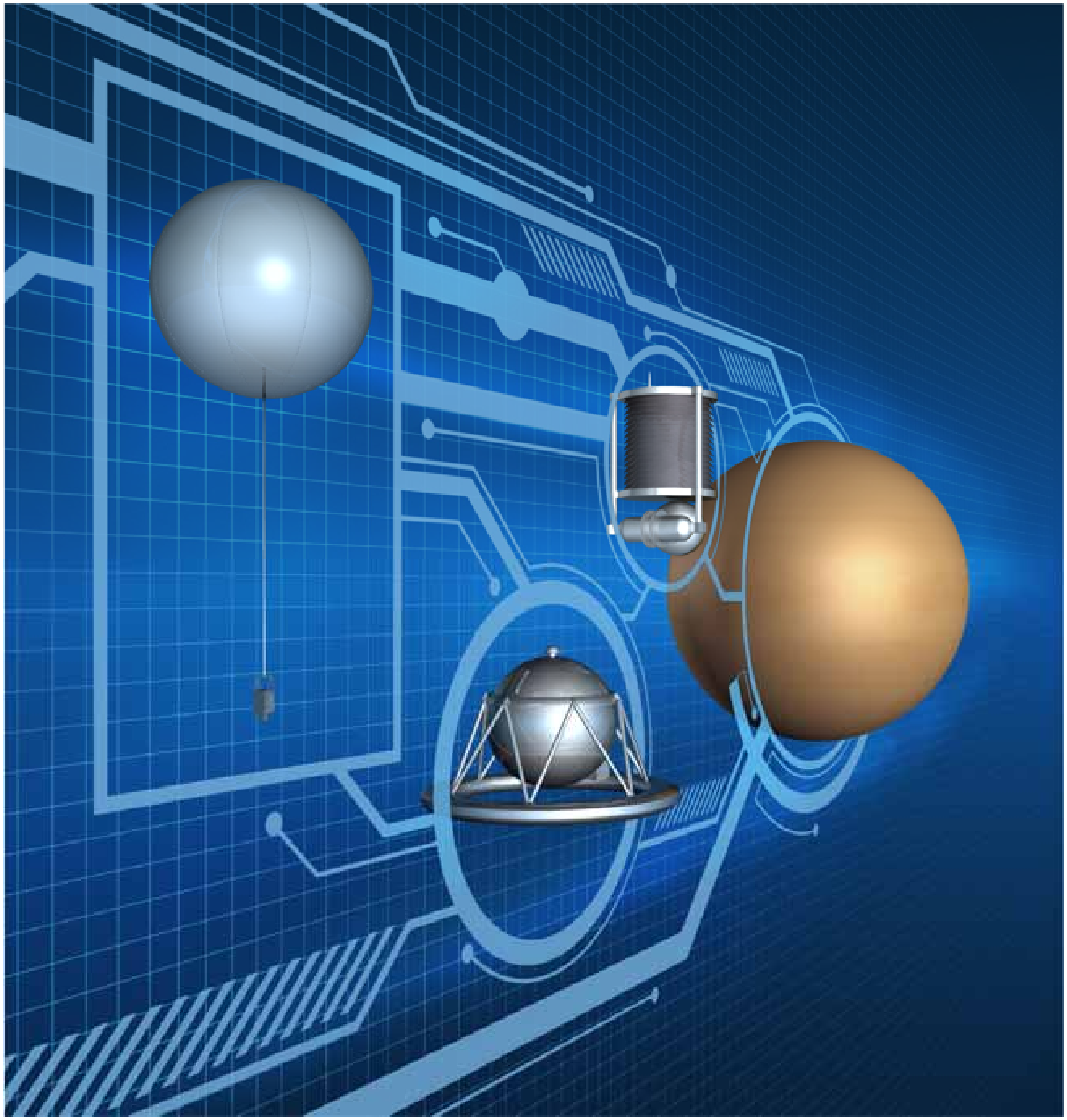
Venus Technology Plan

May 2014



At the Venus Exploration Analysis Group (VEXAG) meeting in November 2012 it was resolved to update the scientific priorities and strategies for Venus exploration. To achieve this goal, three major tasks were defined: (1) update the document prioritizing *Goals, Objectives and Investigations for Venus Exploration: (GOI)*, (2) develop a *Roadmap for Venus Exploration* (*RVE*) that is consistent with VEXAG priorities as well as Planetary Decadal Survey priorities, and (3) develop a Technology Plan for future Venus missions (after a Technology Forum at VEXAG Meeting 11 in November 2013). Here, we present the 2014 *Venus Technology Plan*.

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TABLE OF CONTENTS

VEXAG Charter. The Venus Exploration Analysis Group is NASA's community-based forum designed to provide scientific input and technology development plans for planning and prioritizing the exploration of Venus over the next several decades. VEXAG is chartered by NASA's Planetary Science Division and reports its findings to NASA. Open to all interested scientists, VEXAG regularly evaluates Venus exploration goals, scientific objectives, investigations, and critical measurement requirements, including especially recommendations in the *NRC Decadal Survey* and the *Solar System Exploration Strategic Roadmap*.

VENUS TECHNOLOGY PLAN

1.0 Executive Summary

The planet Venus, with its unique environment, presents unusual challenges for planetary exploration. A number of scientifically important missions could be implemented with existing technology although some may involve engineering development. More ambitious missions involving operations for extended periods in the atmosphere at or near the surface of Venus would require significant investments in new technologies; however, in some cases, these new technologies could leverage recent commercial developments. A potential Venus exploration technology program includes a balance of investments in missions for the short term and technology investments enabling these more ambitious missions that could be conducted in the medium and long term.

The following findings are based on the work discussed within this document, feedback from the Venus Technology Forum of November 19, 2013 and additional responses from members of the VEXAG community. The findings are grouped into two categories: Technology Development and Infrastructure Development. Each category is in priority order.

Technology Development

1. **Entry Technology for Venus:** The thermal protection system (TPS) technology developed for missions involving entry into the Venus atmosphere has not been used for many decades, and the ability to easily replicate it has been lost. Two attractive options for replacing the prior technology, 3D Woven TPS and Adaptable Deployable Entry and Placement Technology (ADEPT) technology, are currently under development under the sponsorship of the Space Technology Missions Directorate (STMD). These developments would not only enable the next generation of Venus entry missions but also promise to be a stable and enduring solution and one that is not prone to premature obsolescence. ***This development needs the continued endorsement of the Planetary Science Division (PSD).***
2. **High-Temperature Subsystems and Components for Long-Duration (months) Surface Operations:** Advances in high-temperature electronics and thermo-electric power generators would enable long-duration missions on the surface of Venus operating for periods as long as a year, where the sensors and all other components operate at Venus surface ambient temperature. These advances are needed for both the long-duration lander and the lander network. ***Development of high-temperature electronics, sensors and the thermo-electric power sources designed for operating in the Venus ambient would be enabling for future missions.***
3. **Aerial Platforms for Missions to Measure Atmospheric Chemical and Physical Properties:** Aerial platforms have a broad impact on exploration of Venus. After more than a decade of development, the technology for deploying balloon payloads approaching 100 kg with floating lifetimes in excess of 30 days near 55 km altitude is approaching maturity. Vehicles for operation at higher and lower elevations in the middle atmosphere and with the ability to change and maintain specific altitudes are much less mature and need development. A buoyant vehicle, operating close to the Venus surface requires major development. Aerial platforms would be an essential part of any atmospheric or surface sample mission. ***Development of aerial platform technologies is enabling for mid-term and far-term missions.***
4. ***In Situ* Instruments for Landed Missions:** Since the Planetary Science Decadal Survey in 2011, there has been significant progress in instruments for surface geology and geochemistry (e.g., laser induced breakdown spectroscopy [LIBS] in conjunction with remote Raman spectroscopy has been demonstrated). Advances in other instruments for "rapid petrology" also appear possible spurred in part by developments underway for investigating the surface of Mars. ***A workshop***

focused on instruments for Venus surface operations would be helpful for defining future directions, and such a workshop is planned for January 2015.

5. **Deep Space Optical Communications:** Development of deep space optical communications technology would enhance the performance of missions involving high resolutions radar imaging of the surface of Venus enabling mapping to be completed much more rapidly than with radio frequency (RF) communications systems. NASA STMD is currently developing the key component technologies for deep space communications and NASA's Space Communications and Navigations Directorate (SCaN) is planning on a 10-m optical ground station by 2015**.** ***Implementation of a flight experiment of optical communications would represent a major step forward in the adoption of the technology, and if implemented on a Venus orbiter mission, it could significantly enhance the science return.***

6. **Advanced Power and Cooling Technology for Long-Duration Surface Operations:** Most scientific objectives at the Venus surface required sensors that operate at temperatures well below 100^{o}C. Current passively-cooled systems are limited to a lifetime of 3 to 5 hours. Advanced liquid-vapor phase change cooling could extend lifetimes to 24 hours and could benefit the Tessera lander conceived as a mid-term mission. Highly efficient mechanical thermal conversion and cooling devices typified by the Stirling cycle-engines and capable of operating in a 460^{o}C environment are required for this purpose. With lifetimes of months, these are enabling the Venus mobile surface and near-surface laboratory mission concepts. ***Investments in advanced power and cooling technology are needed to enable both mid-term and far-term missions.***

7. **Advanced Descent and Landing:** Lander missions for the mid-term would target the Tessarae regions of Venus which radar imaging indicates to be extremely rough and irregular topography. Following the Mars model, achieving safe landings in regions of complex topography will require the development of improved targeting accuracy and precision landing techniques potentially accompanied by hazard avoidance during the terminal-descent phase. ***New concepts are needed for adapting methods of terrain relative navigation and guidance to operation in the dense Venus atmosphere.***

Infrastructure Development

1. **Ames Research Center (ARC) Arc Jet Interaction Heating Facility (IHF) Facility Enhancement:** A new 3-inch nozzle funded by the NASA Science Mission Directorate (SMD) has been installed at the NASA ARC IHF arc jet facility enabling testing of thermal protection materials under Venus relevant testing conditions. ***This enhanced IHF facility will play a vital role in maturing the High Energy Entry Technology (HEEET) for use in a Discovery or New Frontiers mission to Venus.***

2. **NASA Glenn Research Center (GRC) Extreme Environment Rig (GEER):** The NASA GRC GEER (currently under development) is an important step forward. ***PSD now needs a plan for effective use of this facility.***

3. **Instrument Chamber Enhancements:** ***The Venus facilities at Goddard Space Flight Center and Jet Propulsion Laboratory (GSFC and JPL) should be maintained and enhanced according to community needs and requirements.***

4. **Environmental Modelling and Simulation:** Test chambers are a vital element of advancing both science and technology modelling capabilities for Venus, but they require modelling of environments to ensure that the results of the tests can be applied effectively to operations in the natural environments. Considerable expertise has been developed at NASA Ames Research Center and NASA Langley Research Center in modelling of entry environments. ***It is necessary***

to sustain the entry work but also to develop modelling capabilities incorporating the physics and chemistry of gases at the conditions of the Venus surface.

2.0 Overview

This is the third in a series of three documents prepared by the Venus Exploration Analysis Group (VEXAG) to provide NASA's Planetary Science Division with the a basis for formulating a strategic direction for future Venus exploration. The *Venus Goals, Objectives, and Investigation* document [1] establishes the scientific goals for Venus exploration, and it prioritizes the objectives and investigations needed to address those goals. The *Roadmap for Venus Exploration* (*RVE*) [2] translates these objectives into mission modes that can most effectively address the objectives and implement the investigations. The *RVE* also re-examines the recommendations in the *Planetary Science Decadal Survey* [3] to provide an assessment of the state of technical readiness for implementing missions using these different mission modes. The present document, the *Venus Technology Plan*, draws information from both of the prior documents (but primarily the *RVE*) and performs a more detailed assessment of the technologies that require NASA investment and how those investments should be directed.

3.0 Venus Exploration Challenges

While there is a long history of Venus exploration, there has been no dedicated United States mission to Venus since Magellan ceased operations in September 1994.

3.1 Venus Environment

The Venus environment poses varied challenges for robotic exploration missions:

1) The orbital thermal environment is stressing as a result of the high solar reflection from the Venus clouds, but it is a much less challenging environment than Mercury orbits.
2) During planetary atmospheric entry, the velocity and thermal conditions are more severe than for entry at Earth or Mars with conventional aeroshells (but less than Jupiter entry).
3) Once in the atmosphere, missions operating high in the atmosphere can experience a benign environment in terms of temperature and pressure but are exposed to the harsh, chemically reactive environment that is maintained in the sulphuric acid clouds.
4) Descent and landing on Venus is helped by the dense atmosphere, which simplifies both the initial parachute phase and the terminal descent relative to comparable phases at Mars.
5) Surface operations using conventional electronics and passive thermal control systems are limited to a few hours. Long-duration missions require components and packaging that will function at Venus ambient pressure and temperature and/or have active thermal-control systems.

3.2 Spaceflight Heritage and Mission Modes for the future

More than 30 spacecraft have flown to Venus since Mariner 2 flew by the planet 50 years ago (Fig. 3-1). These missions have included flybys, orbiters, probes, short-lived landers, and balloons. All of the *in situ* missions occurred in the first 25 years. The Magellan orbital radar mission, which was completed in 1994, and the European Space Agency's (ESA's) Venus Express which is still operating at Venus after 7 years in orbit, have ensured that Venus observational science from spacecraft have continued. The absence of recent in-situ missions has resulted in loss of some of the technical capabilities important in Venus exploration. Some capabilities are not easily reproduced. However, the early successes provided a proof of principle that orbiters, probes, short-lived landers, and balloons can be successfully deployed at Venus.

Several assessments of Venus technology have been conducted in recent years. In 2006, NASA's *Solar System Exploration Roadmap* [4] included a Venus Mobile Explorer mission and an extensive discussion of the required technology for this mission. In 2007, an assessment of extreme environments technologies for planetary exploration was conducted under the leadership of Jet Propulsion Laboratory (JPL) [5]. This was followed by a monograph focused specifically on Venus technologies [6]. In April 2009, the Science and Technology Definition Team (STDT) for the Venus Flagship Mission [7] conducted an assessment of not only the new technology requirements for the Design Reference Mission but also the mission and payload enhancements for a mission with greatly enhanced science return. Finally, in September 2009, members of VEXAG submitted a white paper [8] to the Planetary Science Decadal Survey on technologies for future Venus exploration. These are all important sources for this document. However, the present *Venus Technology Plan* is guided by the specific recommendations of the 2013 Venus Exploration Roadmap Topical Analysis Group and the *Venus Goals, Objectives, and Investigations* document.

VEXAG's Venus Exploration Roadmap Topical Analysis Group has identified a number of mission modes generally involving different types of instrument-carrying platforms that will be needed to conduct the comprehensive investigation of Venus described in the Roadmap for Venus Exploration. These mission modes require different degrees, and types of, technology. Later in this document we describe the technologies that are needed to enable each of the mission modes.

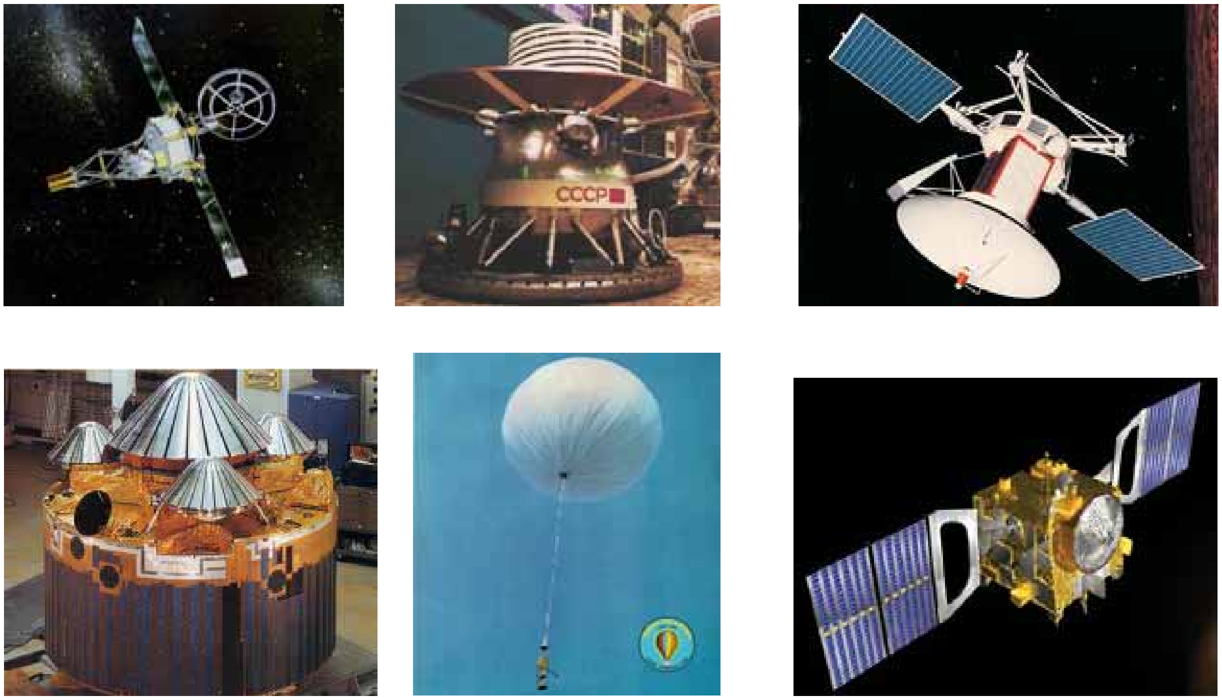

Fig. 3-1. Historical set of Venus missions: Mariner 2 (NASA), Pioneer Venus probe (NASA), Venera X (USSR), VeGA (USSR), Magellan (NASA) and Venus Express (ESA).

4.0 Technology Plan Overview

A summary assessment of the technologies needed for the Roadmap mission modes appears in Table 4-1 (also see Figs. 4-1 and 4-2). The time frame in which each of these technologies is needed is indicated in the second column: N is Near Term (this decade), M is Mid-Term (next decade) and F is Far-Term (beyond the next decade).

A more detailed description of the technologies needed for individual mission modes appears in Sections 5, 6, and 7 and is summarized in Table 4-2A and 4-2B. The technologies are organized into three categories: systems technologies (Section 5) apply at the scale of the spacecraft; subsystems technologies (Section 6) include particularly important components of these systems; science instruments (Section 7) must generally be tailored to the unique conditions at Venus.

In Tables 4-2A and 4-2B, we have characterized the maturity of each technology with respect to the mission mode with a color code, which is explained in the legend. For near-term missions (this decade), technology maturity is very high (green) or high (yellow); for mid-term missions maturity (early in the next decade) it is typically moderate (orange), and for far-term missions (later than next decade) it is typically low (red). For those technologies in the yellow category we have indicated with an up arrow where a funded program exists to bring the technology to full readiness within 1 to 4 years.

Table 4-1. Framework for assessing technologies for Venus exploration.

	Technology Area	Time Frame	Assessment
	Aerobraking and Aerocapture	**N, F**	Aerobraking is a mature technology. Aerocapture requires development but is only needed for far-term missions.
System Technologies	**Entry, Descent, and Landing**	N,M,F	Woven TPS or deployable technologies are needed for entry at Venus since the entry technology used on the Pioneer Venus missions can no longer be replicated. Descent and landing is easier than for Mars. Landing on the plains is an engineering issue. Landing on the tessarae requires new technology because of the complex topography.
	Aerial Platforms	N,F	Technology for near-term missions is mature. Near surface aerial capabiity would be one option for the "regional mobility platform" and does require substantial investment.
	Landed Platforms	N,M,F	Three classes of landed platform will be needed of increasing technical challenge: short duration containing analytical instruments (near term, current technology), long duration with geophysical sensors (mId term) and long durations with a complex instrument suite and surface mobility (far term).
	Ascent Vehicles	F	Ascent vehicles are only needed for Venus sample return. This is a very immature technology and much more demanding than for Mars surface sample return. Some concepts for Venus Surface sample return require the Venus Ascent Vehicle to descend to the surface.
Subsystem Technologies	**Power**	M,F	Thermoelectric generators capable of operating in a 460°C environment are needed for mid-term missions. For some far-term missions, the efficiency of a mechanical converter (e.g., Stirling cycle is essential.
	Thermal Control	M,F	Extending life by a factor of 10 (to 25 hours) is feasible in the mid-term with with passive cooling. Active cooling using mechanical coolers is essential for vehicles that must operate for periods of weeks to months with their payloads at Earth ambient.
	Extreme Environments	N,M,F	Advances in high-temperature mechanisms would be enhancing for a first-generation lander. High-temperature electronics would be needed for the geophysical platform.
	Communications	N,M,F	Optical communications would be enhancing for an orbital radar mission. Proximity communications are needed to enhance data return from all *in situ* missions
	Guidance, Navigation, and Control	M,F	Miniaturized low power systems are needed for localization and attitude knowledge on probes, aerial platforms, dropsondes and for pinpoint landing in the Venus tessarae.
Instruments	**Orbital Remote Sensing**	N	Technology for implementing these missions is here today. Advances in radar and infrared techniques would be enhancing.
	Probe and Balloon	N,M,F	Instruments for middle atmosphere exist but should be miniaturized. Sensors for chemistry in the lower atmosphere need improvement.
	Surface *in situ*	N,M,F	Need technologies in near term for "rapid petrology". In mid term, need geophysical sensors that operate at Venus ambient. In far term, need totally new approaches for mobile laboratory.

Table 4-2A: Mission modes and applicable technologies for near-term missions.

	Mission Mode	Near-Term Missions						
		Radar Orbiter	Remote Sensing Orbiter	Aerial Platform Sustained	Deep Probe	Multiple Shallow Probes	Multiple Shallow Sondes	Lander - Smooth Terrain
	Aerobraking	🟩	🟩					
	Entry			⬆	⬆	⬆		⬆
	Descent and Deployment			🟩	🟩	🟩	🟩	🟩
	Landing							🟩
	Aerial Platforms			🟩			🟩	
	Landers - Short Durations							🟩
Subsystem Technologies	Energy Storage- Batteries	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	Energy Generation - Solar	🟩	🟩	🟨				
	Thermal Control - Passive					🟩	🟩	🟩
	High temperature mechanisms							🟨
	High temperature electronics							🟩
	Communications			🟩	🟩	🟩	🟩	🟩
	Guidance, Navigation and Control			🟩				
Insutrument	Remote Sensing - Active	MM	MM					
	Remote Sensing - Passive	MM	MM					
	Probe - Aerial Platform			MM	MM	MM	MM	
	In Situ Surface - Short Duration							🟨

🟩	Very High. Ready for flight. Same as TRL 6	🟨	High. Limited development and testing still needed
MM	Mix of Maturity. Some ready for flight but others at various maturity levels	⬆	High. Funding is in place to advance to Very High in one to four years

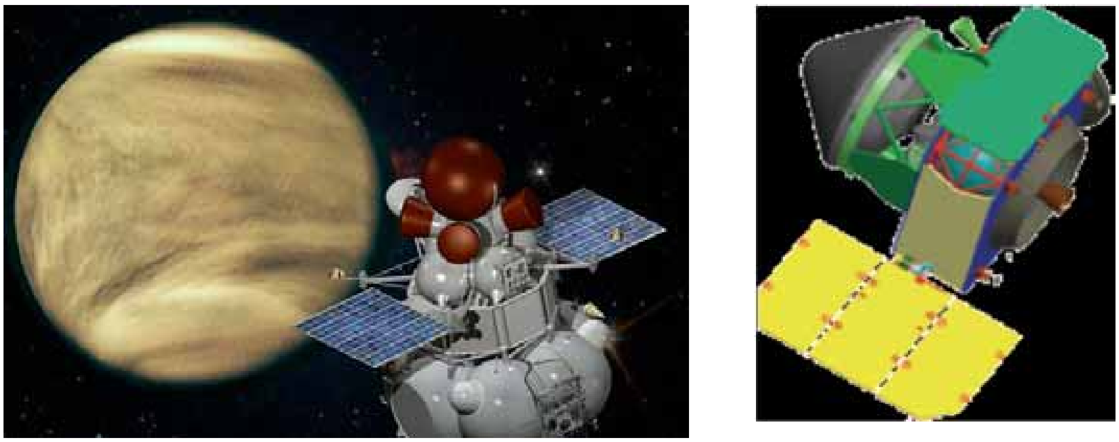

Fig. 4-1. Artist's concepts of the near-term Venera-D and Venus Climate Mission.

Table 4-2B. Mission Modes and applicable technologies for Mid-Term and Far-Term Missions

		Mission Mode	Mid-Term Missions				Far-Term Missions				
			Lander Rough Terrain	Lander Long Duration	Multiple Deep Probe	Mutli Deep Sondes	Lander Network	Mobile Surface	Mobile Near Surface	Sample Return Clouds	Sample Return Surface
Applicable Technologies	System Technologies	Aerocapture								🟧	🟧
		Entry	🟨	🟨	🟨⬆		🟨	🟨	🟨	🟧	🟧
		Descent and Deployment	🟧	🟩	🟩	🟩	🟩	🟨	🟨	🟨	🟥
		Landing	🟧	🟨			🟩	🟧			🟥
		Aerial Platforms				🟨⬆			🟧	🟧	🟥
		Landers - Short Durations	🟩								
		Landers Long Duration - Geophysica		🟧			🟧				
		Mobile Platform - Surface or near surface						🟥	🟥		
		Ascent Vehicle								🟥	🟥
	Subsystem Technologies	Energy Storage- Batteries	🟩	🟧	🟩	🟩	🟥	🟥	🟥		🟥
		Energy Generation - Radioisotope Power		🟧			🟧	🟥	🟥		
		Energy Generation-Alternative Sources		🟧			🟧	🟥	🟥		
		Thermal Control - Passive	🟧	🟧	🟧	🟧					🟥
		Thermal Control - Active					🟥	🟥	🟥		
		High temperature mechanisms	🟨	🟧			🟥	🟥	🟥		🟥
		High temperature electronics	🟩	🟧			🟥	🟥	🟥		🟥
		Communications	🟩	🟧	🟩	🟩	🟥	🟥	🟥		
		Guidance, Navigation, and Control	🟧	🟧		🟧	🟥	🟥	🟥		
	Insutrument	Remote Sensing - Active							🟥		
		Remote Sensing - Passive							🟥		
		Probe - Aerial Platform			🟩	🟩				🟧	
		In Situ Surface - Short Duration	🟨								🟧
		IN Situ Surface - Long Duration - Geophysical		🟧			🟥				
		In Situ Surface - Long Duration - Mobile Lab						🟥	🟥		

🟩	**Very High. Ready for flight. Same as TRL 6**	🟧	**Moderate. Major R&D effort needed.**
🟨⬆	**High. Funding is in place to advance to Very High in 1-4 years**	🟥	**Low. Major R&D effort needed with notable technical challenges.**
🟨	**High. Limited development and testing still needed**		

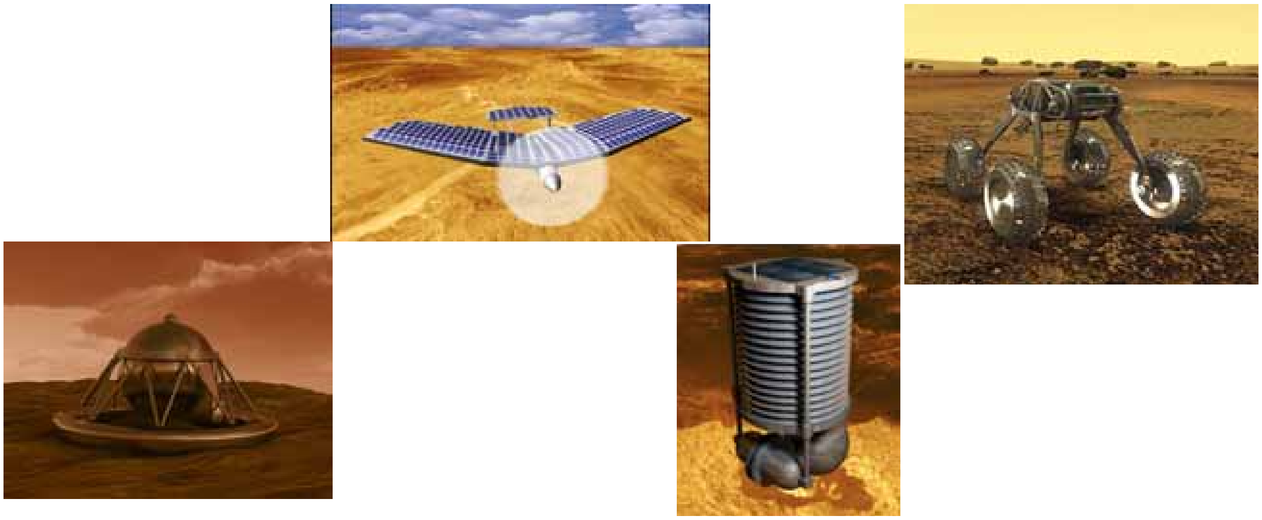

Fig 4-2: Artist concepts of future mid-term and far-term Venus missions.

5.0 System-Level Capabilities

System-level capabilities are typically at the level of the mission modes described in the *RVE*. It is important to recognize that these capabilities cannot be considered in isolation. These system-level capabilities will generally flow down to one or more subsystem technologies described in Section 6.0.

5.1 Aerobraking

Aerobraking technology uses atmospheric drag to modify the orbit of a spacecraft incrementally as the spacecraft dips into the tenuous reaches of the upper atmosphere of the planet. Aerobraking was employed on the Magellan mission to lower the spacecraft orbit to a configuration more suitable for radar mapping, and it was used later in the mission to circularize the orbit for gravity observations. Aerobraking has been used for obtaining circular orbits on Mars missions.

ESA's Venus Express will perform a number of aerobraking maneuvers largely motivated by the need to characterize variability in the upper atmosphere. The *RVE* identifies mission modes – two near-term orbital missions that might benefit from aerobraking. The technology is mature, but the spacecraft design (and particularly that of the solar panels) must be compatible with the Venusian heat and stresses generated. Measurements from Venus Express during aerobraking maneuvers will be relevant to future use of aerobraking at Venus and specifically to how aggressively the maneuvers can be executed to reduce the time needed to achieve the desired orbit.

5.2 Aerocapture

Aerocapture technology is similar, in some ways, to aerobraking technology. The key difference is that the objective is to achieve orbital capture, and this requires a larger velocity change than aerobraking. Specialized drag and lifting structures, essentially identical in nature to those discussed in the Subsection 5.3 on entry technology, are employed. Aerocapture has not yet been employed on a planetary mission, and none of the near-term or mid-term Mission Modes in the *RVE* require aerocapture. However, for Venus Surface Sample Return, the spacecraft that brings the sample back to Earth needs to be in a low near-circular orbit to minimize demands on the sample ascent stage from Venus, and aerocapture could be highly beneficial in achieving this orbit.

5.3 Entry

Entry technologies are needed for implementation of all mission modes designated in Table 4-1 except for remote sensing missions. Although successful entry at Venus has been accomplished many times by Soviet, and later Russian landers, and by both a large probe and three smaller NASA probes, some of the thermal protection technologies used in those NASA missions are no longer available. Several alternative approaches have been identified with the following has been or is under development:

1. *Heritage Carbon Phenolic*: This solution requires a descent into Venus at high entry angles to mitigate the cumulative heat load imposing high-g loads on payloads [9]. Attempting to replicate the material used in previous Venus missions is one approach. Its advantage is that it has been proven to work. The shortcoming is that it would be extremely challenging to reproduce a similar family of materials as the manufacturing processes have atrophied. Consequently, raw material is no longer available, and it would be expensive to qualify replacement materials. Moreover, this solution is prone to premature obsolescence.
2. *3-D Woven Thermal Protection System (Fig. 5-1)*: The use of 3-D woven materials infused with resin to withstand a broad range of entry environment to result in mass-efficient ablative thermal protection system (TPS) is currently under development by NASA's Space Technology Mission Directorate (STMD) and has the potential for infusion into missions in the next few years. The properties of this manufacturing technique permit the ablative TPS to be tailored to a preferred trajectory dictated by Venus missions and thereby reducing the entry environment (heat-flux,

pressure, and g-load). A currently funded development will result in demonstrating a small 1.5-m aeroshell scalable to much larger aeroshell diameters. This development is considered to bring the state of development of the larger aeroshell needed for a Venus lander to a technology readiness level (TRL) 5/6 by the end of fiscal year 2016 (FY'16). Thus, while the current state of readiness is yellow, the up arrow indicates the projected progress in the next few years (given adequate funding) will raise it to mission infusion readiness. A key part of the plan is to use the new testing capabilities funded by the NASA Science Mission Directorate (SMD), which make it possible to test material samples under the severe conditions of Venus entry.

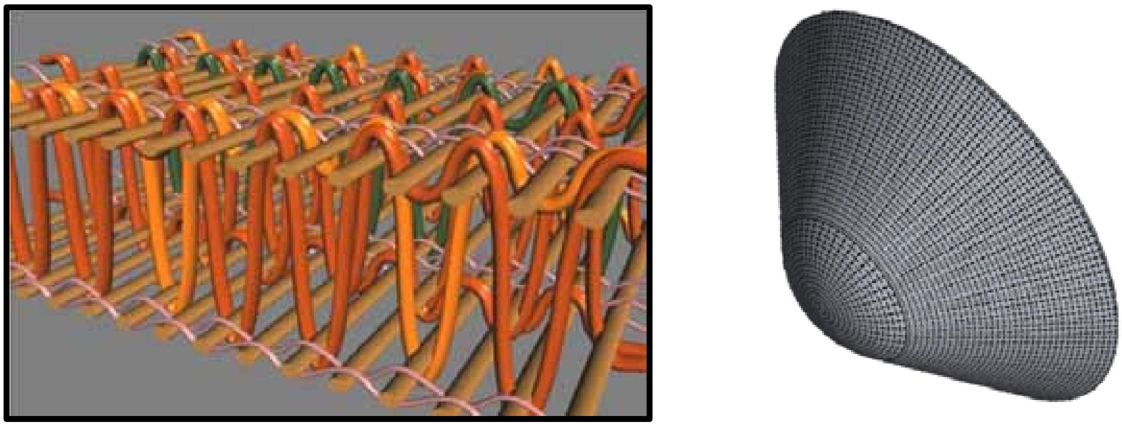

Fig. 5-1. High Energy Entry Environment Technology (HEEET) employs a woven thermal protection system material (left) with the flexibility to be fashioned into the curved protective surface of an aeroshell (right).

3. *Adaptable Deployable Entry and Placement Technology (ADEPT) (Fig. 5-2):* This approach involves reducing the ballistic coefficient of the payload by an umbrella-like deployment of a large-area heat shield. The ADEPT Full Scale Demonstrator Project, which is an STMD Game-Changing Development (GCD) Program-funded new start project in FY'14. This is focused on the design, development, and integrated ground test of a 6-m mechanically deployed decelerator capable of delivery of payloads as massive as 1000 kg (while keeping peak deceleration loads below 30 g's). The ADEPT system decelerates much higher in the atmosphere and results in much lower peak heating. As such, no advanced thermal protection material development is needed, and testing is well within the range of existing facilities [10]. There are also inflatable versions of the ADEPT approach – the Hypersonic Inflatable Aerodynamic Decelerator (HIAD), which have been tested in Earth re-entry tests. A concept for a Venus Atmospheric Maneuverable Platform (VAMP) envisages using an inflatable structure for entry and flotation [11].

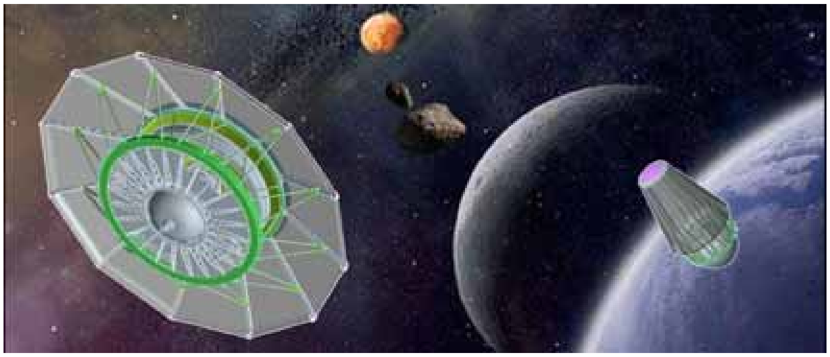

Fig 5-2. The ADEPT heat shield deploys in umbrella-fashion from the folded condition on the right to the fully deployed state at left.

5.4 Descent and Deployment

Descent/deployment capabilities are relevant to the same mission modes as for entry. For probes and landers, it is necessary to control the rate of descent and stabilize vehicle attitude during its passage to the surface through a progressively denser atmosphere.

For a probe mission, velocity and probe attitude must be controlled during descent to provide adequate time to sample the different regions of the atmosphere, while limiting the dwell time at altitudes where the environment is harsh (e.g., hot and corrosive). This may require different sizes of parachutes or other aerodynamic structures. Special materials must be used to accommodate the high temperature and acidity of the atmosphere, but these materials are available. For a landed mission, the objective is usually to bring the vehicle to the surface as quickly as possible to minimize the thermal input to the landing module. Maintaining attitude stability and minimizing jitter during descent is important to acquire images during descent with minimal motion blur. These are engineering challenges with no new technology required.

For aerial platforms it is necessary to establish the conditions required for successful deployment of these vehicles. A successful balloon deployment and inflation test was conducted in the Earth's atmosphere during parachute descent at a velocity of 6.5 m/s [12]. This descent velocity is readily achievable for deployment in the mid-cloud level of the Venus atmosphere (57–65 km). The needed descent velocity for airplane deployment is dependent of the specific design of the aircraft, but again the dense atmosphere is favorable.

Drop-sondes deployed from an aerial platform could be used to sample the atmosphere in multiple locations. Deep drop-sondes, which are able to descend close to the surface, could be used in conjunction with the platforms that deploy them to relay large amounts of high-resolution imaging data on potential landing sites but would require technology development in order to generate images near the surface.

5.5 Landing

Landing on Venus is much more benign than landing on Mars. The *RVE* calls for the near term (current decade) capability of landing on the smooth terrains, similar to where the previous Venera landers were successfully deployed. Landed missions to much rougher terrain, the tesserae, which have not yet been explored, are deferred to the mid-term.

There are two general approaches to the challenge of landing on the rough terrain. One is to make the lander system robust to all possible eventualities. This is not just about surviving but also being positioned on the surface to carry out the science mission; a vehicle that tips over and prevents its sampling arm from reaching the surface may result in mission failure. The other approach is to find a safe area within the general area of challenging terrain and target that safe area. This second approach is the generally preferred approach—as it is for landing on Mars and Europa, as recent analyses have shown. It would also enable improved science through precision targeting.

For a mid-term mission, it would be feasible to draw on the ***pin-point landing*** and ***hazard avoidance technologies*** that have been developed by the Mars program and also by the Space Technology Mission Directorate (STMD) under the Autonomous Landing and Hazard Avoidance Technology (ALHAT) program [13].

1) ***Pin-Point Landing*** involves guiding the vehicle to a designated point on the surface by correlating images obtained from the lander as it descends with a map of the Venus surface. For Venus, the descent images would probably be acquired in the infrared. The reference map would be based on radar—either from Magellan or a new mission. Using heterogeneous data sets like this has been studied and appears feasible. The control function would be quite different from landing on Mars and would use a steerable parachute and not propulsion. This approach is not new and has been used in precision drops from aircraft for several decades. However, for Venus it

would be necessary to study how large an initial landing error could be compensated for and how precise the ultimate landing could be. The state of readiness is characterized as yellow.

2) ***Hazard Avoidance,*** which could be used independently or in combination with pin-point landing, is a different concept. It uses would use surface information (imaging, LIDAR, and radar) during the final stages of descent to identify areas of hazard and to avoid them. For an unknown surface like Venus, knowledge of what the hazardous areas on the surface look like and what dangers exist would be valuable. Once that knowledge exists, it also makes it possible to design robust and resilient landing systems.

5.6 Aerial Platforms

The Roadmap finds that aerial platforms (Fig. 5-3) are “generally at an advanced state of readiness” although they may require improvements in instruments, power, communications, and support capabilities for specific mission architectures. Some of those needed improvements are identified here and elaborated upon in parts of Section 6 .0 Subsystems and Section 7.0 Instruments.

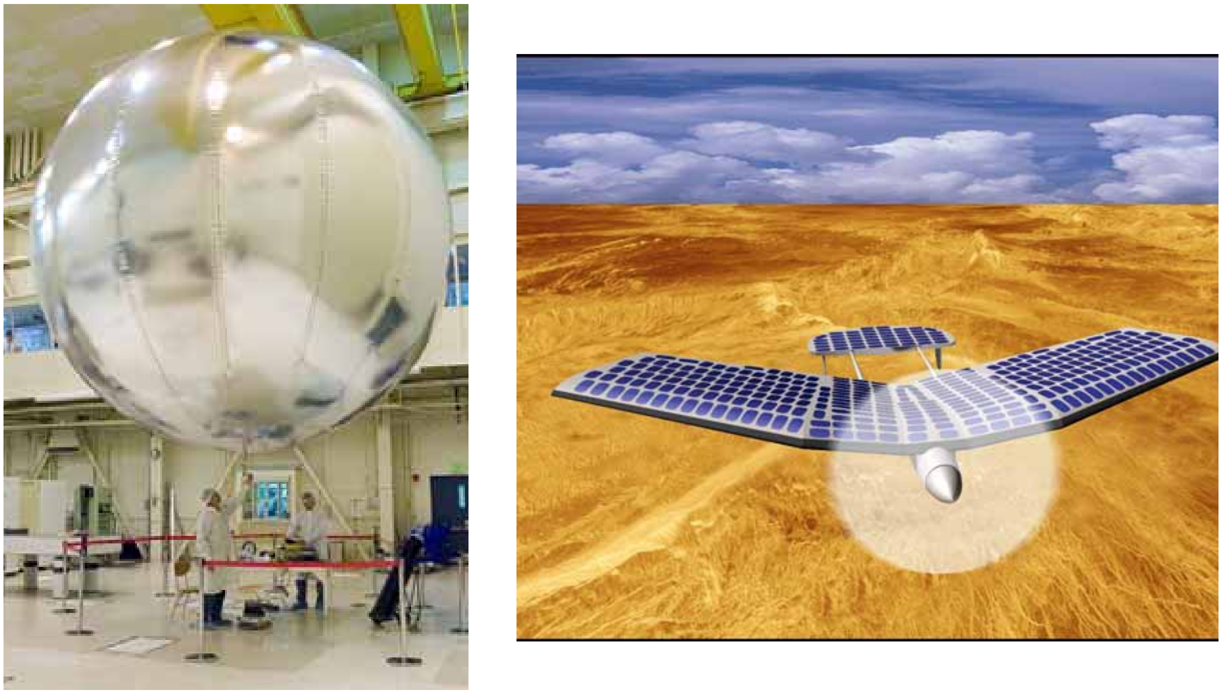

Fig 5-3: The most mature aerial platform concept is the super-pressure balloon concept (left). Solar powered conceptual airplanes (right) have been proposed for controlled flight on the day-side of Venus.

The most mature aerial platform designed for operation near 55 km is the *super-pressure balloon*. Two 3.4-m diameter helium super-pressure balloons were successfully deployed and flown in June 1985 by the Soviet Union. Each balloon returned *in situ* measurements for about 48 hours. It was tracked by an international consortium, led by the Soviet Union and France, and in which NASA participated. Over the last decade, work at NASA and to a lesser extent at ESA, has focused on balloons with a larger payload capability and a potential life time of several months [14]. The technology for a Venus balloon with a payload capacity of 45 kg has been demonstrated and is ready [12] to fly. Development of a larger 7-m balloon with a 100-kg capability is under way and should be complete by 2015.

Approaches for accessing higher parts of the atmosphere (~65km) focused on identifying the nature of the ultraviolet absorber were discussed at a Science and Technology Interchange Meeting (STIM) on the Venus Upper atmosphere that was held in January 2013 at the Glenn Research Center [15] and included advanced balloon concepts for higher altitude flight on Venus, solar powered airplanes, and hybrid blimps [16]. Buoyant vehicles that could operate in the lower atmosphere are considered below under *Mobile Platform at or Near Surface.*

Subsystem developments that could enhance the performance of a balloon include wind assisted balloon navigation and autonomous on-board landmark-based navigation. They require advances in on-board guidance and control.

5.7 Lander Platforms

5.7.1 Landers – Short Duration

During the 1970s and 1980s, the Soviet Union successfully landed seven probes (Venera 8, 9, 10, 13, 14, and VEGA 1 and 2) that operated on the surface of Venus for periods of 1 to 2 hours and returned images as well as other scientific data. This was accomplished with thermally insulated vehicles that maintained imaging sensors, communications systems, computers, and energy storage systems at temperatures below 100°C. The vehicles consisted of insulated pressure vessels, which also contained solid-liquid phase-change material (PCM) to extend surface lifetime. Deployment of similar short-duration missions using passive thermal control, which can survive on the surface of Venus for a period of hours, is viewed as an engineering development rather than a technology development.

Work in the last 5 years, has opened up the possibility of extending the lifetime of these landers by an order of magnitude to 20 to 25 hours—making it possible to carry out missions in which scientists have time to respond to the data and make decisions on limited follow-up observations rather than a totally autonomous mission of 2 to 3 hours duration. These technologies include the use PCMs employing the liquid-vapor transition in water and ammonia [17]. These technologies are unlikely to be demonstrated for a mission in this decade but should certainly be considered, and developed if deemed feasible, for a mid-term lander mission to the Venus tesserae.

5.7.2 Landers – Long Duration – Geophysical

The Venus Exploration Roadmap specifies the need for a platform in the mid-term that would investigate the structure of Venus’s interior and the nature of current activity, and it would conduct the following measurements:

a. Seismology over a large frequency range to constrain interior structure;

b. Heat flow to discriminate between models of current heat loss;

c. Geodesy to determine core size and state and

d. Electromagnetic (EM) sounding to constrain gross interior layering. The specified mission mode is a geophysical lander with a life-time of ~1 Venusian year.

The technical feasibility of a mid-term mission mode that could conduct long-term precision geophysical measurements in the high temperature Venus environment is highly uncertain. Two approaches might be considered:

1) ***Active Cooling*****:** This approach would involve active cooling of the lander with Stirling power generation and refrigeration. The technical challenges are formidable and, in addition, would require a large amount of radioisotope material. It is a more realistic target for the far-term.

2) ***High Temperature electronics*****:** This approach has more promise for mid-term missions. The key question is whether measurements of adequate sensitivity could be made. This topic is examined in Section 7.4. If the scientific requirements were relaxed, this approach could be feasible

Power for this mission mode could be provided by radioisotope power using a thermoelectric transducer exploiting the Peltier effect. Although currently available Multi-Mission Radioisotope Thermoelectric Generators (MMRTGs) are not designed to operate in this environment, there are thermocouples that are capable of operating very efficiently under conditions where the cold junction of the devices is at Venus surface ambient temperature.

5.7.3 Mobile Platform – Surface or near surface

The RVE calls for a mobile platform (Fig. 5-4) that would operate on the surface or in the lower atmosphere with a mobility range of tens to hundreds of kilometers to analyze surface compositional variations on a regional scale. Instruments on this platform would conduct geochemical and mineralogical measurements at multiple sites, undertake remote sensing from low altitudes (<1 km), and provide panoramic and high-resolution images correlated with composition.

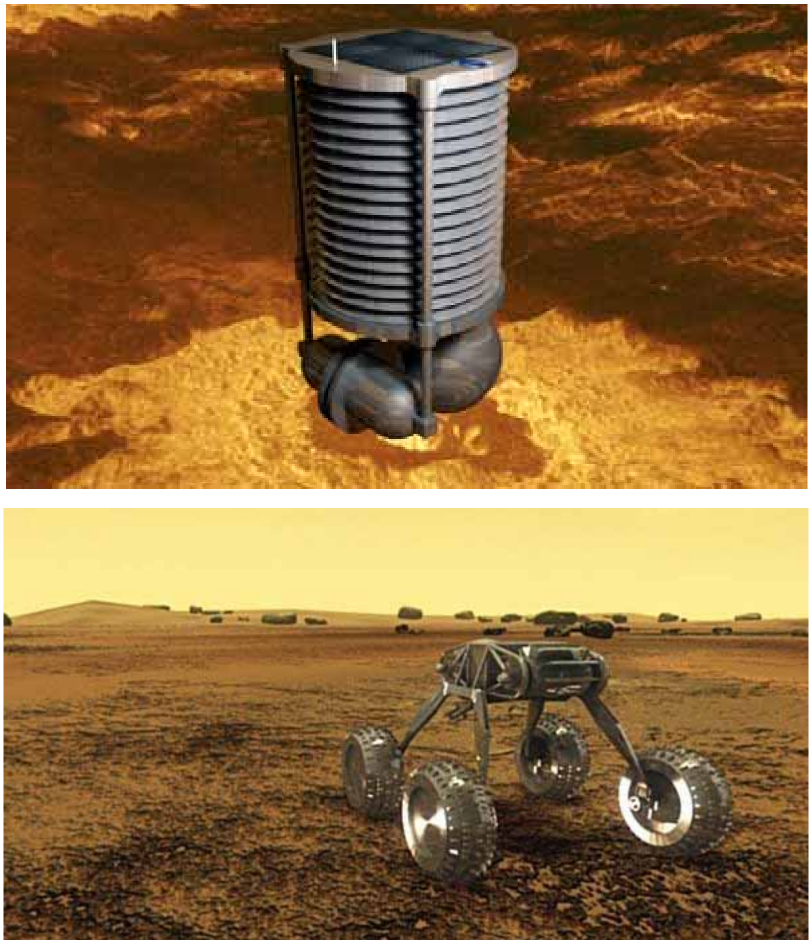

Fig 5-4: These concepts for regional surface exploration would float above the surface in the dense atmosphere (top) or employ a conventional wheeled vehicle (bottom).

Unlike the geophysical landers discussed above, these systems must include payload compartments maintaining temperatures at or below Earth ambient for imaging instruments. Achieving high fidelity, visible imaging, and remote sensing infrared measurements often requires cooling sensors to well below Earth ambient temperature. Operation at Venus surface temperatures would require sensors unlike any available today and may be limited by fundamental physics. Other instruments may be operable in the range 150° to 200°C. Both power and cooling systems that can operate at Venus temperatures would need to be developed.

The mobility range for such vehicles is a lesser challenge, although still formidable. Concepts for floating platforms capable of traversing the altitude range of the Venus surface and hence accessing all terrain types have been devised; however, the near surface conditions on Venus are not well known. Wheeled or legged vehicles require many more mechanisms that would be vulnerable to the conditions near the surface and issues of long-term exposure to the corrosive conditions of the near surface would need to be explored. Attaining the designated 10- to 100-km range would be challenging.

5.8 Ascent Vehicle

The RVE has identified Venus Surface Sample Return (VSSR, Fig. 5-5) as a long-range objective. Past studies of VSSR [18] have used architectures modeled on Mars Surface Sample Return in which a sample canister would be brought from the surface to Venus orbit where it is captured by an orbiting vehicle. Since the planet Venus is comparable in size with the Earth, injecting that sample from the atmosphere to Venus orbit would be comparable to doing the same thing on Earth. The referenced VSSR design concept includes a 2-kg sample canister and a three-stage launch system with a mass of approximately 500 kg and providing a total delta V of almost 8.5 km/s. The concept is at a very low level of maturity and is not likely to advance before there is progress in the development of ascent vehicles for Mars Surface Sample Return, which is a much easier task. Note also that the ascent vehicle is one of several technologies in the red category for the VSSR mission.

A more tractable sample return objective for Venus would be a cloud sample from the “habitable zone” near 55-km altitude. This could be viewed as an initial step towards an ultimate surface sample return. However, so formidable are the technical challenges of VSSR that other approaches to achieving the scientific objectives should be considered.

***Fig 5-5: Artists concept of Venus surface sample*.**

6.0 Subsystem Technologies

This section focuses on those subsystem elements that are critical to the implementation of the systems solutions discussed above.

6.1 Power Subsystems

6.1.1 Energy Storage – Batteries

Of the mission modes described in Table 4-1, many could be implemented successfully with existing technology from orbiter, balloon as well as probe and lander missions. Long-duration landers are one area where technology development may be needed. If long-duration landers could be implemented with sufficiently low-power consumption, then batteries may be a reasonable option; this trade needs to be examined. Secondary batteries may also be required to handle peak loads in conjunction with a robust radioisotope power system.

6.1.2 Energy Generation – Solar

Remote sensing from space with orbital or flyby missions could be implemented with existing capabilities. Solar power is not needed for short duration probes or landers but may be a viable for long-lived aerial platforms designed to float within the clouds. For landers deployed on the surface, the amount of solar energy reaching the surface is limited, and the challenges of developing efficient energy converters to operate at these temperatures are so formidable that solar energy is not a practical solution. Solar cells that operate at higher temperatures generally do so at the expense of only sensing blue and ultraviolet radiation, and very little radiation of these wavelengths penetrates to the surface of Venus.

Advances in solar power technology could be enabling for aerial platforms for operation within or above the clouds. Airplanes require efficient, lightweight, and acid-resistant panels clad on both sides of the deployable wings of an airplane. Long-duration balloons are less demanding since no power is needed to maintain lift, but very lightweight, acid-resistant systems are needed to minimize the payload mass.

6.1.3 Energy Generation – Radioisotope Power

Radioisotope power could play an important part in the *in situ* exploration of Venus. Near the surface there is very little solar power for a long-duration mission. Floating platforms could benefit from radioisotope power on the night side of Venus (although trades with battery options are needed), and as these platforms approach the polar vortex, radioisotope power could extend operations.

1) ***Advanced Stirling Radioisotope Generator (ASRG):*** A highly efficient Stirling engines coupled with linear alternators to convert radioisotope heat to electrical energy. This technology could be implemented on an aerial platform at Venus provided it uses a low ballistic coefficient entry system, such as ADEPT, to mitigate the g loads on entry. The development of ASRG flight units was cancelled in November 2013. Its future prospects are uncertain although the Sterling engines remain in development.

2) ***ASRG for High G Conditions:*** For such entry systems, the ASRG would need to be ruggedized so that it could tolerate and operate through the entry phase. The feasibility of this has not been assessed. There is no current development work on such a device.

3) ***ASRG for High Temperature*:** For operation near the Venus surface, a version of the ASRG capable of operating with its cold end near Venus surface temperatures of approaching 500^{o}C is needed. Research was performed on this very challenging development but is no longer being conducted. Because this device will require high-temperature electronics, we have classified its technology readiness as Low.

4) ***High Temperature Thermoelectric Converter:*** This is an alternative to the ASRG for operation near the Venus surface. It would be designed to operate with its cold end at Venus ambient. We consider its readiness to be moderate because it does not require high temperature electronics.

6.1.4 Alternative Energy Sources

For long duration operation, deep within the Venus atmosphere, it is possible to exploit wind shear and temperature gradients to harvest energy. One technological approach was described in the Venus Geoscience Aerobot study[19]. In this concept, a reversible fluid balloon, cycling up and down used the Venus atmospheric temperature gradient as a heat engine and also harvested power with a rotor beneath the balloon. There are certainly other approaches that should be considered.

6.2 Thermal Control

6.2.1 Passive Thermal Control

Thermal control systems serve two functions in deep-atmosphere and surface probes. The first is to minimize the heat transfer from the environment to the probe. The second is to accommodate the heat generated by the internal components (e.g., power system, transmitter, and instruments). Passive thermal control was used on each of the Venera landers that operated for up to 2 hours on the surface of Venus. The elements are a) insulating materials to prevent heat leaking into the lander b) the thermal capacity of the lander, and c) phase-change materials (PCMs) to absorb the heat entering the lander to mitigate the temperature rise. Minimizing the heat leaks due to windows and cabling is an important part of the design process.

1) *Large Landers:* The readiness of this technology is very high for lifetimes of 2 to 3 hours. As noted in Section 5.3, liquid vapor PCMs may extend this by a factor of 10, but the technology is immature. Techniques use either water or ammonia as the phase change material, and the PCM may be coupled with a lithium getter to avoid the need to vent to the atmosphere.
2) *Microprobes/Dropsondes*: The major impact of technology advances could be in extending the performance of these devices. At present, it is not clear how small a device could be built that would survive and operate down to the surface using conventional silicon technology.

6.2.2 Active Thermal Control

Following an extensive assessment of the technology, the 2007 *Extreme Environments Report* identified an approach to a scalable, efficient, powered refrigeration/cooling system for maintaining temperatures at operational levels for the payload and the subsystems for extended periods of time (as long as months) [5]. The current state of development of active thermal-control technologies (Fig. 6-1) capable of operating in the Venus near-surface environment is low. At present, active coolers also require very high power that needs the efficiency of a Stirling-type radioisotope generator to be feasible.

6.3 Extreme Environments Technologies

6.3.1 High-Temperature Electronics

There are several technical approaches to exploring the surface or near-surface of Venus:

1) *Medium-Temperature Semiconductor-Based Electronics:* Medium-temperature (200–300°C) electronics are not only technically less difficult than electronics that operate at Venus surface temperatures but also have terrestrial commercial applications. A broad set of component options, including microprocessor and memory devices exist. For Venus surface missions, medium-temperature electronics could be used along with a Stirling-based power system/cooler. The use of medium-temperature electronics with cooling systems would significantly reduce the delta-T required, and hence reduce the amount of power required to achieve long-duration surface missions as compared to systems cooled to Earth-ambient temperatures. These electronics could

be used for aerial platforms operating near or below the cloud base, where temperatures reach values higher than can be tolerated by conventional silicon electronics. In this case, no cooling systems would be needed.

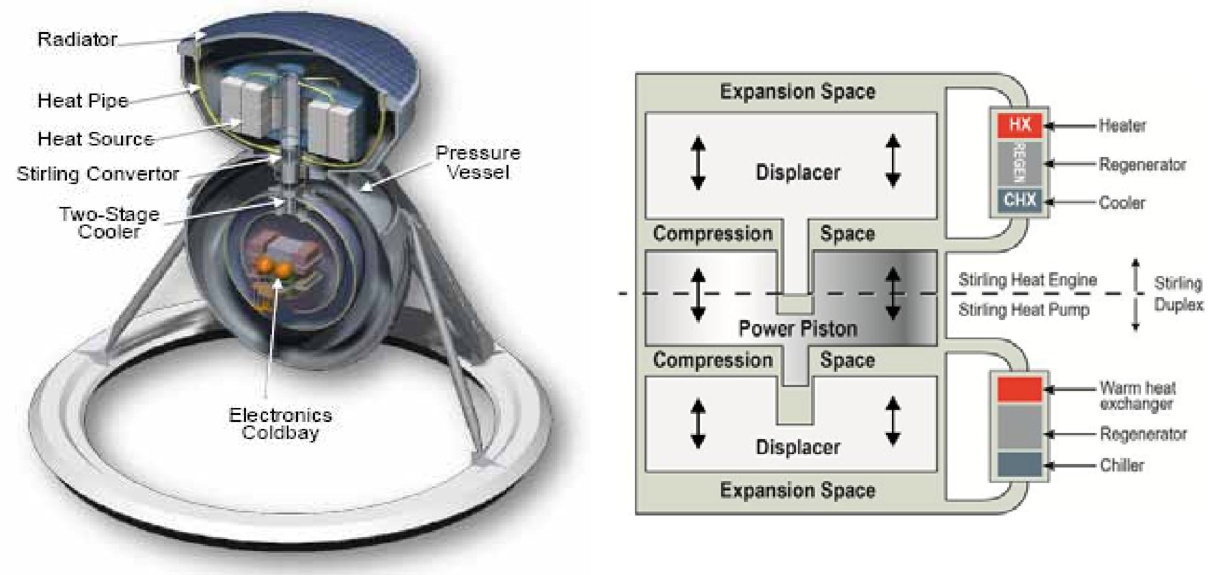

Fig. 6-1. Concept for active thermal control of a long-lived Venus lander uses Stirling-cycle technology for both generating electrical energy and cooling the electronics bay to enable operation at Venus surface ambient temperature.

2) *High Temperature – Semiconductor-based electronics (Fig. 6-2).* Two material systems—silicon carbide and gallium nitride—are being developed in research efforts spearheaded at NASA Glenn Research Center. In silicon carbide electronics, *b*asic electronic components have been demonstrated with long-term operation of thousands of hours at 500°C. The level of complexity that is possible is closer to that of the early 1960s development of silicon electronics. Memory is very limited and has relatively high power consumption. In *Gallium Nitride Electronics*, high-electron-mobility transistor devices with pinch-off values of less than 2 V have been demonstrated at 500°C. More advanced circuits that are under development have increased complexity. Substrates, passive components, and integration techniques (as well as packaging) require development. This technology is still at a very low level of maturity.

High Temperature SiC RF Amplifier Prototype (Softronics)

High Temperature Vacuum Triode Including Heater, Cathode, Grid, and Anode

InAlN/GaN HEMT Design

Fig 6-2. High temperature semiconductor technologies with potential for operation at the Venus surface.

3) *High Temperature – Digital Vacuum Electronics:* Recent efforts in this area have exploited the properties of carbon nanotube electron sources which operate as field emitters without the need

for a heated cathode. This field is immature but shows a great deal of potential for low-powered, high-temperature memory and logic devices because, unlike semiconductors, there are no temperature-dependent leakage currents to deal with [20].

6.3.2 High-Temperature Mechanisms

There are a broad range of mechanism requirements for Venus surface missions and lower atmosphere missions, of which only some can be touched on here:

1) *High-temperature mechanisms for surface missions:* A substantial amount of development is needed in this area. Motors exist today that have operated for long periods at Venus surface temperatures. However, feedback systems require development of high-temperature encoder systems. Many of the required mechanism components, materials, lubricants, etc. have been developed for operation at Venus temperatures. Significant materials development, along with and testing and qualification for the Venus environment is still required, especially at the system level.

2) *High-temperature mechanisms for sample acquisition and storage*: Sample handling and caching techniques need to be tested with the mechanisms and instruments for the Venus surface environment. This includes the algorithms for control and various faults conditions.

6.4 Communications

As with Mars, we need to consider communications for the "Trunk Line" between Venus and Earth and the proximity communications between assets that are deployed to accomplish specific science activities and those assets (typically orbiters) that have the powerful trunk line communications capabilities. These trunk line communications would be:

1) *Communications for orbiters*: Communications systems exist today for Venus orbiters with the ability to communicate at rates up to 10 Mb/s. However, optical communications for Venus-to-Earth communications would enhance the data rate for the missions by at least a factor of 10. Development of three key enabling components of a deep space optical communications system has been is being conducted by the Space Technology Missions Directorate (STMD) Game Changing Development program: a low frequency vibration isolation platform; a ground-based photon counting array; and a flight photon counting receiver for the uplink signal. First use on a science mission now projected to be for a 2024 launch and mission that would still retain a radio frequency communications capability. An important part of the overall plan is that ground infrastructure plans must also move forward. An initial demonstration capability using an existing optical telescope (Palomar Mountain in 2024) and a NASA 10-m optical ground station that is planned for completion by 2025. The European and Japanese Space Agencies (ESA and JAXA, respectively) optical ground stations are also under discussion. A technology demonstration mission is planned that would demonstrate optical communications on a planetary mission. This could greatly enhance the capabilities of any future Venus mission involving radar imaging and interferometry.

2) *Proximity Communications - probes, sondes and aerial platforms:* Communications systems also exist for atmospheric or short duration surface missions supported by relay orbiters. Application of the Mars relay link communication protocols would enable asset leveraging. For *in situ* atmospheric missions with direct-to-Earth communications, the development of phased-array antennas and other more efficient antenna designs would greatly enhance data return.

3) *Communications on the Surface:* Surface-to-orbit or Earth communications systems for long-duration surface missions require significant research and development. Close proximity (2-m, wired or wireless) high-temperature communication systems have been demonstrated for 24 days, however, lifetimes need to be extended for long-duration applications.

6.5 Guidance, Navigation, and Control

Guidance, navigation, and control (GN&C) for the orbital spacecraft envisaged here present no unusual requirement. For the *in situ* elements, GN&C is needed for a range of motion planning, sensing, and vehicle control tasks to achieve desired maneuvers in order to accomplish specific goals. A recent assessment of GN&C technologies covers *in situ* missions at Mars, Venus, and Titan [21]. Here, we focus specifically on the state of technology for Venus missions.

1) Landed Missions—Pin-Point Landing: As described in the landing section (5.5) above, the application of pin-point landing and hazard avoidance technologies would be important for safe landing of a mid-term landed mission to the Venus tesserae. While much of this technology has been developed for other applications, the Venus-unique needs include infrared sensors for imaging the surface during much of the descent phase as well as techniques for matching heterogeneous data sets, in this case infrared and radar imaging data to support pin-point landing.

2) Aerial Platforms—Velocity and Attitude**:** Knowledge of the velocity and attitude of the platform is important for certain scientific objectives as well as for enabling high-gain communications. Recently, developments of navigation systems for micro-aerial vehicles (MAVs), which use only a downward-looking camera and an inertial measurement unit to achieve real-time and on-board autonomous navigation, would be applicable here. These systems have comparatively modest processing requirements [22]. Aerial missions with high-data return requirements, or precise pointing, are needed to achieve science objectives. A specific requirement is low-power infrared cameras for locating surface features. These features can be used not only to localize the platform but also compute its attitude.

3) Aerial Platforms – Global Localization**:** Venus missions that need very precise knowledge must couple the capabilities described above with referencing to a global map of Venus. Since the global map is based on radar data and the platform will most probably use infrared imaging for localization, it will be necessary to extract features from the images in order to correct for the distinctive nature of the sensor signatures [23].

4) Mobile Platforms on The Venus Surface or in the Lower Atmosphere**:** Advanced GN&C technologies would be useful for precision landing although there is no explicit requirement for precision landing in the missions in the Roadmap. Attitude knowledge will be needed for high-gain communications from the mobile vehicle.

7.0 Instruments

This section is structured in five segments: remote sensing instruments that can be deployed on an orbiter; instruments that can be implemented on a probe or balloon and would primarily sense the atmosphere; and three categories of landed instruments.

7.1 Remote Sensing—Active

Because of the dense atmosphere of Venus, techniques that are useful to study the surface of airless bodies and Mars, such as visual imaging, gamma ray detection, and most applications of infrared sensing are not useful. However, radar, which has been used on both NASA (Magellan) and Soviet-era Venera spacecraft, is an effective tool for characterizing the surface. Improvements since that time enable much higher resolution images to be obtained. A variety of techniques have been used for characterizing the atmosphere as exemplified by ESA Venus Express.

7.2 In Situ – Probe and Aerial Platform

Many instruments needed for a variety of atmospheric probes and higher-altitude aerial platforms that maintain internal temperatures well below Venus surface ambient are relatively mature. Many of the advancements needed are better described as achievable engineering challenges specific to missions or measurements rather than significant technology advancements. However, miniaturization of instruments would be of great benefit because payloads are also constrained in mass, power, and volume for these applications.

7.3 In Situ – Short Duration Landed Missions

A primary focus of these missions is to perform elemental, mineralogical, and petrologic analysis on the surface of Venus. With such limited lifetimes on the surface, time is of the essence so the speed with which these measurements can be conducted is vital. Technical developments in the following instruments can have a major impact.

1) ***X ray Diffraction and Fluorescence***: These techniques measure the composition of elements and minerals in a powdered sample placed in the instrument by irradiating it with an X-ray beam. **The Chemistry and Mineralogy**) instrument on the Curiosity rover employs this technique and worked successfully on Mars, but it took 27 hours of integration time to analyze the mineralogy of a sample [24]. The Science and Technology Definition Team (STDT) for the Venus Flagship Mission [7] recognized that speed of operation would be critical for a short lifetime Venus mission and identified the use of a high-flux X-ray source based on a carbon nanotube X-ray emitter as a technology solution in development that would alleviate the problem.
2) ***Laser Induced Breakdown Spectroscopy (LIBS/Raman):*** For the Venus Surface and Atmosphere Geochemical Explorer (SAGE) New Frontiers mission, a team at Los Alamos National Laboratory studied another type of instrument, which is also placed inside the lander and also measures both elemental composition and minerals [25]. A similar LIBS instrument, but without the Raman mode, has been successfully deployed by the Curiosity rover on Mars. The key difference is that this instrument samples remotely by sensing a beam through the window of the pressure vessel to the Venus surface and does not require bringing a sample inside the pressure vessel. The LIBS mode is degraded in the Venus environment, but the Raman mode would not be affected significantly. The instrument also ablates material, which may help in investigating the depth of surface weathering by probing below the rock surface.
3) ***Fine-Scale Elemental and Mineralogical Analysis****:* Neither of the above instrumental approaches has the ability to identify the nature of individual mineral grains in a rock or a soil sample as they are viewed microscopically. As the Mars 2020 Science Definition Team [26] looked at the requirements for that mission, they recognized the geological importance of fine-

scale imaging, fine-scale elemental analysis, and fine-scale mineralogy. We can anticipate that similar requirements are ultimately going to be important on Venus. While these goals seems quite practical for samples brought into the pressurized chamber, the ability to do such measurements *in situ*, where they will be most interesting, will be technologically challenging.

7.4 In Situ – Long Duration – Geophysical

Because of the severe environment, implementing geophysical measurements on the surface of Venus is a formidable challenge. It is important to be able to take advantage of the Venus environment where possible to deal with this challenge; one example is heat-flow measurements. On the Earth, the Moon, and Mars, geophysicists must take account of diurnal or seasonal variations in making the measurements, and these measurements require readings acquired in a bore-hole over an extended period of time. On the Venus surface, where there is little diurnal and seasonal temperature variation, a heat-flux measurement can be implemented with a flux plate that does not require an extended time period for equilibration and consequently can be implemented from a short duration lander [27].

For seismic studies of the interior of Venus, measurements must be made over a long time baseline. NASA is funding some work on a device that could operate on the Venus surface. However, other options, unique to Venus, may exist, as identified in a workshop organized by the Keck Institute for Space Studies in 2010. It was pointed out by Lognonné [28] that because of the high density of the Venus atmosphere, coupling of seismic signals into atmospheric acoustic waves is 60 times more efficient than on the Earth and they become amplified as they rise in the atmosphere and could be detected in the atmosphere from a long duration aerial platform as well as from orbit. This may be a powerful complement to surface seismometry. Very high-temperature electronics and sensors along with instrument thermal control systems may still be needed solutions for some measurements.

7.5 In Situ – Long Duration – Mobile Laboratory

Most concepts for a long-duration surface laboratory have assumed that much of the instrument would be contained in a protected volume whose temperature is controlled to near-Earth ambient and where instruments developed to operate in the laboratory or in martian conditions could function. However, this may be unattainable. Therefore, it is important to understand what can be done with sensors that are operating at Venus surface ambient temperature. The challenges for long-duration geophysics missions all still apply but are even more difficult with more complex instruments. Significant thermal control achievements, enabling mature sensors to be used or high-temperature electronics systems, sensors, memory, etc. specific to those instruments are likely to be needed.

8.0 Findings

The following findings are based on the work discussed within this document, feedback from the Venus Technology Forum of November 19, 2013, and additional responses from members of the VEXAG community. The findings are grouped into two sets of findings, Technology Development and Infrastructure Development. Each of these is in priority order.

1. **Entry Technology for Venus:** The thermal protection system (TPS) technology developed for missions involving entry into the Venus atmosphere has not been used for many decades, and the ability to easily replicate it has been lost. Two attractive options for replacing the prior technology, 3D Woven TPS and ADEPT technology, are currently under development under the sponsorship of the Space Technology Missions Directorate (STMD). These developments would not only enable the next generation of Venus entry missions, but they also promise to be a stable and enduring solution, and one that is not prone to premature obsolescence. ***This development needs the continued endorsement of the Planetary Science Division (PSD).***
2. **High-Temperature Subsystems and Components for Long-Duration (months) Surface Operations:** Advances in high-temperature electronics and thermo electric power generators would enable long-duration missions on the surface of Venus operating for periods of as long as a year, where the sensors and all other components operate at Venus surface ambient temperature. These advances are needed for both the long duration lander and the lander network. ***Development of the high temperature electronics, sensors and the thermo-electric power sources designed for operating in the Venus ambient would be enabling for future missions.***
3. **Aerial Platforms for Missions to Measure Atmospheric Chemical and Physical Properties:** Aerial platforms have a broad impact on exploration of Venus. After more than a decade of development, the technology for deploying balloon payloads approaching 100 kg with floating lifetimes in excess of 30 days near 55 km altitude is approaching maturity. Vehicles for operation at higher and lower elevations in the middle atmosphere and with the ability to change and maintain specific altitudes are much less mature and need development. A buoyant vehicle, operating close to the Venus surface requires major development. Aerial platforms would be an essential part of any atmospheric or surface sample mission. ***Development of these aerial platform technologies is enabling for mid-term and far-term missions.***
4. ***In Situ* Instruments for Landed Missions:** Since the Planetary Science Decadal Survey in 2011, there has been significant progress in instruments for surface geology and geochemistry (e.g., laser induced breakdown spectroscopy [LIBS] in conjunction with remote Raman spectroscopy has been demonstrated). Advances in other instruments for “rapid petrology” also appear possible spurred in part by developments underway for investigating the surface of Mars. ***A workshop focused on instruments for Venus surface operations would be helpful for defining future directions and such a workshop is planned for January 2015.***
5. **Deep Space Optical Communications:** Development of deep space optical communications technology would enhance the performance of missions involving high resolutions radar imaging of the surface of Venus enabling mapping to be completed much more rapidly than with RF communications systems. NASA STMD is currently developing the key component technologies for deep space communications and NASA’s Space Communications and Navigations Directorate (SCaN) is planning on a 10-m optical ground station by 2015**. Implementation of a flight experiment of optical communications would represent a major step forward in the adoption of the technology, and** if **implemented on a Venus orbiter mission, it could significantly enhance the science return.**
6. **Advanced Power and Cooling Technology for Long-Duration Surface Operations:** Most scientific objectives at the Venus surface require sensors that operate at temperatures well below

100°C. Current passively cooled systems are limited to a lifetime of 3 to 5 hours. Advanced liquid-vapor phase change cooling could extend lifetimes to 24 hours and could benefit the Tessera lander conceived as a mid-term mission. Highly efficient mechanical thermal conversion and cooling devices (typified by the Stirling cycle-engines and capable of operating in a 460°C environment) are required for this purpose. With lifetimes of months, these are enabling for the Venus mobile surface and near-surface laboratory mission concepts. ***Investments in advanced power and cooling technology are needed to enable both mid-term and far-term missions.***

7. **Advanced Descent and Landing:** Lander missions for the mid-term would target the Tessarae regions of Venus, which radar imaging indicates to be extremely rough and irregular topography. Following the Mars model, achieving safe landings in regions of complex topography will require the development of improved targeting accuracy and precision landing techniques potentially accompanied by hazard avoidance during the terminal descent phase. ***New concepts are needed for adapting methods of terrain relative navigation and guidance to operation in the dense Venus atmosphere.***

Infrastructure Development

1. **Ames Research Center (ARC) Arc Jet Interaction Heating Facility (IHF) Facility Enhancement:** A new 3-inch nozzle funded by SMD has been installed at the NASA ARC arc jet facility enabling testing has provided Venus relevant testing conditions for the testing of thermal protection materials: ***This enhanced facility will play a vital role in maturing the High Energy Entry Technology (HEEET) for use in a Discovery or New Frontiers mission to Venus.***
2. **NASA Glenn Research Center (GRC) Extreme Environment Rig (GEER).** The NASA GRC GEER (currently under development) is an important step forward. The ***PSD now needs a plan for effective use of this facility.***
3. **Instrument Chamber Enhancements:** ***The Venus facilities at Goddard Space Flight Center (GSFC) and Jet Propulsion Laboratory (JPL) should be maintained and enhanced according to community needs and requirements.***
4. **Environmental Modelling and Simulation:** Test chambers are a vital element of advancing both science and technology modelling capabilities for Venus, but they require modelling of environments to ensure that the results of the tests can be applied effectively to operations in the natural environments. Considerable expertise has been developed at NASA Ames Research Center and NASA Langley Research Center in modelling of entry environments. ***It is necessary to sustain that work but also to develop modelling capabilities incorporating the physics and chemistry of gases at the conditions of the Venus surface.***

General

1. **Uniqueness of Venus Technology Needs**: Some Venus technologies are unique to Venus; others have broader application. Those with other applications may be funded through joint programs. Those truly unique to Venus need special attention from NASA PSD if they are critical to implementing high priority missions. ***PSD should identify where joint sponsorship and dual use development can be leveraged and promote those partnerships that would result in moving the technology forward.***

9.0 Acronyms and Abbreviations

ADEPT	Adaptable Deployable Entry and Placement Technology
ALHAT	Autonomous Landing and Hazard Avoidance Technology
ASRG	Advanced Stirling Radioisotope Generator
EM	electromagnetic
ESA	European Space Agency
GCD	Game-Changing Development
GN&C	guidance, navigation, and control
GOI	*Goals, Objectives and Investigations for Venus Exploration*
GRC	Glenn Research Center
GSFC	Goddard Space Flight Center
HEEET	High Energy Entry Environment Technology
HIAD	Hypersonic Inflatable Aerodynamic Decelerator
IHF	(Ames Research Center) Interaction Heating Facility
JAXA	Japanese Space Agency
JPL	Jet Propulsion Laboratory
LIBS	laser induced breakdown spectroscopy
LIDAR	**li**ght **d**etection **a**nd **r**anging
MAV	micro-aerial vehicle
MMRTG	Multi-Mission Radioisotope Thermoelectric Generator
PCM	phase-change material
PSD	Planetary Science Division
RF	radio frequency
RVE	*Roadmap for Venus Exploration*
SCaN	Space Communications and Navigations (Directorate)
SMD	(NASA) Science Mission Directorate
STDT	Science and Technology Definition Team
STIM	Science and Technology Interchange Meeting
STMD	(NASA) Space Technology Mission Directorate
TPS	thermal protective system
TRL	technology readiness level
VAMP	Venus Atmospheric Maneuverable Platform
VEXAG	Venus Exploration Analysis Group
VSSR	Venus Surface Sample Return

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