National Aeronautics and Space Administration

Venus Mobile Explorer

Mission Concept Study Report to the NRC Decadal Survey Inner Planets Panel

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NASA-GSFC • JPL-Caltech • NASA-ARC

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Venus Mobile Explorer

Final Report

Presented to the Planetary Decadal Survey Steering Committee and Inner Planets Panel

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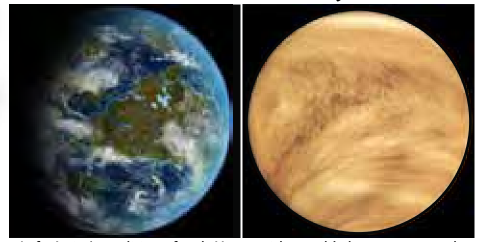
Venus Mobile Explorer

fact sheet

Mission Concept Study Report to the NRC Decadal Survey
Inner Planets Panel • December 18, 2009
Concept Maturity Level: 4 • Cost Range: Low End Flagship
GSFC • JPL • ARC

Nominal Mission:
- Atlas V 551 Short Fairing Launch Vehicle
- Type II trajectory

- Launch on 5/27/2023
- Venus fly-by 10/27/2023
- Landed science 2/15/2024
  - atmospheric chemistry
  - surface chemistry in 2 locations
  - 8 - 16 km aerial imaging traverse



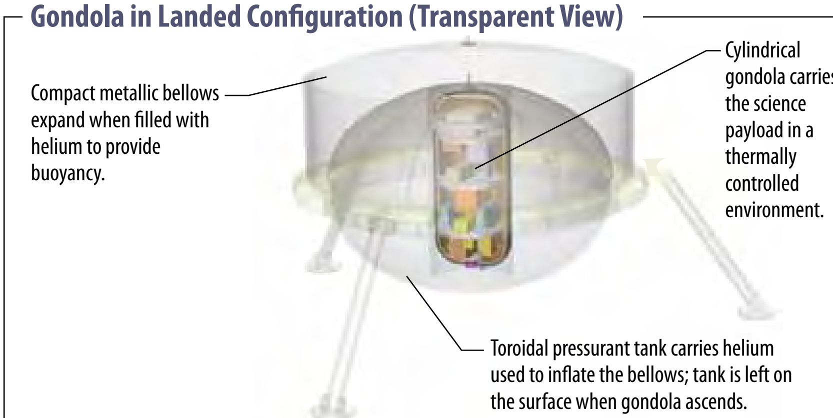
Left: Artist's rendition of early Venus with possible large oceans and a significant hydrologic cycle; Right: Venus today with a dry, thick CO_2 greenhouse atmosphere resulting in surface temperatures of 450°C and pressures in excess of 90 bar.

Mission Driving Science Objectives	Measurement	Instrument	Functional Requirement
Determine the origin and evolution of the Venus atmosphere, and rates of exchange of key chemical species between the surface and atmosphere	In situ measurements of Noble gas isotopes, trace gas mixing ratios and trace gas isotopic ratios	Neutral Mass Spectrometer (NMS) combined with Tunable Laser Spectrometer (TLS)	In situ sampling of the atmosphere as functions of altitude and time
Characterize fundamental geologic units in terms of major rock forming elements, minerals in which those elements are sited, and isotopes	Identify mineralology and elemental chemistry of surface rocks in 2 locations separated by > 8 km	Laser Raman/Laser Induced Breakdown Spectrometer (LIBS)	Land in 2 locations, ~2 m path-length for compositional observation; stable platform for measurement duration
Characterize the geomorphology and relative stratigraphy of major surface units	Airborne near IR imaging along a transect ~8 km in length, at < 5 m spatial resolution	Near infrared (~1.1 micron) imager (FOV TBD, and SNR > 100)	Near-surface aerial mobility; >45° solar incidence, contiguous images of the surface during aerial traverse; 5 hour near surface operational lifetime

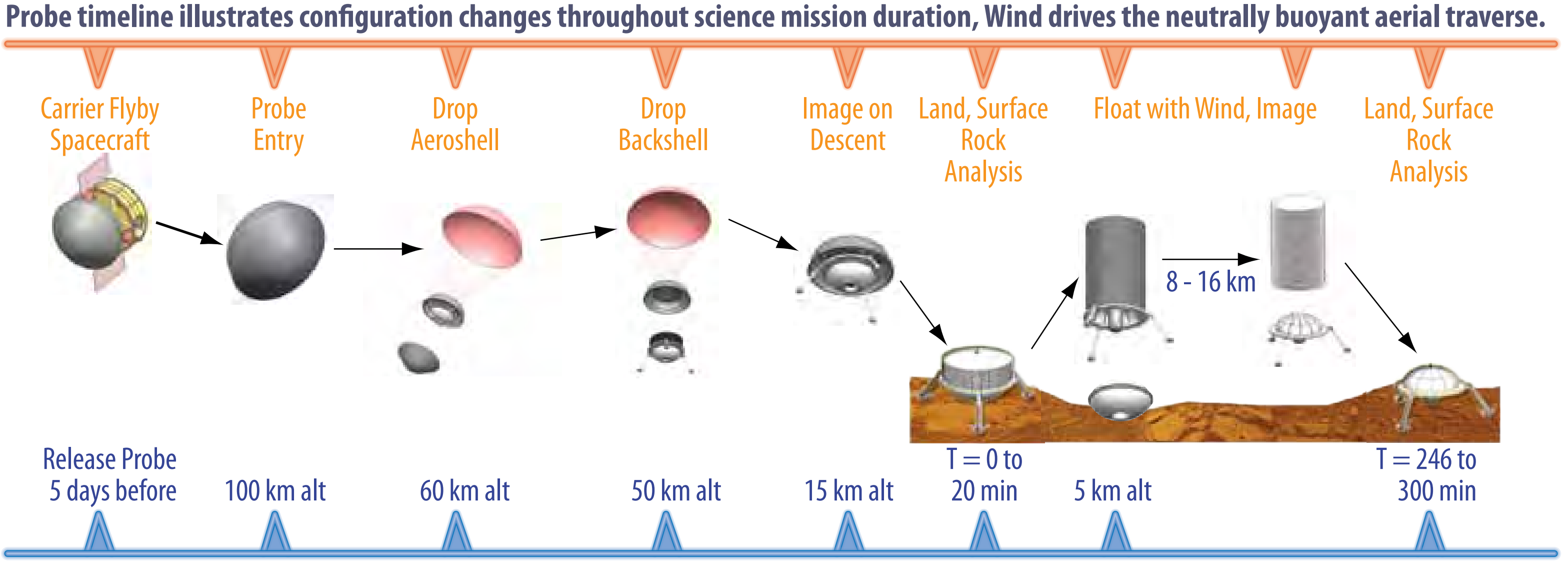
Lander Aeroshell (Cruise Configuration)

The innovative compact design of the science payload into a central cylinder surrounded by a toroidal pressurant tank and capped by the metallic bellows, allows the VME to be accommodated in an accepted aeroshell geometry.

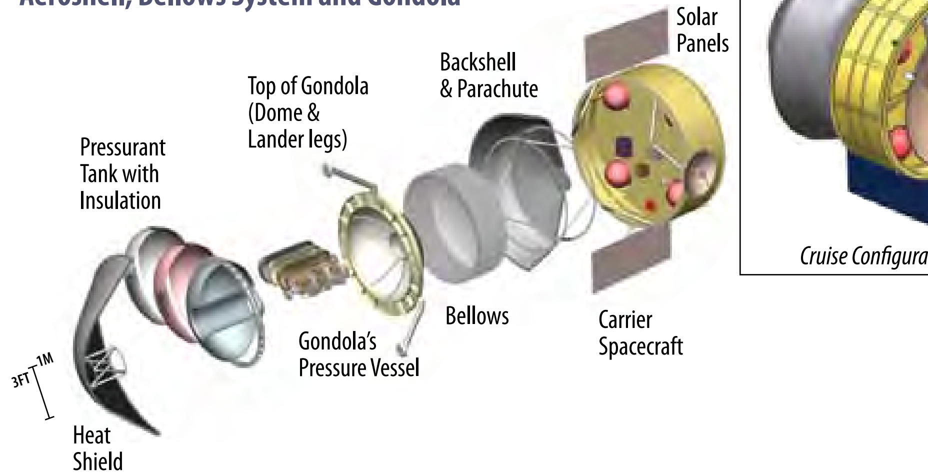
Gondola in Landed Configuration (Transparent View)



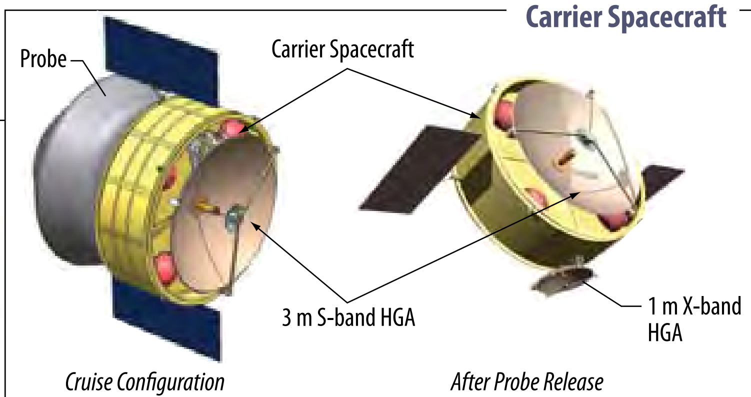
Probe timeline illustrates configuration changes throughout science mission duration, Wind drives the neutrally buoyant aerial traverse.



Exploded view of Carrier Spacecraft, Aeroshell, Bellows System and Gondola



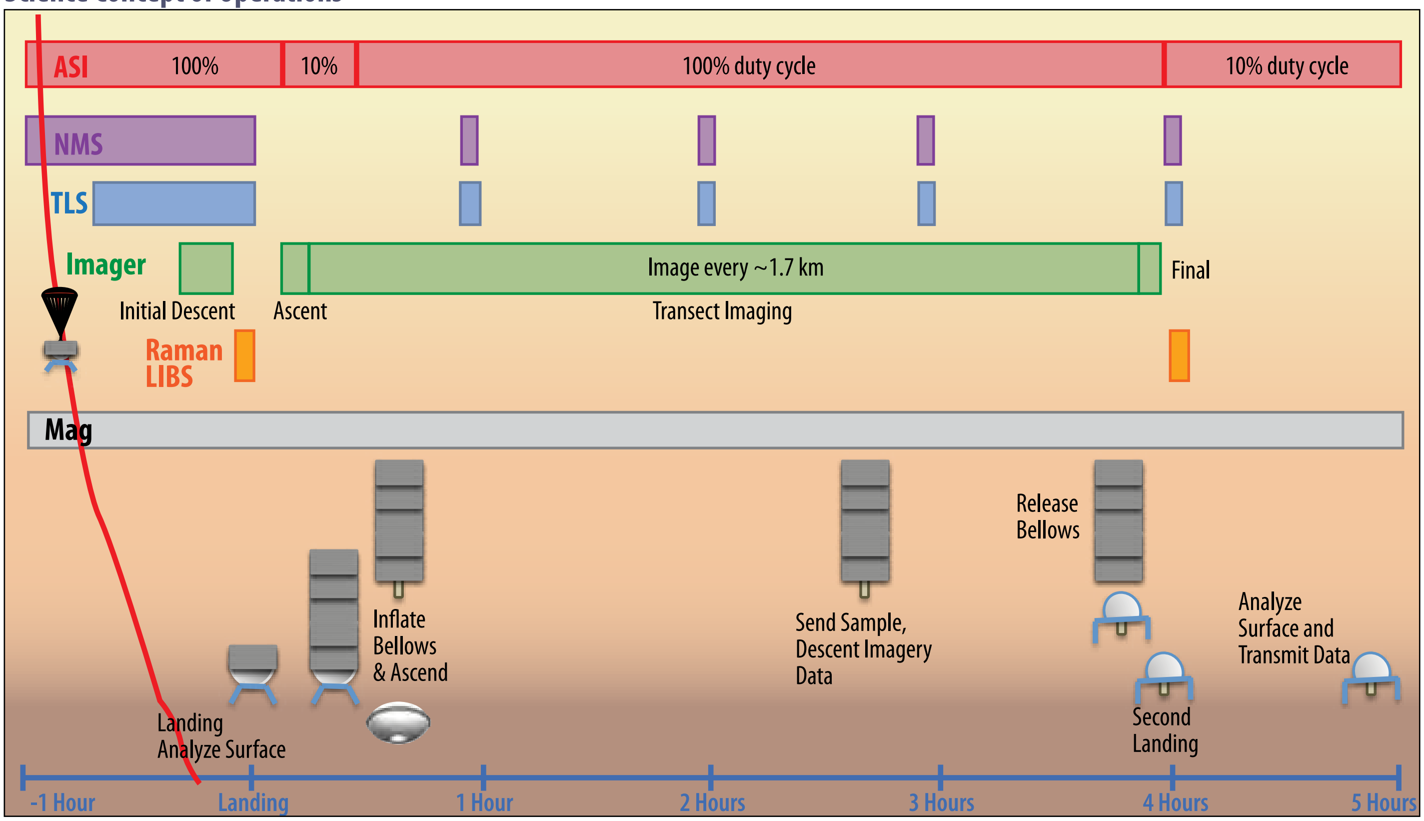
Carrier Spacecraft



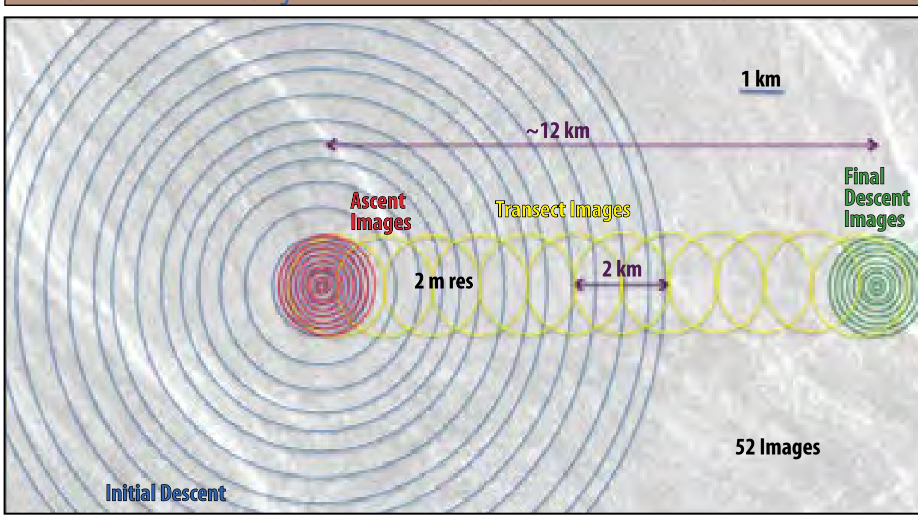
Carrier Telecom

Antenna	Wavelength	Purpose
3 m HGA mesh	S-band	Probe to Carrier uplink
2 omni-directional	X-band	Carrier to Earth contingency
1 m HGA solid	X-band	Carrier to Earth Science

Science Concept of Operations



ASI = Atmospheric Structure Investigation; Mag = Magnetometer



Nominal example of imaging sequence assuming ~12 km aerial traverse. IR Images are taken on initial descent from 15 km to the surface (blue), on ascent (red), as the gondola floats with the wind under the bellows (yellow) and on final descent (green), collecting 52 images.

Mass Breakdown

Component	CBE [kg]	Allow [%]	Max Mass [kg]
Lander	1390	30%	1782
Lander Science Payload	31	30%	41
Lander Subsystems	469	30%	609
Mechanical/Structure	270	30%	351
Mechanisms	51	30%	66
Thermal	113	30%	147
Other	34	30%	44
Bellows	890	30%	1132
Aeroshell	876	30%	1139
Spacecraft	846	30%	1100
Satellite *(S/C + Probe)* Dry Mass	3112	30%	4021

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EXECUTIVE SUMMARY

NASA Headquarters commissioned the Goddard Space Flight Center's (GSFC) Architecture Design Lab with a rapid mission architecture study to support the National Research Council's 2010 Planetary Decadal Survey Inner Planets Panel. The purpose of the study was to determine whether a Venus mission with surface, or near-surface, mobility and realistic operational lifetime could achieve meaningful surface science at two or more independent locations separated by several kilometers on a budget comparable to a New Frontiers cost envelope. The Inner Planets Panel was particularly interested in a metallic bellows concept for aerial mobility and the use of Radioisotope Power Systems (RPS) for power and active cooling. Following completion of this study, the Venus Mobile Explorer (VME) Concept Maturity Level (CML) is raised from 2 to 4. Based on analyses of the mechanical, thermal, power, avionics, and communication designs for the VME probe and the carrier spacecraft, the study team can state with confidence that a Venus mission using the metallic bellows architecture for short-lived aerial mobility is technically feasible. However, the cost estimate for the nominal baseline VME implementation ($1.1B - $1.7B FY15, not including launch vehicle) is at the low end of the Flagship range, beyond what the study team considers plausible for New Frontiers missions in the coming decade. The cost is driven by the metallic bellows and supporting mechanisms for its operation. Technology development, accommodation, and complex integration also contribute to the high cost of the probe.

The VME mission concept affords unique science opportunities and vantage points not previously attainable at Venus. The ability to characterize the surface composition and mineralogy in two locations within the Venus highlands (or volcanic regions) will provide essential new constraints on the origin of crustal material, the history of water in Venus' past, and the variability of the surface composition within the unexplored Venusian highlands. As the VME floats (~3 km above the surface) between the two surface locations, it offers new, high spatial resolution, views of the surface at near infrared (IR) wavelengths. These data provide insights into the processes that have contributed to the evolution of the Venus surface. 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.

The study team developed an elegant, volume efficient cylindrical gondola to accommodate the science payload in a thermally controlled environment. An innovative, highly compact design surrounds the gondola with a toroidal pressure tank capped with the bellows, enabling the entire lander system to fit in an aeroshell with heritage geometry. The thermal design uses heat pipes and phase change material that enable the gondola electronics and instruments to survive 5 hours near the Venus surface, thus providing sufficient time for surface chemistry and an aerial traverse >8 km in the current-like winds. The study team also determined that using an RPS device for power and coupled active cooling requires considerable development costs and increases the system mass well beyond New Frontiers launch vehicle capabilities.

Launched on an Atlas V 551 in either 2021 or 2023, the carrier spacecraft carries the VME probe to Venus on a Type II trajectory. 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, leaving the helium pressure tank on the surface. 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. The total mission time in the Venus atmosphere is 6 hours, which includes 5 hours in the near surface environment. The VME probe transmits data to the flyby carrier spacecraft continuously throughout the 6-hour science mission. After losing contact with the VME probe, the carrier spacecraft then relays all data back to Earth.

VME feasibility within the coming decade depends on advancements in four key technology areas, 1) raising the Technology Readiness Level (TRL) of the metallic bellows system, including the helium pressure tank and plumbing, to TRL 6, 2) verifying the Raman/LIBS implementation and calibrated operation in the Venus surface environment, 3) developing reliable Venus grade mechanisms, and 4) developing techniques to ensure safe landing in potentially rugged terrains (at lander scales).

The bellows mobility concept presented in this report is unable to perform surface science in more than two locations. Multiple landers may offer a lower risk alternative approach to the VME at a comparable cost and could access more than two locations.

1.0 SCIENTIFIC OBJECTIVES

1.1 Science Questions and 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. In the 1970s and 1980s, the plains regions were explored by multiple Soviet Venera Landers, and NASA launched the Pioneer-Venus mission (orbiter plus four atmospheric probes). The NASA Magellan mission (1990-1994) consisted of an orbiting spacecraft with a moderate resolution synthetic aperture radar and radar altimeter to globally map the surface. ESA's Venus Express (VEx) is currently in orbit observing polar cloud dynamics and JAXA is expected to launch Akatsuki in 2010 to monitor equatorial cloud dynamics and weather, complementing VEx's measurements. In addition, Earth based observations using advanced polarimetric radar mapping have contributed significantly to our understanding of Venus.

Missions that have landed on Venus are listed in **Table 1**, highlighting the state of the art nature of VME driven by its science requirement to study the Venus surface in two different surface locations. The longer the surface operations, the greater the departure from heritage missions, but the higher the likelihood of exploring geologically distinctive surface units.

The highest priority science objectives for Venus are expressed in the Venus Exploration Analysis Group (VEXAG) Goals, Objectives, Investigations, and Priorities document [2009], and are reiterated in the Venus Flagship Science and Technology Definition Team Final Report [2009]. The VME concept developed in this study 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 are a subset of those defined by VEXAG and are shown, in priority order, in **Table 2**.

Table 1: Historic capabilities of static landers and atmospheric probes at Venus. The longest surface survival was just over 2 hours, and the most recent mission to touch the surface of Venus was launched in 1984.

Surface Landed Missions	Launch	Surface Survival Time (min)	Pressure Vessel	Thermal Control	Surface Sample Acquisition
Venera 7	1970	23	No	No	No
Venera 8	1972	50	No	Yes	No
Venera 9	1975	53	No	Yes	No
Venera 10	1975	65	No	Yes	No
Venera 11	1978	95	No	PCM	No
Venera 12	1978	110	No	PCM	No
Pioneer Venus	1978	60	Yes	No	No
Venera 13	1981	127	Yes	PCM	Yes
Venera 14	1981	57	Yes	PCM	Yes
Vega 2 Lander	1984	56	Yes	PCM	Yes

The scientifically compelling highland regions known as "complex ridged terrain" (or "tessera") 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 VEx 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 SiO_2, 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

Table 2: Science traceability of primary science objectives (left) to functional mission requirements (right).

Science Objective	Measurement	Instrument	Functional Requirement
Determine whether Venus has a secondary atmosphere resulting from late bombardment and the introduction of significant outer-solar system materials, including volatiles	Measure atmospheric Noble gas isotopes *in situ*	Neutral Mass Spectrometer	In situ sample of atmosphere (1 bulk sample on descent)
Characterize major geologic units in terms of major elements, rock forming minerals in which those elements are sited, and isotopes	Identify mineralogy (SiO_2, FeO, MgO, sulfur bearing, OH^- bearing) and elemental chemistry of surface rocks in ≥ 2 surface locations (separated by > 8 km)	Raman/LIBS	Land in ≥ 2 locations; ~ 2 m path-length for observation; stable platform for measurement duration
Characterize the morphology and relative stratigraphy of surface units	Near IR imaging along an airborne traverse > 8 km in length, at < 5 m spatial resolution	Near-infrared (~1.1 micron) imager with field of view TBD and SNR > 100	Near surface aerial mobility (bellows); Nadir-looking position on gondola to image the surface; platform stability for non-blurred images; > 45° solar incidence angle, acquire contiguous images of the surface during aerial traverse > 8 km (requires ~5 hr lifetime)
Determine the rates of exchange of key chemical species (S, C, O) between the surface and atmosphere	Measure trace gases in the near surface atmosphere (within one scale height)	Neutral Mass Spectrometer; Tunable Laser Spectrometer	*In situ* sampling of atmosphere as functions of altitude and time [f (z, t)]
Place constraints on the size and temporal extent of a possible ocean in Venus's past	Measure D/H ratio in atmospheric water, at least twice	Neutral Mass Spectrometer; Tunable Laser Spectrometer	In situ sampling of atmosphere [f (z, t)]
Characterize variability in physical parameters of the near surface atmosphere (pressure, temperature, winds)	Atmospheric temperature, pressure, winds	Temperature, pressure, accelerometers, USO	*In situ* measurements of T/P, Doppler measurement using communications system for winds
Measure ambient magnetic field from low- and near-surface elevations	Detection of existence or absence of surface magnetic signal	Flux-gate magnetometer	Must be able to detect surface "signal" above a 5-10nT threshold, over and above any payload "noise"

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 VEx, may result in less stringent requirements for imaging SNR, making these areas both scientifically interesting and technically more feasible.

1.2 Science Traceability

Table 2 traces the primary science objectives to the key measurements needed to address each, as a function of required vantage point. The third column of **Table 2** indicates nominal instrumentation that could satisfy the measurement requirements (see **Section 3.1** for details). For surface elemental chemistry and mineralogy, the team selected a laser Raman/Laser Induced Breakdown Spectroscopy (LIBS) remote sensing approach 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). A discussion of this key trade is provided in **Section 3.4.2**. The time required to complete the two surface chemistry measurements, the aerial traverse between the two landing sites, and the uplink of all images to the carrier spacecraft, drives the operational lifetime of the VME to ~5 hours in the near surface environment. The 5 hours of near surface operations combined with the ~1 hour initial atmospheric descent, results in a requirement for 6 hours continuous communication with the carrier spacecraft (at least 10° above the horizon) as it flies by Venus. Neither the surface chemistry nor the imaging traverse place unusual requirements on landing precision. A typical Venus target landing error ellipse on the order of 75 km x 150 km is adequate for targeting large tessera regions, which are often hundreds to thousands of km in diameter.

1.3 Study Objectives

The driving science requirements that led to the VME design presented in this study are: 1) elemental and mineralogical measurements in two different locations separated by >8 km, and, 2) contiguous nadir-viewing, high spatial resolution images of the surface along the >8 km transverse connecting the two surface locations. The final significant driver for this study was to develop a concept that minimized mission cost, and that therefore might enable VME to remain in a New Frontiers cost envelope for the coming decade.

The contiguous images requirement drove the study team toward selecting a mobility platform with multiple-landing capabilities. This allows for the two surface measurements to be interpreted in the context of macro-scale Venus geology. As potential modes of mobility on the Venus surface are extremely limited due to the Venus environment, the Inner Planets Panel (IPP) recommended examining a previously-conceived metallic bellows balloon concept [Kerzhanovich et al., 2005]. While this concept was not explicitly addressed by the 2009 Venus Flagship mission study, it was included in the 2006 NASA Solar System Exploration roadmap, and has been contemplated within Venus exploration scenarios studied by the community for at least 5 years.

An important component of the IPP study request was to better understand the limitation of RPS technology coupled with active cooling and whether such technology could be used to extend the life of a VME-type mission. Unfortunately, no such capability currently exists for the near-surface Venus environment.

The Decadal Survey IPP also expressed a strong interest in tessera terrain exploration because of the regions' potential link to early crustal genesis or the role of water in composition evolution. These unique highland regions are rugged, and typically stand 1.5-2 km above the surrounding plains. For this rapid mission design study, target surface elevations of ~2 km above mean planetary radius (AMPR) were assumed, but flight dynamics were not optimized for a specific target location.

2.0 HIGH-LEVEL MISSION CONCEPT

2.1 Overview

The VME mission concept was arrived at after reviewing various mobility options and receiving direction from the IPP to study the feasibility of a metallic bellows flotation system using positive buoyancy and near surface winds for mobility.

The VME Mission's space segments consist of a probe and flyby carrier spacecraft that is also used as a communications relay (see **Figure 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. The design concepts for each mission element and system are discussed in **Section 3.2**.

Table 3: Carrier Spacecraft Complexity.

Subsystem	Brief Summary Of Concept	Complexity
Systems	Heritage spacecraft designs can be utilized, simple Interfaces to Probe	Low
Flight Dynamics	Driving requirement to release probe on Venus entry interface trajectory	Moderate
Attitude Control Subsystem	Control SC with ¼ lb thrusters and spin up probe to 5 rpm with thrusters	Low
Propulsion	Delta V maneuvers relatively small for planetary missions	Low
Avionics	Low data rate	Low
Communications	Two antennas simplify operations; 3 meter lightweight S-band HGA to communicate with Probe and a 1 meter X-band HGA for communication with Earth	Moderate
Power	Low power needs allow for small solar arrays	Low
Mechanical	Driving requirement to minimize S/C mass, allowing for larger probe	Moderate
Thermal	Heritage thermal designs can be utilized	Low
Integration and Test	Most testing can be completed without probe, facilities exist for S/C testing	Low

Carrier Spacecraft: The three-axis stabilized carrier spacecraft (**Figure 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 to 5 RPM prior to release and having a robust structure to support the probe. **Table 3** details the subsystem drivers for the Carrier Spacecraft.

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 will transmit continuously. The aeroshell is designed with approximately one inch of carbon phenolic mate-

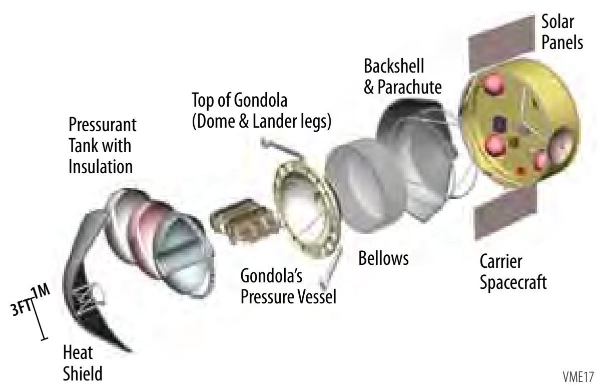


Figure 1: Carrier Spacecraft. and probe, exploded view.

rial that ablates upon entry into the Venus atmosphere, where the probe experiences a deceleration of 157 g (2023 launch) or 167 g (2021 launch). (In all subsequent references to the design, 167 g is assumed to be the bounding static structural load for the probe design.) 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, neutral mass spectrometer, and tunable laser spectrometer measurements are conducted throughout descent, and images are acquired from the near-IR camera from ~15 km to the surface. Once on the surface, the lander performs the Raman/LIBS measurements, 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 decoupled from the bellows, allowing the gondola to rise rapidly to 5 km above mean planetary radius (AMPR). 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. Raman/LIBS measurements are made at the second landing site and the remaining data are transmitted to the carrier spacecraft.

2.2 Concept Maturity Level

Upon receiving the Venus Mobile Explorer Study Questionnaire, the study team performed a review of the current state of Venus near surface mobility technology. The review revealed that the Concept Maturity Level was CML 2 or lower for concepts with near surface mobility to multiple locations. Some near surface Venus mobility options had been studied previously to determine which concepts were feasible, yet there were no architecture trade studies that evaluated the detailed cost, risk, or performance for these options. The study team initially opened the trade space to all Venus mobility options. Initial evaluation of these options was conducted to determine their ability to satisfy the science requirements. At the direction of the IPP, the study team quickly concentrated on the metallic bellows option and the study focused on a point design to meet VME science requirements using the bellows.

The point design described in this study meets the IPP VME science objectives. It establishes a concept that can be successfully achieved within the mass requirements of an Atlas V launch vehicle and demonstrates that power and thermal systems can be fabricated to survive for >5 hours in an environment at or near the Venus surface. While significant technology advancements are still needed, the study shows these technologies can be advanced to appropriate readiness levels early in the process to support the mission schedule. The preliminary risk assessment that was performed encompasses the major developmental and operational risk areas and outlines necessary actions to reduce or eliminate these risks. Therefore, the concept described in this report brings the Venus near surface metallic bellows mobility concept to CML 4, Preferred Design Point.

3.0 TECHNICAL OVERVIEW

3.1 Instrument Payload

Table 4 lists the science instrument payloads identified in the Science Traceability Matrix (**Table 2**) and shows the accommodation resources required for each instrument. This is a nominal payload used for estimating the resources required by the VME concept. Specific implementation is left to future individual mission point designs.

Table 4: Instrument Resource Summary – the instruments in this table represent a notional instrument payload and to the extent possible, existing or proposed instruments were selected for which resources are known or have already been estimated. With the exception of the SAM heritage instruments, there is a substantial uncertainty associated with these numbers.

	Mass (kg)	Power (watts)	Volume (cm)	Data Volume	TRL/Heritage
Neutral Mass Spectrometer (NMS)	11	50	26 x 16 x 19	2 kbps	6-7 MSL/SAM
Tunable Laser Spectrometer (TLS)	4.5	17	25 x 10 x 10	3.4 kbps	6-7 MSL/SAM
Raman/Laser Induced Breakdown Spectroscopy (LIBS)	6.0	6.7	CCD & preamps: 19 x 14 x 19, Optical Head: 08 x 07 x 10, Electronics: 08 x 10 x 40	1.5 Mb/sample	4/ExoMars
Near-IR Imager	1.8	12	17 x 09 x 09	1.65 Mb/image	6/Venus Flagship
Magnetometer	1.0	1.0	20 x 10 x 10	0.1 kbps	6/Various
Atm Structure Investigation (ASI)	2.0	3.2	10 x 10 x 10	2.5 kbps (descent) 0.25 kbps (surface)	6/Venus Flagship

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.

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..

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.

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.

The VME science payload operations concept is detailed in **Section 3.2.1**. The one significant instrument trade explored during this study, the trade between the Raman/LIBS remote sensing approach for composition and the sample-based X-ray Diffraction/X-ray Fluorescence Spectroscopy (XRD/XRFS) approach, is detailed in **Section 3.4.2**.

3.2 Flight System

3.2.1 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 Russian Proton-M launch vehicle would also be feasible). 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

Table 5: Significant Mission Events

Date	Event	Delta V/Comments
May 27, 2023	Launch	30 m/s Earth to Venus TCMs
October 27, 2023	First Venus Flyby	45 m/s Venus to Venus TCMs
February 10, 2024	Lander Release	Flexibility in exact time +/-Day
February 11, 2024	Spacecraft Divert Maneuver	127 m/s Timeline criticality +/-Day
February 15, 2024, 07:12 UTC	Lander atmospheric entry interface	(175 km altitude, -19.0 deg. EFPA)
February 15, 2024, 08:17 UTC	1st Landing	(Approximately 2 degrees from entry interface location)
February 15, 2024, 10:42 UTC	Carrier Flyby Periapsis	N/A
February 15, 2024, 12:23 UTC	2nd Landing	N/A
February 15, 2024, 13:17 UTC	End of Lander Design Lifetime	N/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 (see Section 3.3.4 for additional details). Initially, the 2023 date was thought to be the most viable launch opportunity. Thus, the design concept is based on that window. However, later in the study, the 2021 window was also found to be viable. The timeline of significant events for the May 27, 2023 launch trajectory is shown in **Table 5**.

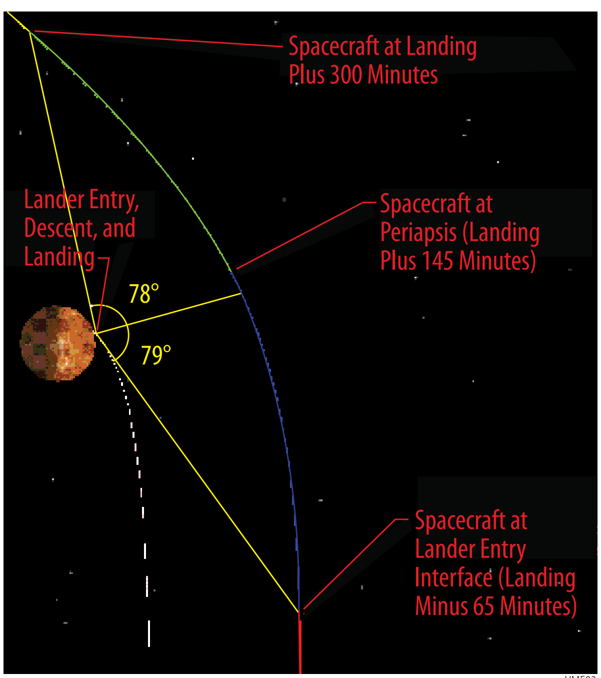


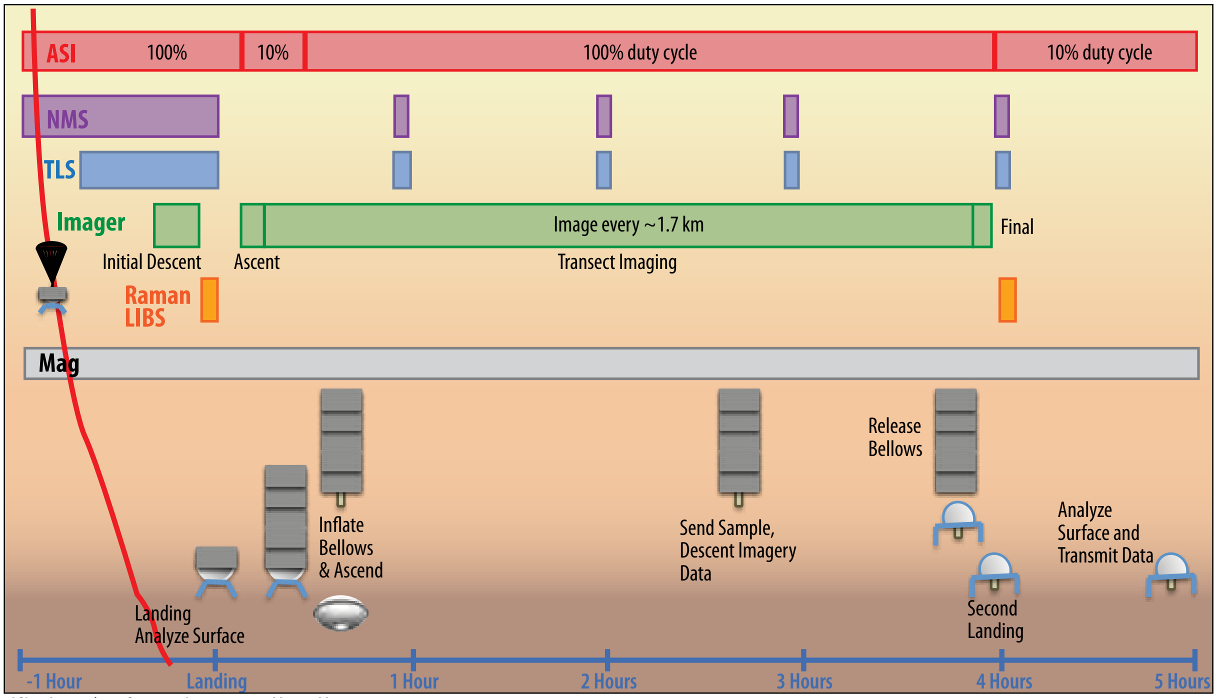
Figure 2: Probe Atmospheric Entry and Descent and Spacecraft Flyby, February 15, 2024 (May 27, 2023 Launch)

Figure 2 is a Venus-centered view of lander entry interface and the spacecraft flyby on February 15, 2024. Lander impact occurs approximately 2° downrange of the entry interface. The 2023 launch window results in a landing 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. Some flexibility in landing locations (that have the same aeroshell constraints and equivalent allowable launch masses) exists. These locations lie upon a line of relatively-fixed latitude, with a longitudinal variability as wide as 40° around the subsolar point. The spacecraft divert delta-V and spacecraft-lander range and elevation profiles for these modified landing locations would be similar to those included in this study report.

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 to drop to the surface at a terminal velocity less than 10 m/s. Communication between the lander and the carrier is maintained through an omni-directional antenna on top of the bellows.

Figure 3 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.



ASI = Atmospheric Structure Investigation; Mag = Magnetometer

VME09

Figure 3: The instrument operations have been defined during descent, and on and near the surface to meet science objectives.

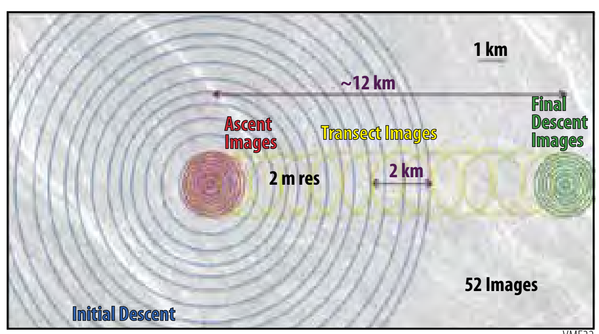
The NMS and the external components of the ASI start operations as soon as the aeroshell is released. The NMS performs trace and noble gas analysis during descent using an external atmospheric inlet port.

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. **Figure 4** 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 is ejected, the lander's second omnidirectional antenna is switched on to continue the uplink, and the gondola descends to the surface. Thermal and battery sensors automatically eject the bellows if



VME32

Figure 4: The NIR Imager acquires discrete images to construct a complete morphological traverse for geologic context (~12 km example traverse is shown). The 1024^2 detector generates 8 bits per pixel, which is 4:1 compressed. The corners of the square detector are rounded off to limit the size of the window. Any subsequent study should evaluate the signal to noise required for the dim, low contrast Venus surface environment. This figure does not show the near – surface sampling site images taken with the alternate focus.

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. Future studies will need to address the issue of potential interference from dust disturbed at touchdown. Once the analysis is completed, it takes the gondola about an hour to complete the data transmission to the carrier spacecraft driven by the 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 **Figure 5**. 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.

3.2.2 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. Carrier spacecraft details are provided in **Table 6**.

The spacecraft power budget is shown in **Table 7**. Solar arrays measure ~1.2 m^2 per side (balancing for 5 RPM 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

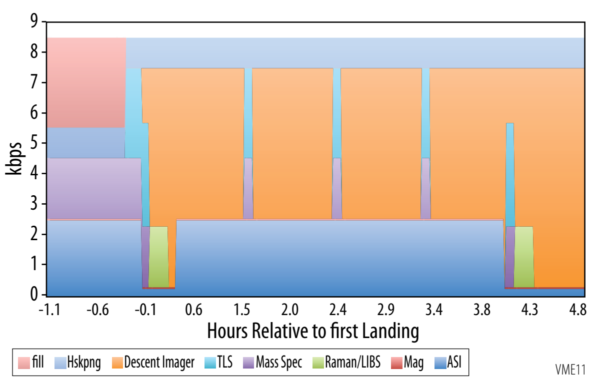


Figure 5: The data rate is a constant 8.5 Kbps. The Imager and Raman/LIBS data are buffered and used to fill the available bandwidth.

Table 6: Carrier dry mass, current best estimates (CBE) and max expected.

Item	CBE [kg]	Composite Mass Growth Allow. [%]	Max Expected Mass [kg]
Spacecraft	846	30%	1100
Probe Separation System	30	30%	39
S/C Mechanical, Structural	506	30%	658
GN&C	11	30%	14
Propulsion Hardware	55	30%	72
Thermal	60	30%	78
Power	28	30%	37
Harness	31	30%	40
RF Comm	50	30%	65
Avionics	45	30%	59
Launch Vehicle Separation System SC side	30	30%	39

Table 7: Carrier power estimates (without contingency).

	All Numbers in Watts			
	Launch	Cruise	Probe Cruise	Fly Away/ Comm
S/C Total	171	304	304	355
GN&C	50	50	50	50
Propulsion Hardware	1	1	1	1
Thermal	0	90	90	90
Power	10	20	20	20
Harness	3	6	6	7
RF Comm	20	50	50	100
Avionics	87	87	87	87

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 (**Table 5**) 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 bipropellant system. Using small thrusters versus reactions 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.

3.2.3 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 **Figure 6**, 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.

The total mass of the aeroshell, including structure, TPS, and parachutes, is 876 kg (not including 30% margin). The heat shield's mass is 634 kg, the back shell's mass is 192 kg, and the parachute and mechanisms are 50 kg.

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. Even assuming a PVLP-sized probe is launched to Venus prior to VME, there is sufficient heritage rayon to construct the VME aeroshell (see **Appendix C**).

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.

3.2.4 Lander

3.2.4.1 Lander Mechanical System

The lander mechanical system is designed to safely transport the instrument suite to multiple landings on the Venus surface. The concept meets the NMS/TLS instruments' requirement for a mini-

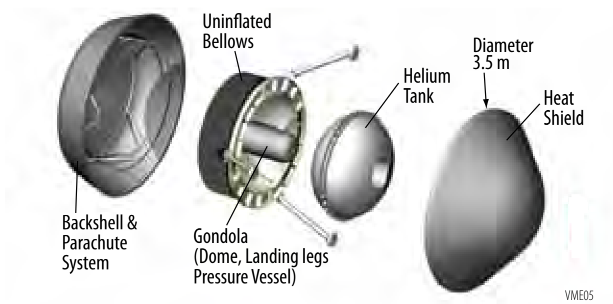


Figure 6: Aeroshell back shell and heat shield are based on Pioneer Venus Large Probe and Stardust geometries.

mum 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 (see **Figure 6**). 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 (estimated at 167 g) 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 is 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 (**Figure 7**). 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

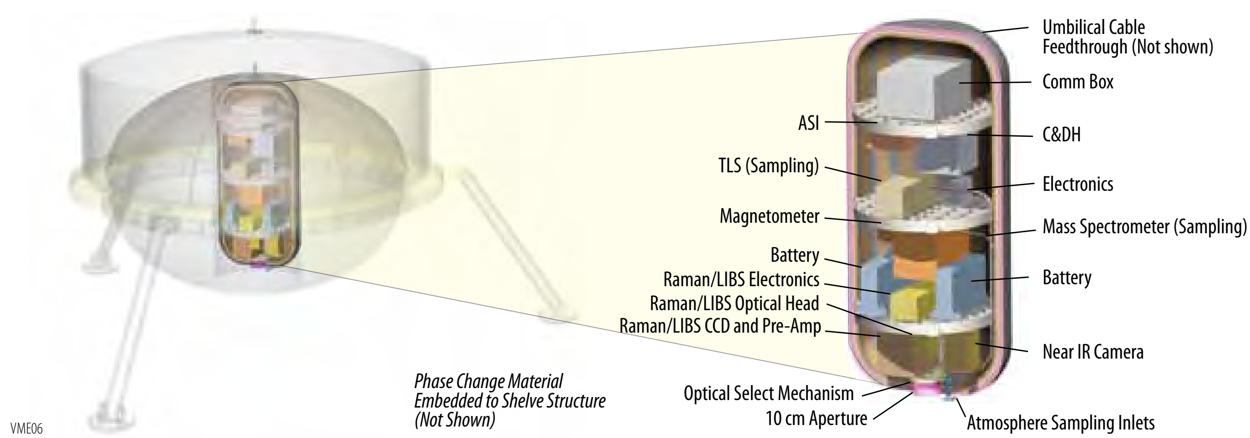


Figure 7: Lander with gondola details, showing instruments and avionics.

Table 8: Mechanism List.

Component	Number of Mechanism	Single Use vs. Multiple Use	Amb or Venus Temp	TRL	Notes
Mass Spec	1	Multiple	Amb	6	Valve for Sampling
TLS	1	Multiple	Amb	6	Valve for Sampling
Atmospheric	0	N/A	N/A		
Near IR Camera	1	Multiple	Amb	8	Focus Adjustment
LIBS/Raman	1	Multiple	Amb	5	Wheel allows LIBS/Raman to view multiple locations
Drop Heat Shield	3	Single	Venus Env/Amb Temp	6	
Open Parachute	3	Single	Venus Env/Amb Temp	6	At 60 km or higher
Drop from Backshell	3	Single	Venus Env/Amb Temp	6	At 50 km or higher
Leg Launch Locks	3	Single	Venus Env/Amb Temp	5	
Leg Spring Mechanisms (Damper and Lock)	3	Single	Venus Temp	4	
Valve to Equlibrate Bellows Pressure	1	Multiple	Venus Temp	4	Maintain Pressure in 0.5 Atm of Venus environment
Valve to Pressurize Bellows	1	Single	Venus Temp	4	Fill Bellows rapidly
Allow omni on bellows coaxial cable to reel out	1	Single	Venus Temp	4	Release coiled cable
Cut Bellows Piping	2	Single	Venus Temp	4	Prior to dropping pressurant tank
Drop Pressurant Tank	3	Single	Venus Temp	4	At first landing site
Sever Wires to Bellows/Umbilical	1	Single	Venus Temp	4	In flight
Drop From Bellows	3	Single	Venus Temp	4	In flight
Total	**31**				

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.

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. The complete mechanisms list is provided in **Table 8**.

3.2.4.2 Lander Mobility System

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 [Seiff et al., 1985]. 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 **Figure 8**, in the various lander configurations.

Based on the prototype bellows tested at JPL [Kerzhanovich et al., 2005], 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. **Section 4.2** discusses the current level of development of all bellows system components.

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 is 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 buoy-

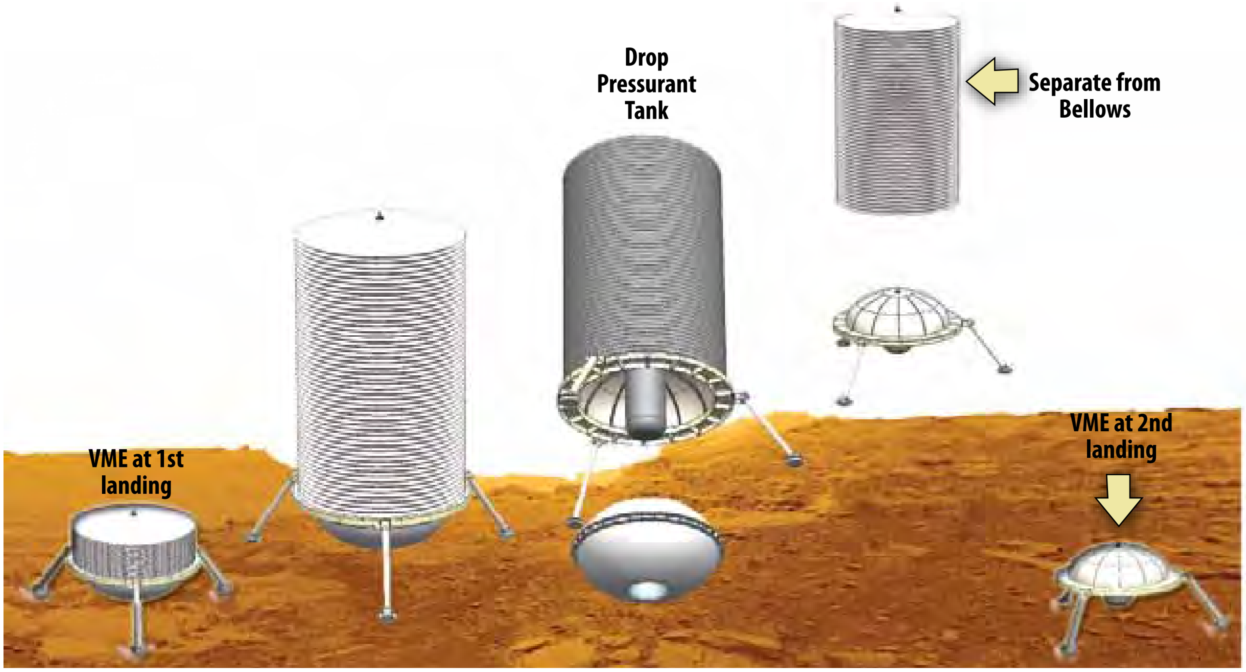


Figure 8: Bellows configuration sequence.

ancy 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 is chosen because it 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. The mechanism development is detailed in **Section 4.0**.

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 C&DH 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.

3.2.4.3 Lander Thermal System

The thermal analysis for this study is based on a previously developed 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^{0} C. Survival heaters on the payload ensure that its temperature is above -20^{0} 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^{0} 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^{0} 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 $1{,}000^{0}$ 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^{0} C mean temperature is used in the model. MLI blankets thermally-shield the payload from the interior surface of the pressure vessel. The thermal insulation layout is shown in **Figure 9**.

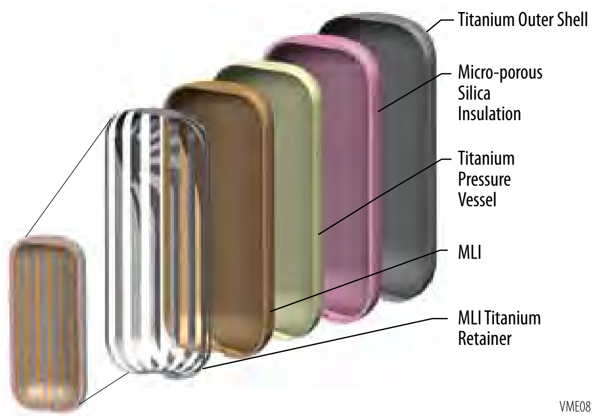


Figure 9: Thermal insulation layout.

The total heat load rises rapidly during descent through the atmosphere and reaches 1,355 W upon landing. **Figure 10a** shows the magnitude of each heat source in the gondola. To extend duration on the surface, Phase Change Material (PCM) is thermally coupled to the payload. The optimum PCM, Lithium Nitrate Trihydrate (LNT), as

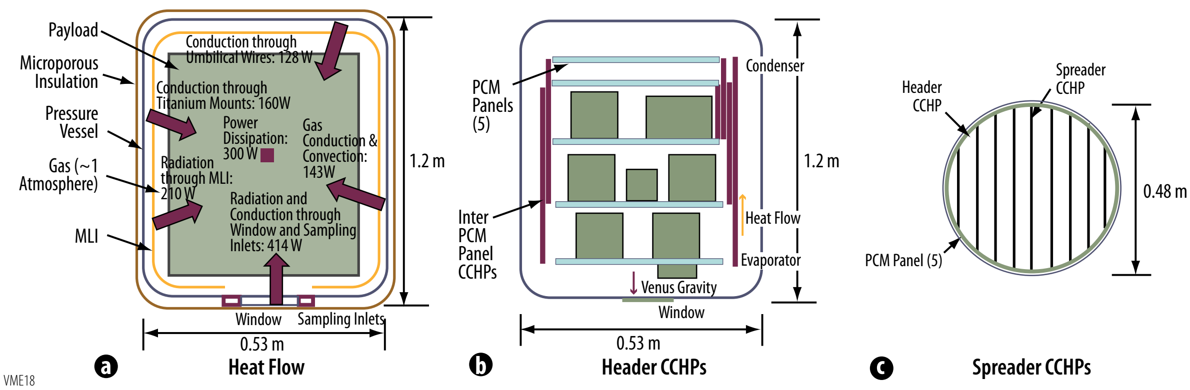


Figure 10: Gondola: a) Heat Flow, b) Header CCHPs, c) Spreader CCHPs.

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 (**Figure 10b**). 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) (**Figure 10b**). CCHP spreaders are used to spread heat within a PCM panel. Each panel has nine CCHP spreaders (**Figure 10c**), and a header CCHP thermally connects the nine CCHPs. The inter PCM panel CCHPs thermally connect the header CCHPs. All the CCHPs are redundant. **Figure 11** shows the relationship between the LNT mass required and mission life on the Venus surface.

3.2.4.4 Lander Avionics

The gondola avionics is driven by the mechanisms and deployments required and by the need to minimize mass, volume, and power. As gondola mass and volume is at a premium, the study team decided a single string avionics box presented an acceptable risk. The power the avionics consumes during the 5-day cruise phase is also a battery driver. To minimize power and mass, careful consideration was taken to minimize the cards and simplify the box. This integrated avionics box solution includes a typical Power System Electronics (PSE), Mechanism and Deployment Electronics (MDE), and Command and Data Handling (C&DH) box. Size of the box was minimized to 25 cm x 24 cm by using 3U-160 size cards. The box is 9.7 kg and dissipates 28.8 W during operational modes and 10 W during the cruise phase if the essential cards are powered. Future studies might explore trades to determine if a Single Board Computer (SBC) is necessary or whether the entire functionality of the probe might be exercised with FPGAs (potentially saving mass, power, and cost), although the flexibility of updating software at a late stage favors the SBC.

The avionics card listing is provided in **Figure 12**. The number of components that require power switching is limited, so two power switch cards are allocated for switching components on and off (half the number used for typical spacecraft). The communications card and SBC cards are combined since the communication card only needs to feed digital signals for uplink to the S-Band Modulator. A digital I/O card is used for instrument interfaces. Spacewire is assumed not for data volume, but because it minimizes power consumption in the instruments and avionics. An analog card is used to monitor the housekeeping within the probe and may do some of the atmospheric package electronics functions. Two cards are dedicated to the deployments and driving the movable mechanisms as required.

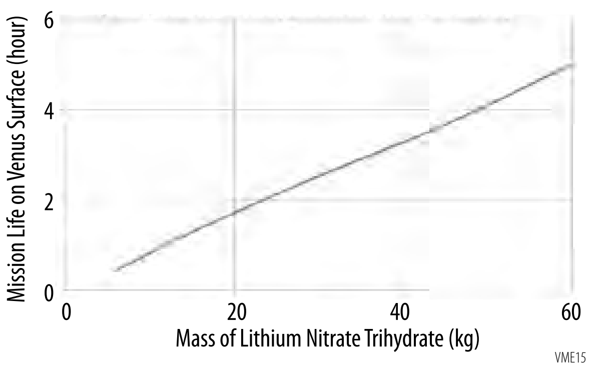


Figure 11: Relationship between gondola LNT mass and mission life on Venus.

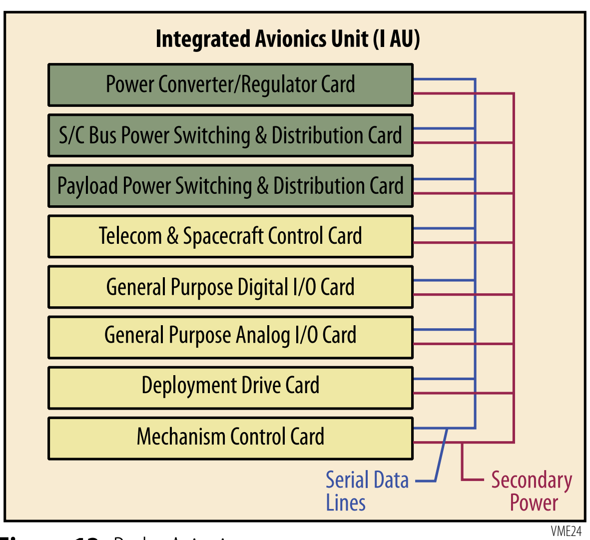


Figure 12: Probe Avionics

The mission Total Ionizing Dose (TID) for VME is not an avionics and harness shielding driver. The TID, behind 100 mil of spherical aluminum shielding, is 6 krad(Si) without Radiation Design Margin (RDM). A RDM of 2 is typically the minimum TID requirement for a mission to account for both the variability in the environment and the inherent uncertainty in the models. This dose, while similar to a modest Low-Earth Orbit (LEO) mission, is obtained from a different, more hazardous environment. While a LEO mission may take five years to accumulate this dose, VME absorbs 6 krad(Si) in less than a year.

3.2.4.5 Lander Communications

The VME mission duration at Venus is significantly longer than previous missions to the Venus surface. S-band is used 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 (**Figure 13**). Only one antenna is used at a time. The initial antenna sits on top of the bellows and is used until the bellows is 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 omnidirectional antenna, which will need to be redesigned to use materials appropriate for the Venus atmospheric composition and temperature.

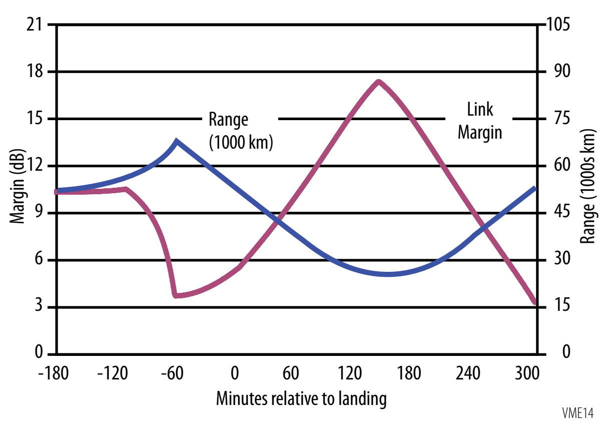


Figure 13: The link margin (magenta) is above 3 dB for the duration of the operations on Venus. The 2021 trajectory is slightly worse than the 2023 trajectory, but the margin is above 3 dB. Also shown is the carrier spacecraft range (blue)

The estimate for the instrument and housekeeping data rates is shown in **Figure 5**.

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.

3.2.4.6 Lander Power

The lander power supply is provided by 100 SAFT LSH-20 Lithium-Thionyl Chloride primary cells. Primary batteries cannot be re-charged once dissipated, adding some Integration and Test (I&T) challenges to this mass saving choice.

Table 9: Mission level mass rackup (**Table 6** shows carrier details).

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
Mechanical/ Structure	270	30%	351
Mechanisms	51	30%	66
Thermal	113	30%	147
Other	34	30%	44
Bellows	890	30%	1132
Aeroshell	**876**	30%	**1139**
Spacecraft	846	30%	1100
Satellite (S/C + Probe) Dry Mass	3112	30%	4021
Propellant Mass	366	1%	370
Satellite Wet Mass	3478		4390
LV Throw Mass available to lift Wet			5141
Mass Margins			
LV Limited Max Wet Mass [kg]			5141
Propellant in LV Limited Max [kg]	428	3%	441
LV Limited Max Dry Mass [kg]			4700
Project Margin (Wet Mass Growth, MEV to LV Limit) [kg]			**751**
Wet Mass Growth (Wet Mass Growth, MEV to LV Limit) [%]			**17%**
Total Possible CBE Dry Mass Growth			**1234**
Total Possible CBE Dry Mass Growth [%]			**35.5%**

This trade, along with a discussion about using RPS devices in the Venus environment, is detailed in Section 3.4.4. The primary batteries have a Watt-hour capacity of 4413 assuming a Voltage/cell of 3.5 V, which corresponds to VME's average power draw during surface operations. The batteries are assumed to lose 3% capacity, corresponding to one year before use, and will reach a depth of discharge of 70% at the completion of the landed mission. The battery package includes 10 kg of battery mass and 2 kg of packaging. The lander batteries dissipate more than half of the power during the 5-day cruise after probe release and before reaching the Venus atmosphere by assuming 15 W for Survival heaters/avionics power.

3.2.5 Lander Mass, Power, Data Rate

The overall launch mass is shown in **Table 9**. 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 exist 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 9**.

Table 10 provides details of power usage and battery sizing. 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. Table 10 shows the current Depth of Discharge (DOD) of the primary battery at 70% after 5 hours on the Venusian surface.

The Probe Data Rate up to the carrier spacecraft is outlined in **Figure 5**. Future studies will look at whether handshaking between the carrier and lander communication system can be achieved.

3.3 Ground Systems

The ground data system is shown in **Figure 14**. VME uses an X-band downlink to the DSN

Table 10: Probe and Carrier Power Details and Probe Battery Sizing (Carrier details shown in **Table 7**).

	Probe Cruise	1 hour before descent	Probe Descent	Probe Science	Probe Travel	Probe Comm	Sizing Max	Sum
Max. Exp. Value (CBE)								
Carrier Load	**319**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**355**	
Probe Power	15	142	246	217	182	143	**246**	
Carrier Power	304	N/A	N/A	N/A	N/A	N/A	**355**	
Probe Watt-hours	1773	142	266	144	685	82		**3092**
	Depth of Discharge		**70%**	Battery Size (W-hr)			**4413.5**	
Science Payload Max. Exp. Values (CBE)								
Lander Average during Duration	**15**	**142**	**246**	**217**	**182**	**143**	**246**	
Lander Science Payload	0	0	83	75	40	1	89	
Mass Spec	0	0	50	50	15	0	50	
TLS	0	0	16.8	16.8	9	0	17	
Atmospheric Package (Temp, Press, Magnmtr, etc.)	0	0	3.2	0.32	3.2	0.32	3.2	
Magnetometer	0	0	1	1	1	1	1	
Near IR Camera	0	0	12	0	12	0	12	
LIBS / Raman	0	0	0	6.7	0	0	6.7	
Total time of use (minutes)	**7200**	**60**	**71**	**40**	**226**	**34**		
Duration of Period (hours)	**120.0**	**1.0**	**1.1**	**0.7**	**3.8**	**0.6**		
Lander Subsystems	**15**	**142**	**142**	**142**	**142**	**142**	**159**	
Mechanical / Structure	0	0	0	0	0	0	0	
Thermal	4	0	0	0	0	0	15	
Power	0	11	11	11	11	11	12	
Harness	0	1	1	1	1	1	2	
Avionics	10	29	29	29	29	29	29	
RF Comm	1*	100	100	100	100	100	100	
Aeroshell (Heatshield + Backshell)	**0**		**0**	**0**	**0**	**0**	**0**	

**Based on 1% Duty Cycle.*

34-meter ground stations for both science data relay (through the 1 m HGA) and contingency communications (through two omni-directional antennas). X-band was selected instead of Ka-band because the carrier spacecraft requires contingency communications and Ka-band omni-directional antennas are not currently available. The low volume of science data (less than 200 Mbits), does not require the performance of Ka-band, resulting in lower cost and mass. If Ka-band is mandated for all science data downlinks, VME could implement it with a modest increase in the cost and complexity of the carrier spacecraft communications system.

VME does not require the use of the 70-meter antennas and uses only one ground station at a time, with the exception of infrequent Delta Doppler One-way Ranging support to refine the navigation. The on-board navigation function is responsible for determining the trajectory of the spacecraft, planning the maneuvers, and supporting the release of the lander.

The Mission Operations Center (MOC) is responsible for carrier spacecraft operations and for monitoring the autonomous lander operations. During lander operations, the carrier spacecraft receives telemetry data from the lander via the S-band High Gain Antenna and relays low rate status data to Earth using an X-band omni-directional antenna. The one-way light time to Earth is about 12 minutes for both the 2021 and 2023 launch windows. After lander operations have ended, the carrier spacecraft points the 1 meter X-band HGA to Earth and sends the data at 25 kbps. The total science data volume is approximately 200 Mbits. Once the data is reliably returned to Earth, the VME mission ends – about 9 months after launch.

The instrument teams process the science data and deliver the science data products to the Planetary Data System within 6 months of the end of mission operations.

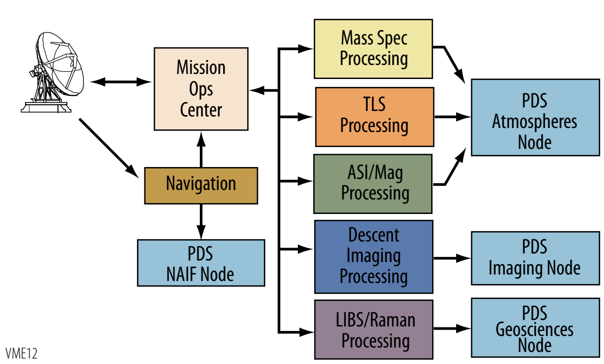


Figure 14: Ground System Block Diagram

3.4 Key Trades

In the course of the study, key trades were identified, including: overall architecture, instrumentation for surface science, flight trajectories, and power system. These trades are detailed below and provide insight into the choices made for the VME baseline design. Additional trades are summarized in **Section 3.4.5**.

3.4.1 Key Architecture Trades

To determine how best to meet the VME requirements for sampling at least two locations separated by at least 8 km, three tiers of architecture trades were performed (**Figure 15**). At the first tier, the study team needed to decide between collecting samples at the surface and then transporting them to a remote lab (in the Venus atmosphere, in orbit around Venus, or on Earth) or performing the sample analysis at the surface. All of the means considered for transporting samples from the surface to the lab (or sample return capsule) would require significant technology development for operation in the Venus environment. An additional drawback of these options is the complexity of the rendezvous with the lab or sample return capsule. Given the relatively higher TRL of the techniques discussed in **Section 3.4.2**, it was decided to perform sample analysis *in situ* at the surface.

Once local sample analysis was selected, a second tier trade was conducted between multiple landers to access multiple sites or a single mobile lander. The multiple lander approach would be lower risk and decrease design complexity since the landers would not need to last as long, would not need as many high temperature mechanisms, and would have more simple structures with less required thermal operational time on the surface. The cost of a second simple landed probe would need to be traded against the cost of the mobility system. However, due to the added requirement of providing moderate resolution, near continuous IR imaging of the surface between sampling sites, the single mobile lander option was selected. The imaging requirement also favored a method of mobility (third tier) that lifted the camera some

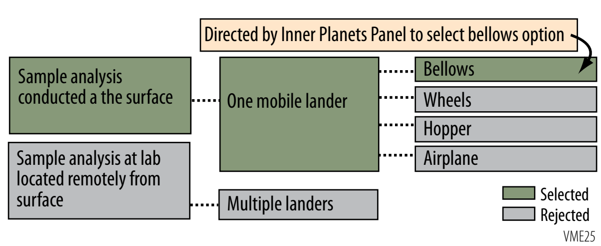


Figure 15: Surface/sample site access trades.

distance above the surface between sampling sites. This requirement, coupled with the slow traverse times and complex hazard avoidance autonomy needed for a wheeled (e.g., rover) option, led to its rejection. The relative maturity of the metallic bellows concept and the high interest of the IPP in this concept led to its selection as the baseline mobility technique in contrast to a rocket-propelled hopper or airplane, both of which offer significant technology challenges in the Venus environment.

3.4.2 Instrumentation Trades

XRD/XRFS requires a sample retrieval capability to bring a sample inside the pressure vessel, making the instrument thermally compromising, resource intensive, expensive, and difficult to accommodate. This led to the selection of Raman/LIBS as the baseline mineralogy and chemistry instrument on the basis of its remote observation capability, which is less resource intensive. A comparison of key resource requirements is shown in **Table 11**.

Although the clear impact to baselining the XRD/XRFS illustrated by **Table 11** is the requirement for a sample retrieval system, XRD/XRFS selection imposes additional burdens on the system design, including:

- Solid sample ingest allows the potential for additional heat to leak into lander. Once the sample is ingested, it must be ground to a small particle size, funneled to a test volume, and randomly oriented (via a piezoelectric mechanism).
- Two hour processing time for XRD/XRFS at each sample location and limited lander lifetime in the Venusian surface environment reduces the distance traversed between the two sample locations by half of the VME baseline traverse.
- Only one sample location at each of two landing sites is possible.
- Ten times greater data volume forces a trade-off between the number of samples that can be taken and the capability of the data storage and communications subsystems.

Table 11: Laser/X-ray comparison

	Raman/ LIBS	XRD/XRF Instrument	XRD/XRF Sample system[1,2]
Mass (kg)	6	1.6	4
Power (W)	6.7	10	60 (for 2 min)
Data Volume	1.5 Mb (6 min/ sample)	15 Mb (2 hr/ sample)	N/A
Volume (cm)	18 x 23 x 40	22 x 6 x 12	See Appendix
TRL	4	4	3
Cost ($M)	16.8	18.1	21

[1]Multiple separate sample systems may be required to avoid cross-contamination, one for each sample location; at a minimum additional hardware may be required to prevent cross-contamination if a single sample retrieval system is used
[2]Does not include internal mechanism or tray to present sample to instrument

Although Raman/LIBS implementation does not require state of the art hardware (detectors, laser, electronics) and Raman analysis is well understood, LIBS analysis is highly dependent on conditions (temperature, pressure, atmospheric composition) at the sample site and poses substantial calibration challenges for a Venus mission.

3.4.3 Flight Trajectory/Launch Opportunities Trade

Three separate spacecraft trajectories for lander entry and descent were considered: two Venus flyby trajectories and one Venus Orbit Insertion (VOI) trajectory. Type I and Type II launch windows from 2020 to 2023 were considered. The 2020 launch window was rejected because of high C3 requirements. For Venus, good C3 launch windows occur about every 16 months. Analysis of spacecraft-lander range data and fuel mass requirements resulted in the selection of a flyby trajectory. A flyby trajectory also insures the landing site illumination requirement can be met across the launch window while meeting all of the other requirements.

Table 12 summarizes the 2021 and 2023 launch windows analyzed for this study. The window open and close cases are patched conic. The middle of window trajectories (May 27, 2023 launch and November 2, 2021 launch) were integrated trajectories used for more detailed analysis and in-

Table 12: Launch Windows, 2021 and 2023 Launch (Type 2)

Launch	Venus Flyby	Lander Impact	Launch C3 (km^2/s^2)	Hyperbolic Excess Velocity at Lander Entry Interface (km/s)	Lander Entry Interface Velocity at 175 km Altitude (km/s)
October 23, 2021	April 5, 2022	July 27, 2022	8.01	4.79	11.3
November 2, 2021	April 7, 2022	July 29, 2022	7.92	4.78	11.3
November 11, 2021	April 10, 2022	August 1, 2022	8.88	4.82	11.3
May 17, 2023	October 27, 2023	February 15, 2024	6.28	3.79	10.9
May 27, 2023	October 27, 2023	February 15, 2024	6.49	3.65	10.8
June 5, 2023	October 27, 2023	February 15, 2024	8.82	3.41	10.8

cluded Solar, Earth, Venus, Lunar, and planetary gravity, Solar radiation pressure, and Venus drag. The absolute value of Declination of Launch Asymptote (DLA) is below 28.5 degrees and the minimum Venus flyby altitude is 6,475 km for all launch opportunities in **Table 12**.

A delta-V budget including statistical and deterministic delta-Vs and margin was determined for the November 2, 2021 and May 27, 2023 launch opportunities. The delta-V requirement was 311 m/s for the 2021 launch opportunity and 277 m/s for the 2023 launch opportunity, resulting in about 19 kg of additional propellant required for launch in 2021. **Figure 13** shows the spacecraft-lander range and **Figure 2** shows the spacecraft elevation relative to the probe for the May 27, 2023 launch opportunity. The 2023 launch is baselined for this study, but where the 2021 launch is bounding or different, the differences are highlighted.

3.4.4 Power System Trade

While the VME carrier can use traditional solar power and secondary (rechargeable) batteries, several options were studied for the VME probe power, including: Advanced Stirling Radioisotope Generator (ASRG), primary, and secondary batteries. An ASRG engineering unit has been developed and tested, but it will only work in deep space or Mars-like atmospheric conditions. Additional development would be required to make an ASRG work on the surface of Venus. Heat rejection of the ASRG cold sink poses significant thermal design issues as does surviving the large g load of entering the Venus atmosphere.

Considering an ASRG-like RPS for power only, the VME probe baseline requires 255 W electrical power. VME would need two conventional ASRGs adapted for Venus to meet the power requirement since each RPS only has an output power of 140 W. Two conventional (30% efficient) ASRGs adapted perfectly for Venus require 42 kg, and additional thermal and power requirements would likely result in mass increases.

Secondary batteries require solar cells or infrared cells to maintain charge on the battery. Solar cells would be ineffective on or near the surface of Venus due to significant atmospheric attenuation. Infrared cells would require significant development. Also, secondary batteries would require additional electronics for charging the battery. A secondary battery could be externally-managed by the orbiter, however it would have to maintain enough capacity to complete the probe mission. A secondary battery does have significant I&T advantages, and provides lower operational risk. The mass for a secondary battery on VME would be 51 kg for the same W-hrs as the baseline.

Lithium-thionyl chloride batteries (Li-SOCl2) are primary batteries that have a low self discharge rate and high energy capacity. No additional electronics for charge maintenance is required. The VME baseline design houses these batteries in the gondola pressure vessel so there is no significant technology development. The mass is also a low 12 kg for 4400 W-hrs as compared to 51 kg for secondary battery or at least 42 kg for a Venus-specific ASRG.

3.4.5 Other Trades

The full trade tree is shown in **Figure 16**. A brief rationale is provided for rejected trade options.

Lander Operational Lifetime: Determining the required surface life of the VME lander involved several considerations, including the time to measure the sample, the quantity of thermal control materials required, material survival, mechanism survival, and the surface wind speeds that dictate the time required to move between sample sites. In particular, the mass of Phase Change Material (PCM) increases as a function of surface stay time (see **Figure 11**), resulting in a domino effect involving mass increases to the gondola structure, bellows, aeroshell, and carrier spacecraft. Ultimately, 5 hours was chosen as the lifetime to accomplish the minimum required surface operations with adequate time, while keeping the overall VME system mass within the target launch vehicle's capability, with margin.

Lander Autonomy: The baseline lander design does not have a receiver. It operates autonomously based on time relative to specific events (such as atmospheric entry and landing). Commandability was evaluated in the course of this study. It provides the ability to optimize the data rate between the lander and the carrier spacecraft. Such optimization could increase the data return significantly; however, the baseline data rate is more than sufficient to meet the science requirements. Commandability from the operations team during lander operations was also considered. The one-way light time is 12 minutes, so any interaction between Earth and lander would be of limited use. Earth commandability may lower the operational risk by allowing an Earth operations center to select redundant mechanisms in cases where the primary ones have failed.

Commandability of the lander was not included because the requirements could be satisfied without it and resulted in a lighter, smaller, and simpler communications system on the lander.

ASRGs for Cooling and High Temperature Electronics: Having an ASRG-like device with active cooler addition to accommodate the roughly 1300 W of cooling power and 255 W of electrical power would be useful for VME-like missions. However, the single stage ASRG/Cryocooler would require on the order of 90 kg of plutonium, resulting in a component mass of 300 kg. By contrast, using batteries for power and PCM for heat absorption for the 5-hour duration VME mission is 71 kg. For missions without metallic bellows, the ASRG for Venus with active cooling may be implemented within the mission mass, but it is incompatible with the VME concept.

If only a few instrument components require cooling, or less power is required, or slightly higher operational temperatures are allowed, then the mass and plutonium requirements drop consid-

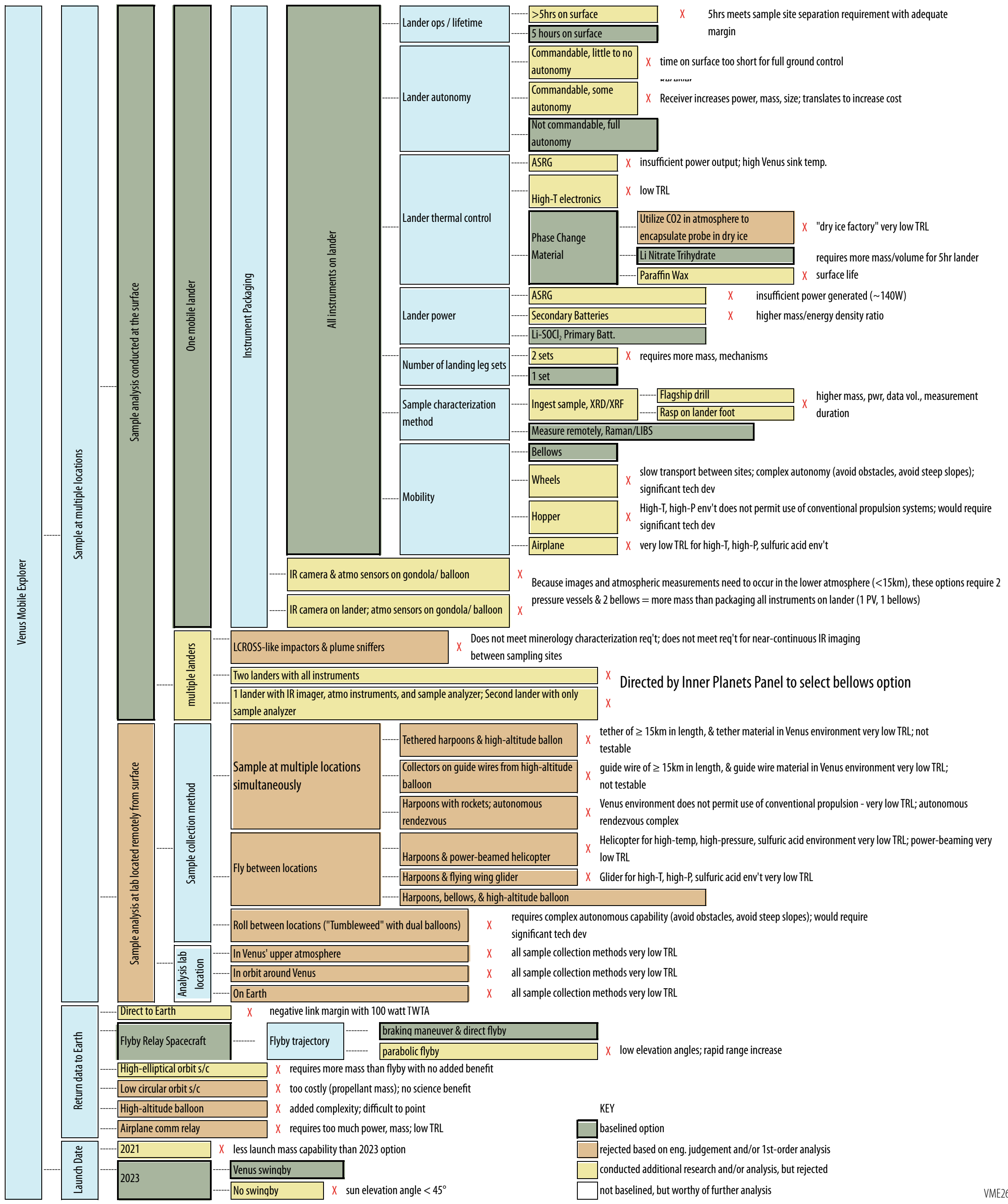


Figure 16: VME trade tree

erably. The combination of demonstrated Command and Data Handling (C&DH) and Power System Electronics (PSE) functions at higher temperature will be most desirable to achieve since this has the greatest impact on plutonium requirements. ASRG technology is currently at TRL 3 to 5 at the component level and needs box level implementation to mature the technology.

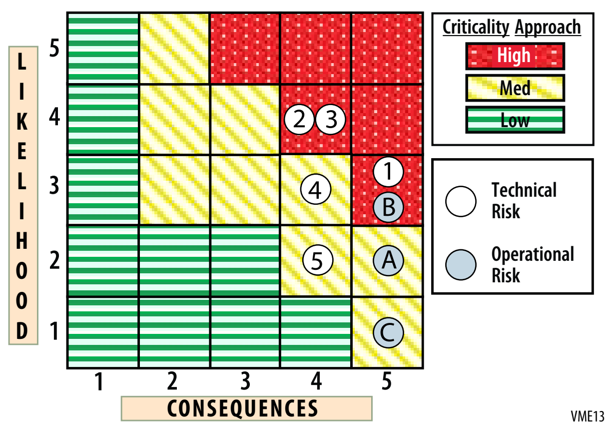
The planned 2011 high temperature seismometer electronics and 2015 Stirling duplex demonstrations will be of significant interest to the Venus exploration community, but are not compatible with a bellows mobility explorer with this instrument suite.

3.5 Risk List

The study team identified five significant VME development risks and three operational risks. Each risk is described in **Figure 17**.

Development Risks

1. *Bellows Concept Development*: The bellows pressurant tank is a thermally and mechanically difficult structure that must be built to handle 10,000 psi and 167 g of atmospheric entry deceleration. Building titanium alloy tanks so large and then testing them to ensure performance is a challenge. In addition, the bellows system requires 17 high-temperature mechanisms. Traditional pyros cannot be used, as gunpowder ignites below Venus surface temperatures. The valves used to inflate the bellows and maintain no more than 0.5 bar difference between the atmosphere and the internal pressure will also be challenging, because they will need to function at Venus' severe temperatures and pressures. Testing to ensure the external harnesses and mechanisms can all function in the Venus environment will likewise be a demanding part of the I&T flow. Initial studies will be necessary by 2011 to prepare for the 2013 (2021 launch) major development effort. Until the studies are complete and testing shows viable mechanism designs, this risk will remain red.
2. *Safe Landing Assurance*: The lander has not been equipped with Rough Terrain Avoidance due to the complexity of adding last minute mobility. Preferred science targets in the tessera terrains are expected to be rugged on a broad range of scales. Developing a robust landing system that can ensure survival in rough terrain was beyond the scope of this concept study, but will commence in the pre-Phase A portion of the mission, lowering this risk.
3. *Test Facilities:* The VME carrier spacecraft testing can follow a traditional path for deep space satellites and does not pose any significant facility challenges. However, the "test like you fly" philosophy is challenging for the VME probe due to the high temperature, high pressure, and unique Venusian atmosphere. Facilities that could be used to simulate Venus entry conditions and Venus surface conditions are not designed to accommodate large test samples. Design validation begins with materials and component testing to identify those that can withstand the Venusian temperature, pressure, and chemical environment and still perform their function. Once materials and component concepts have been identified, modeling will be used for some flight hardware design, but testing in a near full scale facility will remain crucial to keep the mission risk within acceptable limits.
Arcjet facilities and high energy laser or solar facilities can be used to characterize candidate materials. For qualifying the aeroshell, several arcjet facilities for material testing currently exist in the US and around the world. However, there are limitations to achieving applicable conditions in ground test facilities for CP qualification. This is a potential risk, as heritage CP is the only material known to work for Venus entries. (See Venkatapathy et al., 2008; 2009 for additional information about qualification and risks associated with



#	Technical Risks	Letter	Operational Risks
1	Bellows Concept Development	A	Bellows Mobility
2	Safe Landing Assurance		
3	Test Facilities	B	Landing Risk
4	Critical Events Timing		
5	Raman/LIBS Development	C	Aeroshell Operations

Figure 17: Risk Matrix.

CP). Recommendations have been made to upgrade existing arcjet facilities to generate very high heat fluxes (7-8kW/cm^2) as well as operate in CO_2.

The most critical portion of mitigating this risk is the need to build a large Venus environmental test chamber. The technology exists to develop such a facility, however significant funding is needed. Existing thermal and thermal vacuum chambers can still be used to test the Engineering Test Units (ETUs) to gain some confidence in the design and workmanship. A large-scale facility with 81 bar CO_2 pressure capability is crucial to VME bellows system development.

4. *Critical Events Timing*: All interplanetary missions have critical events during which an action must occur at a certain time or science is compromised. VME Critical Events of interest are: Separation from the launch vehicle, Trajectory Correction Maneuvers, Lander release, Spacecraft divert maneuver, and Lander operations from above the atmosphere to end of lander mission. Additionally, the deployment and operation of the bellows adds critical timing events not seen by earlier missions. Developing fail safe mechanisms and lower risk operational scenarios is crucial to lowering this development risk.
5. *Raman/LIBS Development*: The baseline LIBS instrument needs additional development to reduce calibration and focusing complexities that introduce uncertainty into the measurements, particularly in the Venus environment. This design baselines a mechanism that allows imaging near each of the lander's three feet to maximize the chance that a single good measurement will be obtained.

Operational Risks

A. *Bellows Mobility:* Even with successful qualifications of all piece parts for the bellows mobility concept, there is still a reliability risk that all deployments and operations necessary to

Table 13: Technology maturity levels.

Significant technology development	~TRL	Notes	Development duration
Bellows system	3	Inflation system, valves, materials, reliability. Model of the bellows concept created. Specific technologies listed below.	24 months
Bellows system testing	4	No large scale Venus environmental test chamber.	18 months
Bellows system Integration	5	Integration of the large bellows system, high pressure tank and related separation mechanisms around the instrument pressure vessel may require specialized approaches and equipment	12 months
High temp/press gondola tank separation system	4	Mechanisms will need to operate in the high temperature and pressure environment.	24 months
Laser raman/LIBS instrument and window.	4	Requires the ability to focus over a selected range. Need to control heat flow through the window.	12 months
High Temperature and pressure testing with CO_2 of very large subsystems.	3 to 6	Technology available but requires large investment to develop facilities.	12 months
Accompanying technology development			
Materials optimizations			
A. Optimization of bellows materials.	5	Prototype used stainless steel with a wall thickness of 0.18 mm. Material thickness; plastic/elastic deformations and other optimizations will be part of the technology trades.	12 months
B. Optimization of the primary structures materials.	6	Metal matrix and other materials could reduce mass. Coated high temperature composites for some structures like the tank are possible.	N/A TRL ≥ 6
C. Thermal gradient during inflation.	6	The effects of local cooling by helium at the bellows' intake and other effects during inflation could add thermal stresses to the bellows wall.	N/A TRL ≥ 6
Bellows performance over Venus pressures.	4	Identify materials that can maintain pressure throughout bellows operation.	18 months
Pressure regulator and release valves	4	Identify materials that can maintain pressure throughout bellows operation.	18 months
Mechanism operation over temperature and pressure.	4	The design has multiple load bearing bolt and umbilical cuts at Venus surface temperature and pressure.	24 months
Carbon Phenolic material verification and availability	9	Depending on use of existing stocks before this mission, new manufacturing and qualification processes need to be recertified. Flying a Pioneer-Venus size probe before VME is assumed so the Rayon to Carbon Phenolic process is assumed to be qualified.	N/A TRL ≥ 6
Future relevant technology development			
Heritage XRF/XRD instruments	4	Mechanisms in the sample acquisition system require adaptation for reliable operation in high temperature and pressure environment.	Not a VME baseline concept
Venus surface RPSs with cooling	3/4	Mass, packaging and sink temperature requirements are very difficult and will require significant investments. Integrating with active cooling systems also requires significant i°nvestments	Not a VME baseline concept
Active thermal control approaches	3	Longer survivals enabled by active power require active thermal systems	Not a VME baseline concept

perform mobility will not occur as planned. Adding single fault tolerance to key mechanisms would help mitigate this risk.

B. *Landing Risk:* There is an inherent risk that the lander may not land on its feet due to unforeseen circumstance (e.g., a boulder or hole). This risk is residual throughout the mission, but can be mitigated by gathering higher-detailed images of the Venus surface.

C. *Aeroshell Operations:* Due to operations complexity and significant mechanical and thermal loads, the aeroshell may not perform as planned. This is a difficult "test like you fly" component and this risk is residual throughout the mission.

3.6 Technology Maturity

Technology issues for the VME mission are listed in **Table 13**. Many of these 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.

The ability to focus the LIBS telescope within the resultant plasma plume in a Venus environment will need development.

4.0 DEVELOPMENT SCHEDULE AND SCHEDULE CONSTRAINTS

4.1 High-Level Mission Schedule

The high-level mission schedule is shown in **Figure 18**. For a 2023 launch, VME development would start at the beginning of 2015.

4.2 Technology Development Plan

Three assumptions were made when assessing potential VME technology development approaches and plans. Assumption 1: Large Venus environment test chambers that meet VME requirements will be available at the beginning of the mission for

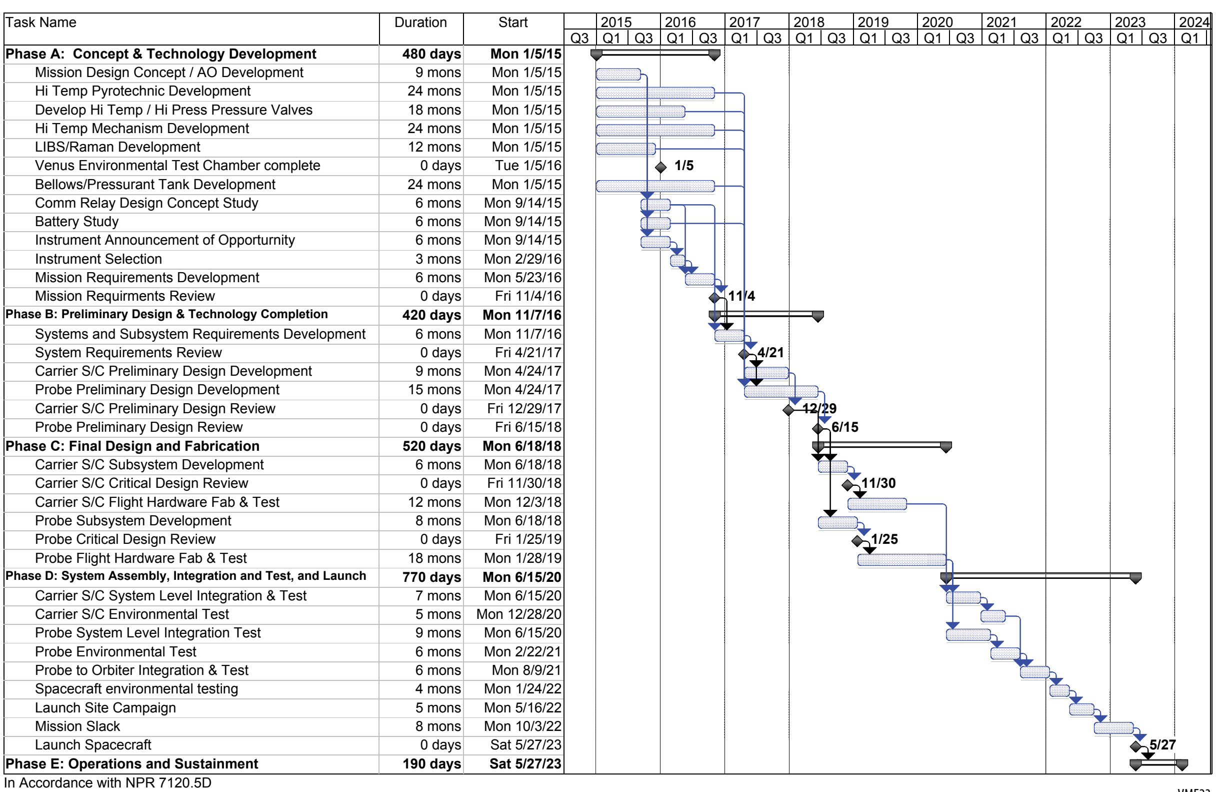


Figure 18: High-level mission schedule.

technology development tests and are not included in the VME cost estimate. (Chamber development could be paid for with a supplement to the VME budget. To be effective, such funds would need to be spent pre-Phase A, however, that funding profile is unlikely in any competed mission process, such as New Frontiers.) Assumption 2: Measurable progress in many areas will be made via internal research and development, during pre-Phase A, and through other investments made before the start of the mission. Assumption 3: Mission specific targeted technology development would start at the beginning of Phase A. This assumption is not compatible with a typical New Frontiers mission selection process, where the large sums of money required for development could not be spent so early in the mission funding profile.

The VME technology plan's primary drivers are to advance the maturity of the bellows system and related mechanisms and valves so they are capable of operating in Venus' high pressure and temperature environment. A prototype test bellows was built at JPL and inflated under Venus relevant high temperature conditions (although not in relevant pressure and not in CO_2). The prototype bellows had a diameter of ~0.35 m, a folded height of ~0.35 m, and demonstrated the feasibility of the concept. Balloon inflation systems, including the helium tank, valves, and piping, are routinely used on terrestrial superpressure balloons, but at Earth ambient conditions. Because titanium pressure vessels are used for terrestrial applications, the VME concept's custom toroidal tank requires significant new development. The valves on heritage inflation systems are not designed to operate at Venus surface conditions and need to be developed and tested. The bellows, inflation system, and valves are considered TRL 4 at this time. The separation mechanisms are not complex, but modifications and testing to the environment would be required.

VME's technologies, challenges, and development timelines are discussed in **Section 3.6** and **Table 13**. The basic development approach is that items below TRL 6 need to be matured to TRL 6, or preferably higher, during the early mission design phase. This requires almost all of the mission's technology development work to occur in less than ~24 months. Under the constraints of the three assumptions above, the 24-month development schedule may be possible if mission requirements and early designs are worked aggressively. Many of the most significant and challenging steps will be prototype design and functional tests in a Venus environment.

Table 14: Table technology development costs

Technology Development Element	Cost ($M)	Cost with Reserve ($M)
Instruments	18	27
Mechanisms	32	48
Bellows	25	38
Aeroshell	15	23
Total	**90**	**136**

Detailed costing and schedules for the technology development plans required for this work are beyond the scope of this quick architecture study. This study's cost estimates include technology development for lower TRL areas plus margin – **Table 14** shows the approximate budget of the total technology development for VME. Many challenges could increase these costs and durations. Independent of cost risk, VME also has a schedule risk. If technology development in key areas takes longer than planned, the VME schedule could exceed typical New Frontiers durations.

5.0 MISSION LIFE-CYCLE COST

5.1 Costing Methodology and Basis of Estimate

VME costing methodology for the probe and carrier spacecraft is based on a mix of parametric cost modeling, analogies to prior missions, and historic cost wrap factors (to account for "overhead" costs such as program support, facilities, unallocated expenses, etc.). Price H parametric model estimates are driven by preliminary Master Equipment Lists (MELs). The MEL line item masses, types of materials, TRLs, and complexity are combined with mission-level cost wrap factors to derive an initial estimated mission cost. No grassroots estimate was developed for the study. A reserve of 50% on Phases A-D and 25% on Phase E was added to the total derived cost, with the exception of the carrier spacecraft, where a 30% reserve was added. The 50% reserve equates to an approximate 70% confidence level in the cost certainty in conventional cost risk analysis. No reserve was added to the Launch Vehicle. All costs are in Fiscal Year (FY) 2015 dollars. The Venus surface mission is unique. The engineering and development complexities of landing on Venus are outside of recent surface landing mission experiences, therefore it is recognized that the parametric cost model could have greater uncertainty.

5.2 Cost Estimate

Based on the Price H model and cost analogies during this 5-week study, we estimated at 70% confidence level the VME mission concept total cost of $1.1B to $1.7B (without launch vehicle; $1.9B with launch vehicle). This is beyond the New Frontiers cost limit (assumed to be $750M FY15), but 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. Technology development costs are detailed in **Table 14**. The Technology Development plan is provided in **Section 4.2**. 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.

6.0 CONCLUSIONS

This study 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.

7.0 OPEN TOPICS FOR FURTHER CONCEPT DEVELOPMENT

The short duration of this 5-week study did not allow the team to develop an in-depth concept. Therefore, the study team recommends future studies to examine:

- Bellows Pressurant Tank Design and Plumbing System Design: Additional structural modeling is required to understand the optimum shapes and wall thicknesses needed to meet VME's operations requirements.
- High Temperature Mechanisms and Pyro-like Devices: The bellows mechanisms and valves do not have Venus heritage and need additional concept development.
- Lander and Carrier Mechanical Structure Optimization: As the Lander has to withstand 167 g, the structure's design and material selection is crucial. The mass provided in this report is conservative because it lacked extensive mechanical analysis. Titanium Metal Matrix might be considered as a possible structural material.
- Stability of Lander with Bellows in Venus Winds (aerodynamics): The height and width of the bellows will add challenges to both the first landing and to the floating portion of the mission. Future studies are needed to model how wind blowing on the bellows might affect the near-IR images and lander stability.

- Robust Landing Design: To ensure the mechanical design survives landing future studies should evaluate the associated aerodynamic and center of gravity implications. The concept provides adequate mass and volume to meet anticipated requirements. Work in the future should be performed to ensure an upright landing thru passive (cg) or active (drag plate) means.
- Mitigation of Expected Surface Dust Impact on Optical Measurements: Evaluate dust kicked up as a result of landing and its obscuration of optical windows.
- Evaluate Landing Risks: Study the current concept's sensitivity to non-flat regions using known Venus topography.
- Raman/LIBS Implementation: Need to calibrate LIBS pointing and measurement uncertainties in the Venus near surface atmosphere.

The VME mission concept provides unique science opportunities never before achieved at Venus. The ability to characterize the surface composition and mineralogy in two locations within the Venus highlands, coupled with high resolution imaging of an 8 km swath of this surface, will provide critical new information regarding the origin of crustal material, the history of water in Venus' past and the variability of the surface. VME feasibility depends on advancements in four key areas: 1) metallic bellows system, including helium pressure tank and plumbing, 2) Raman/LIBS verification for the Venus surface environment, 3) reliable Venus grade mechanisms, and 4) techniques to ensure safe landing. With appropriate funding profiles to support these needed developments, VME could succeed as a small flagship mission, providing unique and timely measurements of Earth's "sister" that may help to unlock a better understanding of our own planet.

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APPENDIX A - ACRONYMS LIST

Acronym	Definition
AMPR	Above Mean Planetary Radius
ARC	NASA's Ames Research Center
ASI	Atmospheric Structure Investigation
ASRG	Advanced Stirling Radioisotope Generator
BPSK	Binary Phase Shift Keying
C&DH	Command and Data Handling Box
C3	Launch Energy
CCHP	Constant Conductance Heat Pipes
CIT	California Institute of Technology
cm	centimeter
CMCP	Chopped Molded Carbon Phenolic
CO_2	carbon dioxide
CP	Carbon Phenolic
dB	decibel
DLA	Decline of Launch Asymptote
DOD	Depth of Discharge
DSN	Deep Space Network
EDE	Entry and Desent Element
EDS	Entry and Desent System
EFPA	Entry Flight Path Angle
ETU	Engineering Test Unit
FPA	Focal Plane Assembly
FY	Fiscal Year
g	measurement versus earth gravitational acceleration (9.81 m/s^2)
GRC	NASA's Glenn Research Center
GSFC	Goddard Space Flight Center
He	helium
HGA	High Gain Antenna
I/O	Input/Output
I&T	Integration and Test
IPP	Inner Planets Panel
IR	Infrared
JPL	Jet Propulsion Laboratory
K	Kelvin
Ka-Band	Ka band Communication frequencies of 26.5-40GHz
kbps	kilobits pers second
km	kilometer
km/s	kilometers per second
krad	kilorad
kW	kiloWatt
LEO	Low-Earth Orbit
$Li\text{-}SOCL_2$	Lithium-thionyl chloride batteries
LNT	Lithium Nitrate Trihydrate
LSH-20	Battery Cell Model number from SAFT
m	meter
m/s	meters per second
MDE	Mechanisms and Deployment Electronics
MLI	Multi-Layer Insulation
mm	millimeter
MSL	Mars Science Laboratory
NIR	Near Infrared
NMS	Neutral Mass Spectrometer

Acronym	Definition
PAF	Payload Adapter Fitting
PCM	Phase Change Material
PICA	Phenolic Impregnated Carbon Ablator
PSE	Power System Electronics
PVLP	Pioneer Venus Large Probe
Raman/LIBS	Raman/Laser Induced Breakdown Spectroscopy
RDM	Radiation Design Margin
RF	Radio Frequency
RPS	Radioisotope Power Systems
S-Band	2 to 4 GHz Communications Band
SAFT	SAFT Battery Vendor
SBC	Single Board Computer
Si	Silicon
SNR	Signal to Noise Ratio
TID	Total Ionizing Dose
TLS	Tunable Laser Spectrometer
TWCP	Tape Wrapped Carbon Phenolic
VEx	ESA Venus Express
VEXAG	Venus Exploration Analysis Group
VME	Venus Mobile Explorer
VOI	Venus Orbit Insertion
W	Watt
X-Band	X-band is 7.0 to 11.2 gigahertz
XRD/XRFS	X-ray Diffraction/X-ray Fluorescence Spectroscopy

APPENDIX B - REFERENCES

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