VENUS MOBILE EXPLORER (VME): A MISSION CONCEPT STUDY FOR THE NATIONAL RESEARCH COUNCIL PLANETARY DECACAL SURVEY

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ABSTRACT

The Venus Mobile Explorer (VME) mission concept provides the ability to characterize the surface composition and mineralogy in two locations within the Venus highlands and offers high spatial resolution views of the surface as the VME floats with the wind (~3 km above the surface) between the two surface locations. After release from the carrier, the VME probe enters the atmosphere, descends on a parachute briefly, and then free-falls to the surface. Science is conducted on descent and at the surface. While collecting data at the first site, the bellows are filled with helium and when buoyant, rise with the gondola. Driven by the ambient winds, the gondola floats with the bellows for ~220 minutes, conducting additional science. At the completion of the 8–16 km aerial traverse, the bellows are jettisoned and the gondola free falls back to the surface, where final surface science measurements are performed.

1. SCIENCE OBJECTIVES

Venus is often referred to as Earth's sister because of their similar size and position within the solar system. Yet, despite their similar origins, the two planets have apparently followed very different evolutionary paths. The highest priority science objectives for Venus are expressed in the Venus Exploration Analysis Group (VEXAG) Goals, Objectives, Investigations, and Priorities document [1], and are reiterated in the Venus Flagship Science and Technology Definition Team Final Report [2]. The VME concept developed in this study [3] is a mission to explore the surface and near surface environments of Venus to determine surface mineralogy and associated compositional variations, to understand chemical exchange mechanisms between the surface and atmosphere, to constrain whether a widespread ocean (with its associated hydrologic cycles and mineralogies) existed and was subsequently lost, and whether Venus could have ever maintained surface conditions capable of supporting life.

VME's primary science objectives [3] are a subset of those defined by VEXAG [1] and include, 1) determine whether Venus has a secondary atmosphere resulting from late bombardment and the introduction of significant outer-solar system materials, including volatiles, 2) characterize major geologic units in terms of major elements, rock forming minerals in which those elements are sited, and isotopes, 3) characterize morphology and relative stratigraphy of surface units, 4) determine the rates of exchange of key chemical species (S, C, O) between the surface and atmosphere, 5) place constraints on the size and temporal extent of a possible ocean in Venus's past, 6) characterize variability in physical parameters of the near surface atmosphere (pressure, temperature, winds), and 7) measure the ambient magnetic field from low- and near-surface elevations.

The scientifically compelling highland regions known as "complex ridged terrain" (or "tessera") are a prime target for a VME-type mission. These terrains hold the most potential for providing new insight into the thermal evolution of the Venus interior, including the possibility of the preservation of ancient continental crust and the role of water in Venus' past. Recent results from Venus Express [4] and the Cassini fly-by

of Venus [5] indicate that the highlands may have a higher surface albedo in the near IR than the basaltic plains, suggesting the highlands have a more evolved composition. Furthermore, because the basaltic plains have already been explored many times by the Soviet Venera and Vega missions, the tessera (or possibly large volcanic centers) will provide the highest probability of compositional diversity compared to previous measurements. The ability to sample the major elements and mineralogy (particularly SiO2, FeO, MgO, S-bearing, and OH-bearing minerals) of such surfaces in multiple locations decreases statistical sampling uncertainty.

Imaging these unique terrains in optical wavelengths at very high spatial resolutions will provide new insights into the physical processes that have contributed to the evolution of the Venus surface. Even a relatively short aerial traverse across the tessera can provide details regarding the scales of geomorphic roughness and evidence for localized tectonic deformation, and possibly evidence of mass-wasting in areas with topographic variability. Because of the super-critical CO_2 lower atmosphere, illumination is extremely diffuse (dominated by Rayleigh scattering) and there are no shadows at the Venus surface. In addition, the volcanic surfaces of low albedo basalt are monochromatic with very low contrast, resulting in the need for a very high signal to noise ratio (SNR) in any imaging system. The higher near IR reflectivity of the highland regions, as observed by Venus Express, may result in less stringent requirements for imaging SNR, making these areas both scientifically interesting and technically more feasible.

The science objectives are achieved by a nominal payload that conducts *in situ* measurements of noble and trace gases in the atmosphere, conducts elemental chemistry and mineralogy at two surface locations separated by ~8–16 km, images the surface on descent and along the airborne traverse connecting the two surface locations, measures physical attributes of the atmosphere, and detects potential signatures of a crustal dipole magnetic field.

2. MISSION CONCEPT

The VME Mission's space segments consist of a probe and flyby carrier spacecraft that is also used as a communications relay (Fig. 1). The probe is comprised of two top level elements, the Entry and Descent Element (EDE), which includes the aeroshell and parachute systems, and the Lander. The lander has two major systems: 1) the gondola system that carries the science instruments and subsystems inside a thermally protected pressure vessel, and, 2) the bellows aerial mobility system, including the bellows and the inflation subsystems.

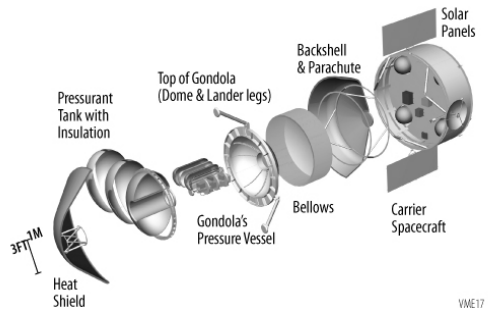

Fig. 1 Carrier Spacecraft and probe, exploded view

Carrier Spacecraft: The three-axis stabilized carrier spacecraft (Fig. 1) performs three functions: 1) delivers the probe on an interplanetary trajectory to Venus, 2) releases the probe on an appropriately pointing trajectory to enter the Venus atmosphere, and 3) acts as a communication relay between the VME and the Earth. Because of the flyby trajectory, the required fuel mass is relatively small, thermal and power tasks are simple, and electronics and communication systems are straightforward. The drivers for the carrier spacecraft design include spinning up the probe prior to release and having a robust structure to support the probe.

Probe: The probe is released from the carrier 5 days before reaching the Venus atmosphere. The communications system is switched on 1 hour before encountering the atmosphere and transmits continuously. The aeroshell is designed with approximately one inch of carbon phenolic material that ablates upon entry into the Venus atmosphere, where the probe experiences a deceleration of 167 g. The heat shield is jettisoned minutes after the parachute system on the backshell is deployed (at an altitude of ~60 km). Following this operation, the backshell and parachute system are released from the lander. During the descent, a regulating valve maintains the pressure within the bellows to within 0.5 bar of the gradually increasing ambient pressure. *In situ* atmospheric structure and chemistry measurements are conducted throughout descent, and images are acquired from ~15 km to the surface. Once on the surface, the lander performs elemental and isotopic measurements of the surface rocks, then the bellows are inflated from the helium tank to prepare for the aerial mobility phase of the mission. The heavy helium pressurant tank is disconnected from the bellows, allowing the gondola to rise rapidly to 5 km above mean planetary radius (AMPR) (~3 km above a highland surface). Because the pressure at 5 km AMPR is lower than on the surface, excess helium is vented to keep the bellows pressure within 0.5 bar of

the atmosphere. After 220 minutes of floating in the 0.6 to 1.2 m/s near surface winds and taking contiguous surface images along the traverse, the bellows are released, and the gondola free falls to the surface. Surface chemistry measurements are made at the second landing site and the remaining data are transmitted to the carrier spacecraft.

3. INSTRUMENT PAYLOAD

The following instruments comprise the nominal VME payload. Specific implementation is left to future individual mission point designs.

Neutral Mass Spectrometer (NMS): provides *in situ* measurement of noble gas isotopes and multiple trace gas mixing ratios. The NMS instrument consists of three modules: an ion source to convert gas phase sample molecules into ions; a mass analyzer, which applies electromagnetic fields to sort the ions by mass; and a detector, which measures the abundance of each ion present. Gas samples are ingested through gas inlet ports in the bottom of the gondola. Due to the difficulty of exhausting gas to a 81 bar environment, exhaust sample gas is captured in a reservoir inside the instrument.

Tunable Laser Spectrometer (TLS): measures trace gases, including multiple isotopes of sulfur- and hydrogen-bearing species. Of particular interest, the TLS measures the Deuterium/Hydrogen ratio in atmospheric water via measurement of molecular line parameters for infrared molecular absorption lines. Utilizing extremely small tunable laser spectrometers with room-temperature laser-detector arrays in a Herriott cell configuration, TLS provides multi-wavelength *in situ* measurements of the Venusian atmosphere. Gas inlet ports at the bottom of the gondola feed sample gas into the Herriott cell; the number and detailed implementation of the NMS and TLS gas inlet ports can be determined by future mission designs. As with the NMS, exhaust sample gas is captured in a reservoir inside the instrument. TLS is combined with the NMS, sharing common electronics and piping, but is listed separately since each spectrometer has unique measuring timelines.

Raman/Laser Induced Breakdown Spectrometer (LIBS): is a combined instrument, utilizing a single laser and a single telescope to provide mineralogy and elemental chemistry of surface rocks. Raman illuminates the remotely located (~2 m away or less) sample with a low power laser pulse and observes the scattered return to determine the vibrational modes of the chemical bonds in the target. LIBS utilizes this same laser at a higher power level to vaporize and ionize a portion of the target material, creating a plasma. By measuring the intensity and energy of the photons emitted by the plasma, the elemental chemical composition of the sample can be inferred. The instrument accesses the sample area through a viewing window in the bottom of the lander and requires a 2 cm clear aperture. This is achieved by sharing the 10 cm window required by the nadir viewing near-IR Imager. The implementation assumed in this study report includes a wheel mechanism with reflecting optics that allows the Raman/LIBS instrument to point directly at the Venusian surface adjacent to each of the lander's three feet. These three points were chosen to provide a fixed focus for a known distance, regardless of landing orientation. Future studies will need to address the issue of potential interference from dust disturbed at touchdown. The laser Raman/LIBS remote sensing approach was selected for surface elemental chemistry and mineralogy over more traditional X-ray Diffraction/X-ray Fluorescence Spectroscopy (XRD/XRFS) because it offers implementation advantages (i.e., absence of sample acquisition, handling, and transfer to an XRD/XRFS).

Near-IR Imager: points in the nadir direction and acquires images during the initial descent, the aerial traverse between the landing sites, and during the second descent. Images of the area the Raman/LIBS will sample are recorded during the final moments of each descent, providing additional information about the site prior to landing. The camera requires a 10 cm viewing window, which is shared with the Raman/LIBS instrument. The 1 k x 1 k Focal Plane Assembly (FPA) has a 2 km square field of view at 2 km above the surface (50° FOV) or 2 meter pixel size. It also has a mechanism that allows it to refocus by moving the FPA; enabling near surface imaging. Future studies will need to address the issue of potential interference from dust disturbed at touchdown, particularly the possibility of dust adhering to the window.

Atmospheric Structure Investigation (ASI): has sensors located on the outside of the lander that are used to characterize gross atmospheric properties, including temperature and pressure. This package consists of a temperature sensor, a pressure transducer, and an accelerometer. The nominal implementation concept does not utilize a boom or mast; exact implementation of this instrument package is left to a future study.

Triaxial Fluxgate Magnetometer: determines the presence or absence of a planetary magnetic field. This

instrument is inside the lander, so no boom is required; however, effects from the other payloads in the lander and the lander itself must be factored into its calibration.

4. CONCEPT OF OPERATIONS AND MISSION DESIGN

Two 20-day Type II launch windows in 2021 and 2023 were analyzed for launch on an Atlas V 551. The study team selected launch windows that meet the launch mass and probe entry interface velocity constraints. A Venus re-encounter trajectory with an initial flyby and a second Venus encounter approximately 112 days later was used to ensure the landing site illumination constraints could be met with either launch opportunity. After releasing the probe 5 days prior to the second Venus encounter, the spacecraft performs a Venus flyby and receives data throughout the lander science mission.

The May 2023 launch window results in a landing on 15 February 2024, at Venus IAU latitude N 22.6°, longitude E 8.4° (near Gula and Sif Montes), close to local noon (sun elevation at the landing site is ~68°, where 90° would be the subsolar point). The 2021 launch window has a landing at latitude S 15.5°, longitude E 61.4° (near Ovda Regio), close to local noon (sun elevation is ~75°). Both of these opportunities satisfy the required greater than 45° sun angle for near-IR images. Flight dynamics were not optimized for specific target landing locations during this study.

VME operations at Venus are autonomous, based on time relative to specific events. The probe is in low power mode during the 5-day coast after separation from the carrier spacecraft. Daily brief telemetry transmissions to the carrier spacecraft are performed to allow the carrier spacecraft to verify its pointing to the probe. The probe turns on one hour before predicted atmospheric entry to ensure adequate time to adjust carrier pointing if necessary; the probe then transmits continuously for the next 7 hours.

The aeroshell protects the lander during atmospheric entry. After the probe has slowed (~1 minute), the parachute is deployed, extracting the lander from the heat shield. The parachute is then released, and the lander free-falls to the surface. The lander has enough drag (from either the stowed bellows or through use of drag plates) to spend >60 minutes in the descent; this allows time for atmospheric measurements and results in a landing velocity of less than 10 m/s. Communication between the lander and the carrier is maintained through an omni-directional antenna on top of the bellows.

Fig. 2 illustrates the instrument operations during descent. The magnetometer and the internal components of the Atmospheric Structure Investigation (ASI) operate from above the atmosphere through the end of the mission. The NMS and the

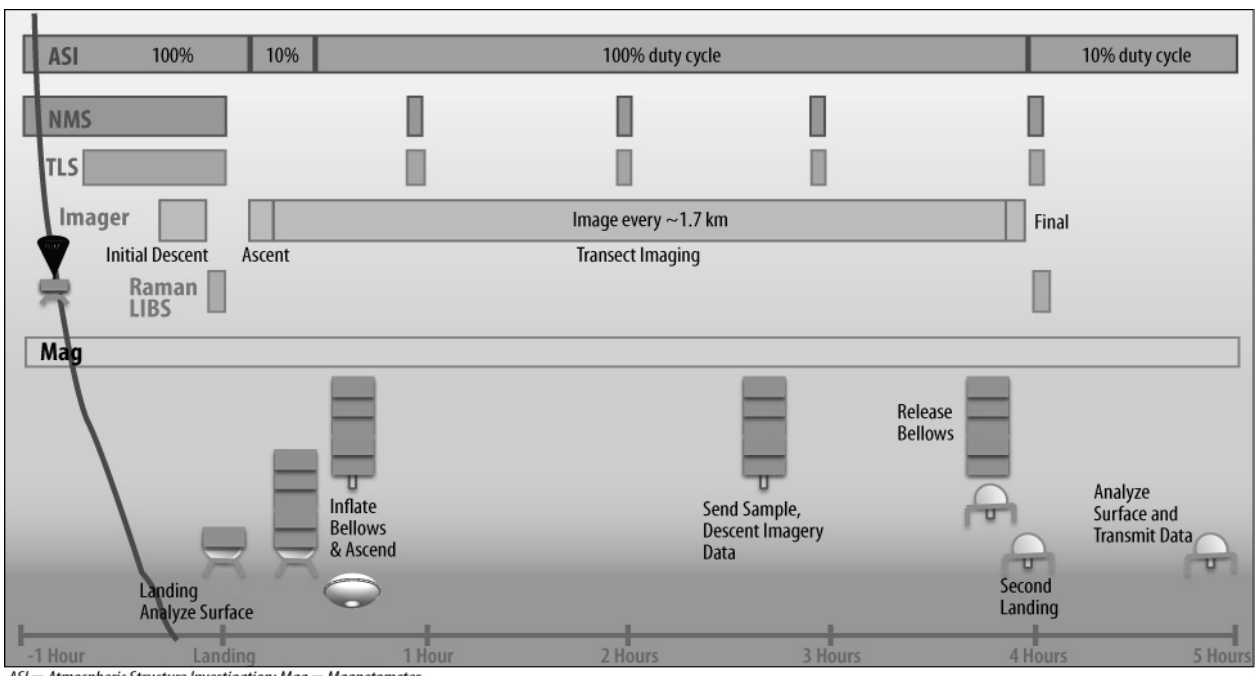

Fig. 2 The instrument operations have been defined during descent, and on and near the surface to meet science objectives.

external components of the ASI start operations as soon as the aeroshell is released. The NMS performs trace and noble gas analysis during descent using an external atmospheric inlet port.

The TLS operates from below the clouds to the surface. The near-IR Imager starts imaging between 15 and 20 km, buffering its 8-bit per pixel images. The murky atmosphere and motion from the lander during descent will affect image quality. The imager is capable of evaluating the clarity of the images and alternates focal lengths as it nears the predicted impact to ensure it images the sampling site just before landing. Only higher quality images are uplinked.

After landing, the ASI reduces its duty cycle. The Raman/LIBS instrument immediately begins analysis of the surface upon landing and samples multiple locations, requiring a total of about 15 minutes. The NMS and TLS operate in parallel with the Raman/LIBS instrument to provide atmospheric context for the surface analysis.

Once the Raman/LIBS analysis is complete, the bellows are inflated and the lander, minus the helium tank, ascends to about 5 km AMPR (~3 km above a highland surface), and is blown by Venusian winds for 220 minutes to a new location 8 to 16 km distant (estimated distance traveled is based on expected average wind speeds of 0.6 to 1.2 m/s between the surface and the floating altitude of 5 km). The near-IR Imager collects images throughout the ascent, the drift, and the descent. Fig. 3 illustrates imaging near the Venus surface. The ASI returns to 100% duty cycle during the floating phase. The NMS and TLS perform atmospheric analysis about once per hour.

At a specific time from ascent, the bellows are ejected, the lander's second omnidirectional antenna is switched on to continue the uplink, and the

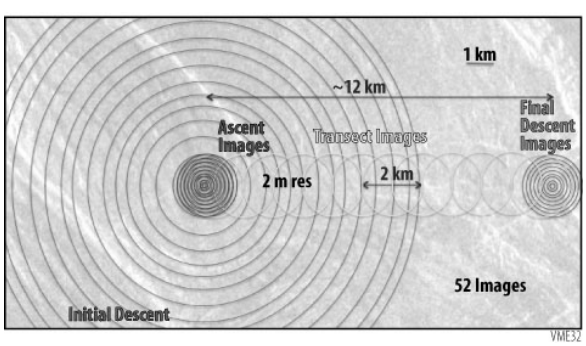

Fig. 3 The NIR Imager acquires discrete images to construct a complete morphological traverse for geologic context (~12 km example traverse is shown).

gondola descends to the surface. Thermal and battery sensors automatically eject the bellows if they sense a deteriorating thermal condition or state of charge situation. The near-IR Imager collects descent images. The Raman/LIBS performs its analysis upon landing, while the NMS and TLS perform their last analysis of the atmosphere. Once the analysis is completed, it takes the gondola about an hour to complete the data transmission to the carrier spacecraft driven by the data volume of images taken during the second descent.

The gondola is designed to operate for 5 hours after the initial landing. At the end of the 5 hours, the gondola continues to send buffered images and replays high priority data for as long as it and the communication link lasts.

The gondola's Data Rate up to the carrier spacecraft is outlined in Fig. 4. The 8.5 Kbits/sec fixed data rate is filled with buffered near-IR Imager data after imaging starts during the descent. The study team recommends that future studies should investigate handshaking between the carrier and the lander's communications system to increase the volume of data returned.

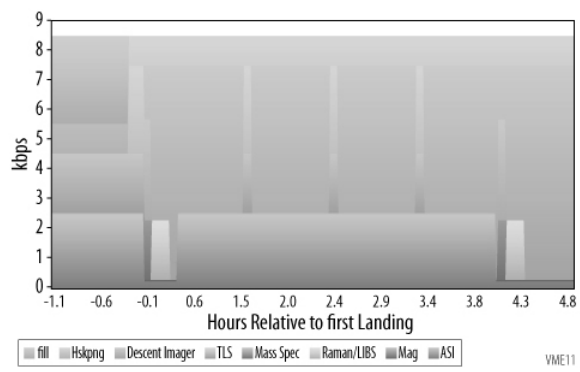

Fig. 4 The data rate is a constant 8.5 Kbps. The Imager and Raman/LIBS data are buffered and used to fill the available bandwidth.

5. SPACECRAFT

The carrier spacecraft is three-axis stabilized and based on low-complexity, high-heritage designs. Spacecraft mass is dominated by the structure required to support the probe, with the remaining sub-systems rather modest in size. Optimization of the carrier structure would likely result in mass savings.

Solar arrays measure ~1.2 m^2 per side (balanced for probe spin up) and are attached to single axis actuators, allowing the carrier to slew about the actuator axis. The secondary (rechargeable Lithium-ion) battery is small, as no significant eclipse is expected. Even

though it will experience ~1.9 suns, the solar array will stay below 140º C since it is not body-mounted.

Fuel mass fraction (366 kg versus overall carrier dry mass of 846 kg) of the carrier is low compared to many interplanetary carrier spacecraft. Approximately half the delta-V budget of 280 m/s is used before probe release and half is used after for the carrier's divert maneuver. A hydrazine system is baselined, however, mass savings of ~70 kg may be possible by using a more expensive bi-propellant system. Using small thrusters versus reaction wheels to achieve three-axis stabilization (which simplifies the thermal and power subsystems) also saves mass, volume, and power.

The carrier communication sub-system includes a 3-meter low mass mesh S-band antenna for uplink communication with the probe, and a smaller 1-meter solid X-band antenna for downlink Deep Space Network (DSN) communication. If the 3-meter antenna was utilized for both X- and S-Band, a lightweight mesh antenna could not have been used, which would have added 50 kg to the overall carrier mass. The 3-meter HGA size reduces the uplink RF power requirements on the probe. The carrier's pointing requirement for carrier-to-probe communications is within 0.8 degrees. The carrier pointing location does not change as the gondola traverses to the second landing site. A 3302 Truss Payload Adapter Fitting (PAF) is used to allow the 3-meter mesh antenna to be located on the launch vehicle interface side of the carrier. When data from the probe are fully uploaded, the carrier spacecraft re-orients to point the 1-meter fixed X-band HGA within 0.2 degrees of the DSN ground station, and downlinks at 25 kbps. Two X-band omni-directional antennas allow the carrier spacecraft to be commandable at all times. Because Ka-band omni-directional antennas have yet to be demonstrated, for this study, X-band was assumed for all communications with Earth. The cost to develop Ka band omni-directional antennas is modest and would enable carrier-to-Earth communications to use Ka band if driven by DSN 2021 capabilities, as suggested by the study ground rules.

6. ENTRY AND DESCENT ELEMENT

The Entry and Descent Element (EDE) is composed of the aeroshell, parachute, and deployment mechanisms. The EDE provides aerodynamic drag during entry and also protects the probe from entry heating. The aeroshell structure and thermal protection system (TPS) materials are designed to sustain the high deceleration loads (~167 g) during entry for the bounding 2021 launch. Sensitivity studies were performed for the VME mission parameters based on scaled versions of the Pioneer Venus Large Probe (PVLP). The 19° Entry Flight Path Angle (EFPA) and entry velocity of 11.3 km/s (2021 bounding) were selected to minimize g-loads (for ease of qualifying instruments and minimizing the structural mass of the aeroshell structure) and total heat load on the heat shield (for minimal TPS mass).

After withstanding peak deceleration and heating, the parachute is deployed at 60 km, and the heat shield is separated from the lander using explosive separation bolts. Finally, the parachute and backshell are severed from the lander element, completing payload extraction.

The monocoque 3.5 m diameter, 45° sphere cone aeroshell (heritage), shown in Fig. 5, encapsulates the lander, supports launch and entry loads, and enables safe and reliable atmospheric extraction of the lander. The heat shield is a scaled version of PVLP (which was 1.42-m diameter), while the back shell is similar in shape to Stardust. The structure is a 2-inch (5.08 cm) sandwich configuration with composite face sheets and aluminum honeycomb, providing mass savings over solid aluminum with sufficient structural integrity up to 175 g.

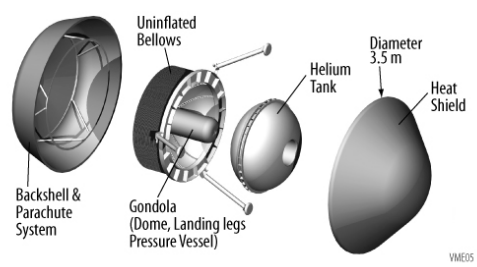

Fig. 5 Aeroshell back shell and heat shield are based on Pioneer Venus Large Probe and Stardust geometries.

The heat shield TPS consists of 1-inch (2.54 cm) total tape wrapped and chopped molded carbon phenolic (TWCP and CMCP) onto the honeycomb structure. CMCP and TWCP are the only materials flight-qualified for the severe conditions of Venus entry. Peak stagnation heat flux (combined convective and radiative) on the heat shield is calculated to be 2.3 kW/cm^2 (2023 launch) or 2.7 kW/cm^2 (2021 launch). Both CMCP and TWCP were flown on the Pioneer-Venus and Galileo entry probes. Although heritage carbon phenolic (CP) production has been discontinued since the 1980s because the supplier

ceased production of the rayon precursor, ARC has a sufficient supply of the original CP precursor to fabricate a VME-sized probe and the associated test and evaluation billets.

Based on engineering estimates for the backshell environment, Phenolic Impregnated Carbon Ablator (PICA), a light weight ablator, can be used as the back shell TPS material. The PICA tiles are bonded to the structure using HT-424, with RTV-560 filled gaps, using the same manufacturing techniques as Mars Science Laboratory (MSL). PICA has flown on Stardust and has been extensively evaluated and characterized as a heat shield material for MSL and was a candidate heat shield for Orion.

7. LANDER

The lander mechanical system is designed to safely transport the instrument suite to two landings on the Venus surface. The concept meets the NMS/TLS instruments' requirement for a minimum of two small inlet vents for atmospheric sampling, field-of-view requirements for ground imaging during landing and transit, and an unobstructed view for Raman/LIBS measurements near each of the gondola's three feet. The structural system design accommodates the high performance thermal control system, which includes isolation and insulation systems, heat pipes, and Phase Change Materials (PCMs). To accommodate the two landings and aerial mobility, the structure is designed to support a large helium tank and an inflatable bellows assembly. The packaged lander is designed to fit into an aeroshell system, requiring a volume efficient design (Fig. 5). The resulting mechanical design is simple, compact, and robust.

The field of view requirements are met for the near-IR Imager and Raman/LIBS instruments with a 10 cm transparent ceramic (e.g., sapphire or spinel) aperture at the bottom of the gondola. The rotating wheel selection mechanism allows the near-IR Imager and Raman/LIBS instruments to use the same window and remain fixed while the reflecting mirrors target the location of interest. Atmosphere sampling needs are met by two 5-mm diameter vent inlets with frangible ceramic solenoid actuated caps. The packaging is also designed to accommodate the high performance thermal control system, including 59 kg of PCM within the gondola that is thermally coupled to the heat sources via a network of heat pipes. The gondola primary structure is a hermetically sealed pressure vessel to prevent the influx of Venusian atmosphere. The primary structure is designed to handle the deceleration loads (worst case 167 g) on the probe during the Venus atmosphere entry phase and a 10 m/s expected impact velocity for each landing. The leg system allows a dampened stroke, reducing the landing loads to 34 g. The overall system volume is constrained by the competing needs of accommodating the large helium tank and gondola assembly yet being compact enough to fit into the aeroshell volume. The use of nested systems provides a clever, compact design solution.

Launch and the more significant entry loads act in opposite directions on the lander support structure. The interface to the spacecraft mounting is through the backshell at three discreet points, reducing heat load through the backshell during entry. Inside the backshell, the probe is mounted to a truss. During launch, the truss members are in compression, and during entry, are in tension. A unique design feature of the lander is the structural load path between the outer ring of the lander shell and the inner structure supporting the gondola. The lander's helium tank is jettisoned after the first landing to reduce the mass the bellows are required to lift. The bellows system must also be as compact as possible. The resulting concept uses a "mushroom cap" design that transitions the loads from the dome, across the top of the helium tank, to the inner gondola core. The hemispherical shape and wing-like construction of the dome is extremely strong and lightweight, and efficiently uses the empty volume within the stowed bellows.

To improve the packing density while reducing the overall height of the stowed system, a combination of nesting structures and multiple-use load paths are utilized. The pressurized helium tank dominates the volume and mass. Using a single tank and nesting that tank inside the stowed bellows volume maximizes all available space and reduces the height of the total assembly. Use of a cylindrical gondola provides efficient space utilization within the lander (Fig. 6). A preliminary model of the PCM volumes indicates that there is more than adequate volume available to accommodate the PCM and locate it so the heat pipe network can spread the heat in the 0.9 g Venus environment in reflux mode. All major components can be accommodated in this design, with margin.

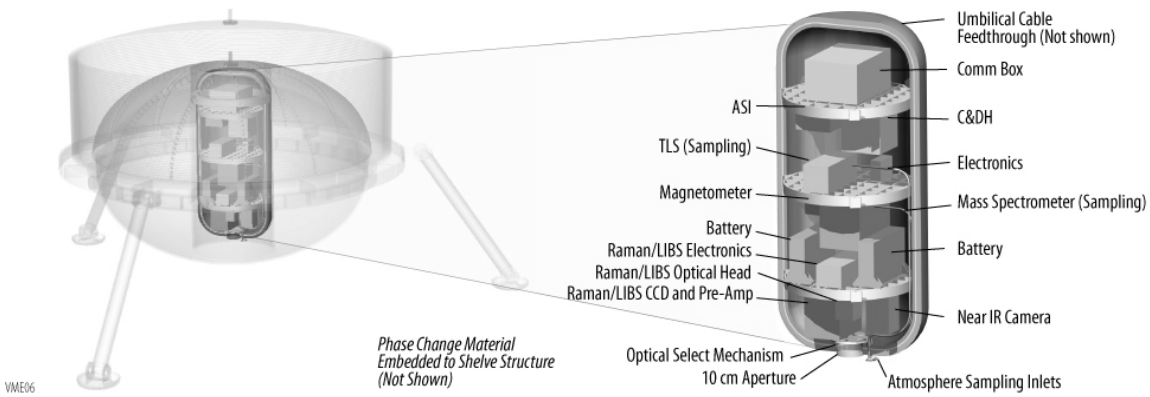

Fig. 6 Lander with gondola details, showing instruments and avionics.

The environmental extremes and high g-loads the lander will experience drove the structural default material to Titanium alloy, which is lightweight and high temperature tolerant.

A conceptual design for each low TRL mechanism provides a basis for mass estimating, though much proof of concept work remains. Mechanisms that must actuate after the first landing are the primary concern due to exposure to the harsh Venus environment. Mechanisms inside the gondola are assumed to be in a temperature-controlled environment and should not face the same level of thermal and pressure challenges that the external mechanisms must confront. All mechanisms will need to survive the high g-loads of entry.

8. LANDER MOBILITY

VME's aerial mobility requirement calls for a system that operates near the surface (2 km to 5 km AMPR), where the temperatures and pressures vary from 447° C to 424° C, and 81 bar to 67 bar, respectively [6]. Key mobility system sub-systems include the metallic bellows, the helium storage tank, helium fill gas, and the related piping, valves, structures, and mechanisms and are shown in Fig. 7, in the various lander configurations.

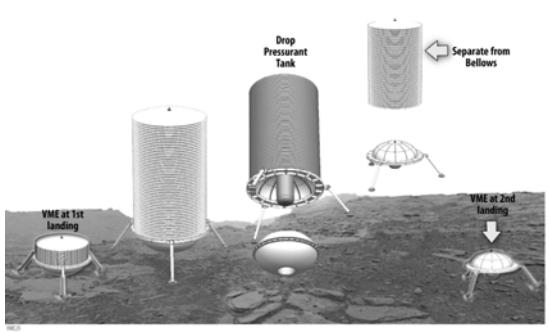

Fig. 7 Bellows configuration sequence

Based on the prototype bellows tested at JPL [7], the current bellows design is a stainless steel sheet based configuration with a wall thickness of 0.18 mm. The bellows are designed to maintain 0.5 bar pressure over the ambient. This design parameter is met with a valve that uses pressurant tanks to fill the bellows during descent and that vents pressure as the gondola/bellows rise.

The metallic bellows system is designed to provide the lander with the buoyancy required to obtain a desired altitude. Like other balloon systems, the metallic bellows provide buoyancy by displacing the heavy ambient gas (CO_2) with a lighter one (He). The current VME design uses a constant volume bellows. To keep the internal pressure 0.5 bar above ambient at the surface, the bellows are filled with more helium than at float altitude. The helium is gradually released as the bellows ascend to the float altitude. Beside considerations for *in situ* operations, the thin-walled bellows structurally exceed the 167 g high entry g-load requirement without buckling or breaking. Since the accordion folded side walls provide sufficient structural support, main consideration is given to the upper and lower domes and to the overall load path. During inflation, an L/D elastic ratio of five is assumed, which could be achieved based on experience with the 2005 prototype bellows.

For the VME, helium is chosen as the fill gas, since it is light, inert, and thus easy to handle. Due to the heavy payload (the gondola is ~650 kg including 30% margin), the bellows need to displace about 14 m^3 of CO_2 to provide the required buoyancy at float altitude for the coupled bellows/gondola system. The helium mass for the VME lander is 84.4 kg (without margin) at surface conditions. The helium is compressed to 10,000 psi for efficient storage in a compact pressurant tank, which reduces its volume to ~2 m^3. Titanium alloy is chosen for the pressurant tank due to its high

heritage and concerns about survivability of composite materials in Venus' corrosive, high temperature environment. Titanium has the best mass-to-strength ratio for fixed tanks, whereas stainless steel works best for the bellows due to its more ductile nature. Based on top level calculations, the storage system requires about 6-7 kg of tankage mass for every kg of helium. The requirement to keep the helium below 70˚ C necessitates a 1 cm layer of thermal insulation around the tank. This adds about 30 kg to the storage system mass. In comparison, the mass would be ~2.5 times heavier if sized to tolerate the 460˚ C ambient temperature using the same volume. To save mass and improve accommodation while inside the aeroshell, the storage system is designed with a single toroidal tank. This custom configuration provides compact packaging for the gondola in the middle of the torus.

The inflation system is equipped with a number of valves. Fill valves are used when initially filling the helium tank on Earth, and a separate set of valves is used to fill the bellows on the Venusian surface. During descent, a limited helium transfer via a mechanism is required to keep the stowed bellows pressure neutral, since this thin-walled vessel is not designed to tolerate high pressure differentials. A mechanism is needed to keep the pressure 0.5 bar below the local Venusian pressure upon descent. After filling the bellows to 0.5 bar above the local Venusian pressure at the first landing site, the helium tank is disconnected, resulting in the buoyant bellows/gondola system rapidly (within 20 minutes) rising to a float altitude. As the pressure in the constant-volume bellows needs to be kept at 0.5 bar above ambient, a pressure relief valve is used to discard about 7 to 18 kg of excess helium, depending on the elevation change from surface to float altitude (e.g., from 2 km to 5 km AMPR). The mechanisms required for the bellows system are quite challenging due to their need to operate on the surface of Venus. Thermally protecting individual mechanisms could be achieved by adding mass for a thermally protected enclosure, resulting in easier development.

At the end of the 220-minute float period, the gondola and its supporting structures need to separate safely from the bellows. The separation mechanisms are initiated autonomously, driven by the Command and Data Handling system on the gondola. This concept is limited to one traverse, as the helium tank is released at the first landing site and reuse of the inflated bellows is not possible due to plastic deformation.

9. LANDER THERMAL SYSTEM

The thermal analysis for this study is based on a model with heritage from previous missions that operated in the Venus atmosphere. Conduction, radiation, and convection couplings were adjusted in the model to provide a good agreement between the temperature predictions and PVLP flight data. For VME, the model is modified to incorporate the geometry and dimensions of the gondola pressure vessel. The model predicts heat flow and temperature for this design concept.

After probe release from the carrier, the solar flux incident on the spin-stabilized aeroshell is equivalent to about 1.9 suns. The exteriors of both the heat shield and backshell are coated with white paint to cold bias the probe payload to above the cold survival temperature limit and no warmer than -5°C. Survival heaters on the payload ensure that its temperature is above -20°C. A 15 W survival heater power/Avionics load is budgeted. Before release, the Carrier Spacecraft provides any heater power required by the probe.

The bellows system pressurant tank and gondola both need thermal insulation from the Venus environment. The atmospheric temperature at the Venus surface can be up to 462°C. The bellows system pressurant tank exterior is covered with 1-cm thick microporous silica insulation wrapped in a thin titanium skin. This provides thermal protection to the pressurant tank during the 70-minute duration (65 minute descent and 5 minutes on Venus surface) the tank is exposed to the Venusian environment to keep the helium average temperature below 70°C. During the descent, as atmospheric pressure and temperature increase, the microporous silica insulation thermal conductivity also increases. The average thermal conductivity is about 0.03 W m^{-1} K^{-1} during descent.

The gondola payload and equipment decks are isolated from the gondola pressure vessel by low conductivity titanium alloy mounts. To minimize convective and radiative coupling through the gondola pressure vessel, 2.2 cm thick microporous silica insulation is attached to the pressure vessel exterior, and Multi-Layer Insulation (MLI) is used on the interior surface. The exterior insulation is enclosed in a thin titanium alloy skin and therefore sealed from sulfuric acid during descent. This insulation has a service temperature of up to 1,000°C. The thermal conductivity of the insulation depends on the silica density, silica temperature, and atmospheric pressure. An insulation density of 290 kg m^{-3} is assumed. Based on the manufacturer's data on thermal conductivity under

high pressure, a thermal conductivity of 0.06 W m^{-1} K^{-1} at a 350°C mean temperature is used in the model. MLI blankets thermally-shield the payload from the interior surface of the pressure vessel.

The total heat load rises rapidly during descent through the atmosphere and reaches 1,355 W upon landing. To extend duration on the surface, Phase Change Material (PCM) is thermally coupled to the payload. The optimum PCM, Lithium Nitrate Trihydrate (LNT), as flown on the Soviet Venera landers, is selected to minimize mass and volume and is encapsulated in thin hermetically-sealed aluminum faced panels. LNT's properties, including latent heat of fusion 290 kJ kg^{-1}; 30°C melting point; density of 1,550 kg m^{-3}; and, liquid specific heat of 3 kJ kg^{-1} C^{-1} make it the best PCM candidate. The system requires 59 kg (0.0381 m^3) of LNT to maintain the payload temperature below the maximum operating temperature limit of 40°C at the end of the 6-hour mission life and to provide a 5°C margin on operational temperature (15°C margin on qualification temperatures). The maximum LNT thickness is assumed to be 3.72 cm to ensure sufficient heat conduction. Five PCM panels are distributed from top to bottom in the pressure vessel. The bottom PCM panel is close to the camera window and atmospheric sampling inlets, where significant heat leak occurs. This PCM panel is also thermally coupled to the equipment deck. The top two panels have low power dissipation components mounted to them. Inter PCM panel ammonia constant conductance heat pipes (CCHP) transfer heat from lower to upper panels in reflux mode (thermal siphon). CCHP spreaders are used to spread heat within a PCM panel. Each panel has nine CCHP spreaders, and a header CCHP thermally connects the nine CCHPs. The inter PCM panel CCHPs thermally connect the header CCHPs. All the CCHPs are redundant.

10. LANDER COMMUNICATIONS

The lander communication system uses S-band because lower frequencies have less attenuation due to the Venus atmosphere. The S-band atmospheric attenuation from the surface is less than 3 dB for elevation angles above 10°. The trajectory is designed to provide reliable communications throughout the mission duration and keep the elevation angle above 10°.

The VME Probe Communication Subsystem is S-Band transmit only. It is designed to transmit at a constant rate of 8.5 kbps to the carrier spacecraft. The data is rate-½ convolution encoded and BPSK modulated. The system provides 3 dB or better RF link margin with a bit-error-rate of 10^{-6} at all ranges and elevations through the use of a 50 Watt RF TWTA and two omni-directional antennas (Fig. 8). Only one antenna is used at a time. The initial antenna sits on top of the bellows and is used until the bellows are ejected, when the RF signal is switched to the antenna on the top of the gondola. The antenna on top of the bellows is connected to the transmitter by a coiled cable that runs through the interior of the bellows. A mechanism allows the cable to uncoil as the bellows expand. Subsystem components are commercial off the shelf, except for the omni-directional antenna, which will need to be redesigned to use materials appropriate for the Venus atmospheric composition and temperature.

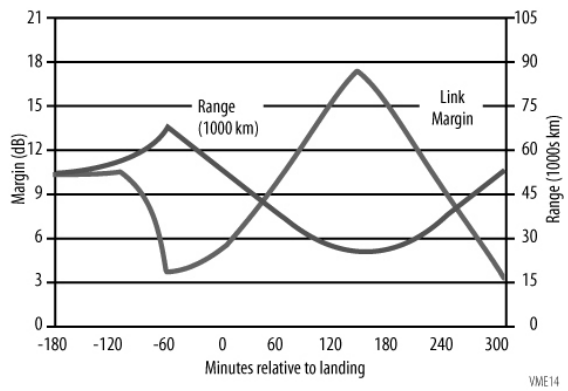

Fig. 8 The link margin is above 3 dB for the duration of operations on Venus. Also shown is the carrier spacecraft range.

The study considered Direct to Earth communication, which Pioneer Venus used. This option was rejected due to the data volumes of the more sophisticated instruments required to meet VME's science objectives, the lack of future S-band support at the DSN, the need for alternate trajectories to reduce the Earth/Venus range, and the significantly more robust communications system that would be required on the lander.

11. LANDER MASS, POWER, DATA RATE

The overall launch mass is shown in Table 1. The mobility system (including the inflation system and supporting elements) is 65% of the lander mass. Within the gondola, the structure and the thermal design are the primary subsystem drivers. Each kg of gondola instrument mass equates to 5 kg of structure and to almost 50 kg of launch mass. Mass margin still exists for the mission, even after applying 30% mass growth allowance to the current best estimates for both

the 2021 and 2023 launch windows, although the 2021 launch window would require 19 kg of additional propellant versus the 2021 launch numbers, which are shown in Table 1.

Table 1. Mission level mass rackup

Item	CBE (kg)	Composite Mass Growth Allow. (%)	Max Expected Mass (kg)
Lander	**1390**	30%	**1782**
Lander Science Payload	31	30%	41
Lander Subsystems	469	30%	609
Bellows	890	30%	1132
Aeroshell	**876**	30%	**1139**
Spacecraft	**846**	30%	**1100**
Total Dry Mass	**3112**	30%	**4021**
Propellant Mass	366	1%	370
Total Wet Mass	**3478**		**4390**
LV Throw Mass			**5141**

During the 5-day coast from the carrier spacecraft to the Venus atmosphere, 15 W is assumed for communications, avionics, and positive thermal control to ensure that the probe encounters the Venus atmosphere as cold as possible. The communication system is only turned on to broadcast for brief periods daily. The current Depth of Discharge (DOD) of the primary battery is 70% after 5 hours on the Venusian surface.

The Probe link margin for a constant data rate of 8.5 kbps up to the carrier spacecraft is shown in Figure 5. Future studies will look at whether handshaking between the carrier and lander communication system can be achieved.

12. TECHNOLOGY MATURITY

Most of the technology issues for VME involve developing designs that can operate in Venus' high temperature, high pressure, and corrosive atmosphere. The VME design utilizes many types of mechanisms, including separation systems, bolt cutters, valves, and motors. The design challenges for these mechanisms will be finding the right materials to operate through the Venus environment while minimizing mass and volume. The bellows and helium tank will need to be designed to withstand Venus' large temperature and pressure gradients while also minimizing mass and volume. The lack of a large Venus environmental test chamber (to allow system and large component level testing) also increases development risk for these systems. The pressure and temperature gradients the mechanism will experience as it travels through the Venus atmosphere complicates simulating descent and ascent conditions for testing the bellows inflation system.

13. COST ESTIMATE

Based on Price H model and cost analogies during this 5-week study [3], the VME mission concept total cost of $1.7B (without launch vehicle; $1.9B with launch vehicle) , is estimated at the 70% confidence level. This is in the low end of the flagship range. Technology-development costs of $90M (to bring new technology to a TRL 6 level) are included in the above mission cost estimate. A tremendous amount of uncertainty exists in the technology development cost, due to the immature nature of most of the essential technologies and unique testing which may not perform as assumed in this report. Unforeseen development problems will likely cause cost increases. Not included in this estimate is the cost to develop a Venus near surface environmental test facility. The study assumes a suitable facility will be available when needed. Other cost risks were not analyzed in detail and were beyond the scope of this rapid mission architecture study.

14. CONCLUSIONS

This study [3] has shown the VME concept is technically viable. The VME mission concept has at least 45% mass margin if launched in either the 2021 or 2023 launch windows. The cost falls outside the New Frontiers cost cap and is at the lower end for flagship missions.

The lander and mobility systems fit within a modified aeroshell with Pioneer-Venus geometry, and therefore have a viable design. Gondola structural and landing system design, thermal PCM integration, and the high temperature valve and mechanism development are the challenging subsystem areas. Mission-level Integration and Test (I&T) to ensure operation of VME's many specialized mechanisms will be equally challenging. Furthermore, the gondola and pressurant tank design interfaces will be complex.

Using Raman/LIBS instrumentation at the surface instead of XRD/XRFS has mission implementation advantages. To implement each XRD/XRFS measurement, ~4 kg of sample ingestion equipment would be required (8 kg total for VME). As the XRD/XRFS processing takes a minimum of 2 hours

per sample, there would also be a severely curtailed floating portion of the mission (sample processing duration cuts the mobility distance in half as landing needs to occur early enough to ensure adequate XRD/XRFS processing at the second site).

The bellows mobility concept is likely one of the lower cost ways to visit two different landing sites, though it has a higher risk versus multiple heritage landers because the entire science payload is contained in one architectural element that requires longer Venus survival times and many complex operations. The mass and volume budgets allow for two or three static landers in a single VME-like aeroshell, with each lander carrying an identical instrument complement. The downside of the multiple landers concept is that this solution makes the contiguous near-IR imaging requirement more difficult to meet. But, multiple landers would have considerably less operational risk due to shorter required lifetimes and significantly fewer mission critical mechanisms.

Other technologies that were considered in VME architecture trades would enhance future mission concepts but are not compatible with a VME launch in 2021 or 2023. These technologies include high temperature motors, high temperature electronics, and RPSs with cooling. Developing high temperature electronics and ASRG-like RPSs with cooling that can work on the Venus surface would enable significant increases in science return. However, even if Venus RPSs were sufficiently mature, they would be too heavy for landers using bellows for mobility.

15. REFERENCES

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