of radio tracking missile technology and that derived from kinetic kill vehicle (KKV) developments. The tracking technology could be used to provide orientation of the ascent rocket to the orbiter passing overhead. This would allow the rocket to "acquire and track" the orbiter radio providing guidance information at a lower mass/complexity cost that INS based approaches. For the case of KKV technologies, the sample carrier would be spun and equipped with a ring of small solid rocket thrusters. These thrusters would be fired to change the low mass sample carrier orbit rather than that of the massive Earth return vehicle. Sensor and control technology from the KKV vehicle program exists to enable this rendezvous to take place. An alternate strategy proposed by B Wilcox (private communication) would place the sensing and control equipment in the Earth return vehicle and use radio control of the sample carrier. The use of either of these approaches would greatly simplify the rendezvous process, perhaps even allowing multiple samples to be obtained on future missions. They would certainly simplify the orbiter propulsion requirements.

From an affordability standpoint, the complexity and number of major elements required for this mission, place it well outside the scope of, for example, a Discovery project. It should, however, be possible to perform this mission for significantly less than the flagship missions of recent decades. This will be enabled by the reduction of the mission to a single launch, maintaining a tight focus on the science scope and combining this with today's streamlined management and operations styles. Given these factors, this mission is well worth continued consideration, even in today's constrained fiscal environment. It is anticipated that the technology developments needed will be accomplished within the current NASA technology program.

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