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VENUS TECHNOLOGY PLAN

Report of the VEXAG Focus Group on Technology and Laboratory Instrumentation

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Note: This document is a work in progress and is being distributed to the community for feedback. The next revision will be focused on refining the alignment of the content with the two companion documents: the Venus Exploration Roadmap and Venus Goals, Objectives and Investigations

1.0 EXECUTIVE SUMMARY

The planet Venus, with its unique environment, presents unusual challenges for planetary exploration. A number of scientifically important missions can be implemented with existing technology although some may involve engineering development. However, missions involving operations for extended periods in the atmosphere, at or near the surface of Venus are going to require significant investments in new technology but can leverage off commercial developments. A Venus exploration program should include a balanced investments in missions for the short term and technology investments enabling these more ambitious missions that can be conducted in the medium and long term.

2.0 BACKGROUND

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 (VGOI) document[1] establishes the scientific goals for Venus exploration and prioritizes the objectives and investigations needed to address those goals. The Venus Exploration Roadmap (VER) [2] translates these objectives into Mission Modes that can most effectively address the objectives and implement the investigations. The VER also reexamines 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 (VTP), draws information from both of the prior documents but primarily the VER and performs a more detailed assessment of the technologies that require NASA investment.

3.0 VENUS EXPLORATION CHALLENGES

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

3.1 Venus Environment

The Venus environment poses mission challenges like few other potential planetary destinations:

1) In orbit the thermal environment is challenging but less so than for Mercury
2) During planetary atmospheric entry, the velocity and thermal conditions are more severe than for entry at Earth or Mars (but less than Jupiter)
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 maintains the sulfuric acid clouds
4) Landing on Venus is less challenging because of the dense atmosphere which eases both the initial parachute phase and terminal descent relative to Mars
5) Surface operations using conventional electronics and passive thermal control systems are limited to a few hours by the high temperatures. Long duration missions require components and packaging that will function in Venus ambient 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. 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 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 could 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 JPL[5]. This was followed by a monograph focused specifically on Venus technologies[6]. In April 2009, the Science and Technology Definition Team for the Venus Flagship Mission[7] conducted an assessment of not only the new technology requirements for the Design Reference Mission (DRM) but also the mission and payload enhancements for what it referred to as extraordinary science return. Finally, in September 2009, a white paper [8]was submitted to the Planetary Science Decadal Survey by members of VEXAG on technologies for future Venus exploration. These are all important sources for the present document. However, the present document is guided by the specific recommendations of the Venus Roadmap team and the Venus Goals, Objectives and Investigations document.

The Road Map team 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. These Mission Modes require different levels and types of technology. Later in this document we describe the technologies that are needed to enable each of the mission modes.

4.0 TECHNOLOGY PLAN OVERVIEW

A summary assessment of the technologies needed for the Roadmap Mission Modes appears in Table 1. The time frame in which those technologies are 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 2. 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 by tailored to the unique conditions at Venus.

In Table 2, 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, technology maturity is very high; for mid-term missions maturity it is typically moderate and for far term missions it is typically low.

Table 1: Framework for assessment of technologies for Venus Exploration

	Technology Area	Time Frame	Assessment
System Technologies	**Aerobraking and Aerocapture**	**N, F**	Aerobraking is a mature technology. Aerocapture requires development but is only needed for far term missions
	Entry Descent and Landing	N,M,F	Need new woven TPS or deployable technologies for entry at Venus since there is currently no technology that does the job. Descent and landing easier than for Mars and landing on the plains is an engineering issue. Landing on the tessarae requires new technology.
	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 (current technology), long duration with geophysical sensors and long durations with a complex instrument suite and surface mobility
	Ascent Vehicles	F	Only needed for Venus Sample return. Very immature technology. Some concepts for Venus Surface sample return require the Venus Ascent Vehicle to descend to the surface
Subsystem Technologies	**Power**	M,F	Most compelling mid term need is for thermoelectric generators operating in a 460°C environment. In the far term, the efficiency of Stirling is essential
	Thermal Control	M,F	Challenge is extending lifetime once on the surface. Good prospects for extending life by factor of 10 to 25 hours with passive cooling. Active cooling using Stirling cycle is essential for vehicles that must operate with payloads at Earth ambient for periods greater than an Earth day
	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 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

Note: N indicates near-term or this decade, M is mid-term or next decade and F is far-term or beyond the next decade.

5.0 SYSTEM LEVEL CAPABILITIES

System level capabilities are typically at the level of the Mission Modes described in the Roadmap. It is important to recognize that these capabilities cannot be considered in isolation. These system level capabilities will generally feed 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 has been used for similar reasons on Mars missions. ESA's Venus Express will be carrying out a number of aerobraking maneuvers largely motivated by attempting to characterize variability in the upper atmosphere. The Exploration Roadmap 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 heat and stresses

Table 2: Mission Modes and Applicable Technologies

		Mission Mode	Near-Term Missions							Mid Term Missions				Far Term Missions				
			Radar Orbiter	Remote Sensing Orbiter	Aerial Platform Sustained	Deep Probe	Multiple Shallow Probes	Multiple Shallow Sondes	Lander - Smooth Terrain	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															🟧 X	🟧 X
		Aerobraking	🟩 X	🟩 X														
		Entry			🟨 X	🟨 X	🟨 X		🟨 X	🟨 X	🟨 X	🟨 X		🟨 X	🟨 X	🟨 X	🟧	🟧
		Descent and Deployment			🟩 X	🟩 X	🟩 X	🟩 X	🟩 X	🟩 X	🟨 X	🟩 X	🟩 X	🟩 X	🟨 X	🟨 X	🟨	🟥
		Landing							🟩 X	🟨 X	🟨 X			🟩 X	🟧 X			🟥
		Aerial Platforms			🟩 X			🟩 X					🟨 X			🟧 X	🟧	🟥
		Landers - Short Durations							🟩 X	🟩 X								
		Landers Long Duration - Geophysica									🟧 X			🟧 X				
		Mobile Platform - Surface or near surface													🟥 X	🟥 X		
		Ascent Vehicle															🟥 X	🟥 X
	Subsysystem Technologies	Energy Storage- Batteries	🟩 X	🟩 X	🟩 X	🟩 X	🟩 X	🟩 X	🟩 X	🟩 X	🟧 X	🟩 X	🟩 X	🟥 X	🟥 X	🟥 X		
		Energy Generation - Solar	🟩 X	🟩 X	🟨 X													
		Energy Generation - Radioisotope Power									🟧 X			🟥	🟥 X	🟥 X		
		Thermal Control - Passive					🟩 X	🟩 X	🟩 X	🟧 X	🟧 X	🟧 X	🟧 X					🟥 X
		Thermal Control - Active												🟥 X	🟥 X	🟥 X		
		High temperature mechanisms							🟨 X	🟨 X	🟧 X			🟥 X	🟥 X	🟥 X		🟥 X
		High temperature electronics							🟩 X	🟩 X	🟧 X			🟥 X	🟥 X	🟥 X		🟥 X
		Communications			🟩 X	🟩 X	🟩 X	🟩 X	🟩 X	🟩 X	🟧 X	🟩 X	🟩 X	🟥 X	🟥 X	🟥 X		
		Guidance, Navigation and Control			🟩 X					🟧 X	🟧 X		🟧 X	🟥 X	🟥 X	🟥 X		
	Insutrument	Remote Sensing - Active	🟩 X	🟩 X														
		Remote Sensing - Passive	🟩 X	🟩 X														
		Probe - Aerial Platform			🟩 X	🟩 X	🟩 X	🟩 X				🟩 X	🟩 X				🟨 X	
		In Situ Surface - Short Duration							🟨 X	🟨 X								🟧 X
		IN Situ Surface - Long Duration - Geophysical									🟧 X			🟥 X				
		In Situ Surface - Long Duration - Mobile Lab													🟥 X	🟥 X		

🟩	**Very High. Ready for flight. Same as TRL 6**	🟨	**High. Limited development and testing still needed**
🟧	**Moderate. Major R&D effort needed.**	🟥	**Low. Major R&D effort needed with notable technical challenges.**

generated. Measurements from Venus Express during aerobraking maneuvers will be relevant to future use of aerobraking at Venus and specifically how aggressively the maneuvers can be executed to reduce the time needed to achieve the desired orbit.

5.2 Aerocapture:

Aerocapture technology bears a superficial resemblance to aerobraking technology. The key difference is that the objective is to achieve orbital capture and a large velocity change is required. Specialized drag and lifting structures essentially identical in nature to those discussed in the Section 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 VER require aerocapture. 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. Aerocapture could be highly beneficial in achieving this orbit.

5.3 Entry

Entry technologies are needed for implementation of all the mission modes designated in Table 1 except for remote sensing from space. 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, the technologies used in those NASA missions is no longer available. Several alternative approaches have been identified and some are 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 similar family of material as the manufacturing processes have atrophied and raw material no longer available and also expensive to qualify. Moreover this solution is prone to premature obsolescence.

2. *3-D Woven Thermal Protection System*: The use of 3-D woven materials infused with resin to withstand a broad range of entry environment to result in mass efficient ablative 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 aero-shell scalable to much bigger aeroshell diameter. This development is considered to bring the state of development of the larger aero-shell needed for a Venus lander to TRL 5/6 by the end of FY'16.
3. *Adaptable Deployable Entry and Placement Technology (ADEPT):* 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 (FSD) Project is a STMD Game Changing funded new start project in FY14. The ADEPT FSD is focused on design, development, and integrated ground test of a 6m mechanically deployed decelerator capable of delivery of payloads up to 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 range of existing facilities[10]

5.4 Descent and Deployment

Descent/deployment capabilities are relevant to the same five 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 were the environment is harsh (e.g. hot, corrosive). This may require different sizes of parachutes or other aerodynamic structures. Special materials must be used to accommodate the 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 if images are to be acquired during descent to minimize 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 the aerial vehicle. For balloon deployment and inflation, experience indicates descent velocities of less than 10m/sec.[11]. These are readily achievable in the dense atmosphere of Venus. The needed descent velocity for airplane deployment is dependent on the design specifics of the aircraft but again the dense atmosphere is favorable.

Dropsondes deployed from an aerial platform can be used to sample the atmosphere in multiple locations. Deep dropsondes able to descend close to the surface can be used in conjunction with the platform that deploys them to relay large amounts of high resolution imaging data on potential landing sites but will require technology development in order to generate images in near surface conditions.

5.5 Landing

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

There are two general approaches to the challenging terrain problem. 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 its science mission. A vehicle that is tipped over so that its sampling arm cannot reach the surface is a failure. The other approach is to find a safe area within the general area of challenging terrain and target to that. This second approach is the generally preferred approach if it is feasible – not only for Mars but as recent analyses have shown yet again - for Europa. It also enables improved science through precision targeting.

For a mid-term mission, it seems prudent to draw on the ***pin point landing*** and ***hazard avoidance technologies*** that have been developed in the Mars program and also by the Space Technology Mission Directorate (STMD) under the ALHAT program.[12]

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 studies and seems quite feasible. The control function would be quite different than for Mars and would use a steerable parachute and not propulsion. This approach is not new and is used in precision drops from aircraft these days. However, for Venus it would be necessary to study how big an initial landing error could be compensated for and how precise the ultimate landing could be.
2) ***Hazard Avoidance*****,** which can be used independently or in combination with pin point landing is a different concept. It uses surface information (imaging, lidar, radar) during the final stages of descent to identify areas of hazard and to avoid them. For an unknown surface like Venus, it would benefit from knowledge of what hazardous areas on the surface look like. 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 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.

The most mature aerial platform is the *superpressure balloon* designed for operation near 55 km. Two 3.4 m diameter helium superpressure balloons were successfully deployed and flown in June 1985 by the Soviet Union. Each balloon returned in situ measurements for about 48 hours, as it was tracked by an international consortium, led by the Soviet Union and CNES, 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 with a potential life times of several months[13]. This technology is ready[14] to fly.

Approaches for accessing higher parts of the atmosphere focused on identifying the nature of the UV 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 include 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 under *Section 5.7 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.

LANDER PLATFORMS

5.7 Landers – Short Duration

During the 1970s and 1980s, the Soviet Union successfully landed 6 probes (Venera 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 five 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 the totally autonomous mission of 2 to 3 hours duration. These technologies include the use of phase change materials (PSMs) 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 for the mid-term lander mission to the Venus tesserae.

5.8 Landers – Long Duration – Geophysical

The Exploration Roadmap specifies the need for a platform in the Mid Term that would investigate the structure of Venus' interior and the nature of current activity and 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. 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 involving 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 the Mid Term. The key question here questionable that an adequate set of scientific measurements can 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 a radioisotope power using a thermoelectric transducer exploiting the Peltier effect. Although currently available 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.

5.9 Mobile Platform – Surface or near surface

The VER calls for a mobile platform that would operate on the surface or in the lower atmosphere with a mobility range of 10s to 100s of kilometers that would analyze surface compositional variations on a regional scale. This would include conducting geochemistry and mineralogy measurements at multiple sites, remote sensing from low altitudes (<1km) and panoramic and high-resolution imaging correlated with composition.

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 of sensors to well below Earth ambient. Operation of those sensors 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^{o}C. Both a power system and a cooling system that can operate at Venus temperatures will need to be developed.

The mobility range for such a vehicle is a lesser challenge although still formidable. Concepts for floating platforms capable of traversing all terrain types have been devised, however, the near surface conditions on Venus are not 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 10 to 100 km range called for would be challenging.

5.10 Ascent Vehicle

The VER has identified Venus Surface Sample Return (VSSR) as a long range objective. Past studies of VSSR[18] have used architectures modeled on Mars Surface Sample Return in which a sample canister is 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 of Venus to Venus orbit is 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/sec. 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 that is, in comparison, a much easier task.

6.0 SUBSYSTEM TECHNOLOGIES

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

POWER

6.1 Energy Storage – Batteries

Of the Mission Modes described in Table 1, many can be implemented successfully with existing technology; orbiter missions, balloon missions as well as probe and lander missions. Long duration landers are one area where technology development may be needed. If long duration landers can 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 radioisotope power system.

6.2 Energy Generation – Solar

Remote Sensing from space with orbital missions or flyby missions can be implemented with existing capabilities. Solar power is not needed for short duration probes or landers but may be a viable technology 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 is 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 of this 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 that can clad – on both sides – 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.

6.3 Energy Generation – Radioisotope Power

Radioisotope power can 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 may benefit from radioisotope power on the night side of Venus although trades with battery options are needed and as they approach the polar vortex radioisotope power can extend operations.

1) *Advanced Radioisotope Stirling Generator (ASRG):* The ASRG, currently under development, uses 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.
2) *ASRG for High G:* For other 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.
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

500C is needed. Research has been 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. We consider its readiness to be moderate because it does not require high temperature electronics. However, the efficiency of this device will be much lower than the ASRG and it is unlikely that it would be practical for use with active cooling (see next section).

THERMAL CONTROL

6.4 Thermal control- passive

The thermal control systems serve two functions on 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 insulating materials to prevent heat leaking into the lander and thermal capacity and phase change materials 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 Phase Change Materials may extend this by a factor of 10 but the technology is immature. Techniques use either a water or ammonia as the phase change material and it may be coupled with a lithium getter to avoid the need to vent to the atmosphere.
2) *Microprobes/Dropsondes*: The major impact of technology could be in the 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.

6.5 Thermal Control - active

Following an assessment of the technology, the Extreme Environments Report of 2007 identified thermal control goals. There has been only limited progress towards these goals and so these are no repeated here. A scalable and efficient powered refrigeration/cooling system is needed to maintain temperatures at operational levels for the payload and the subsystems for extended periods of time (e.g. months)[19]. The current state of development of active thermal control technologies capable of operating in the Venus near-surface environment is low.

EXTREME ENVIRONMENTS TECHNOLOGIES

6.6 High temperature electronics

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

1) *Medium Temperature Semiconductor Based Electronics:* Medium temperature (200-300°C) electronics not only are technically less difficult than electronics that operates at Venus temperature 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.

2) *High Temperature – Semiconductor based electronics.* 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 in silicon carbide electronics with long term operation (thousand of hours at 500°C). The level of complexity that is possible is closer to the early formation of silicon electronics. Memory is very limited and has relatively high power consumption. In *Gallium Nitride Electronics*, High Electron Mobility Transistor (HEMT) devices with pinch off less than 2V have been demonstrated at 500°C More advanced circuits are under development that 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 with only very small devices practical and

3) *High Temperature – Digital Vacuum Electronics:* Recent efforts in this area have exploited the properties of Carbon NanoTube (CNT) 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].

6.7 High temperature mechanisms

There will be 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) *Sample acquisition*: 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.

6.8 Communications

As with Mars, we need to consider communications for the "Trunk Line" between Venus and Earth and 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

1) *Communications for orbiters*: Communications systems exist today for Venus orbiters. However, optical communications for Venus to Earth communications would enhance high data rate for the missions. A technology demonstration mission is planned that would demonstrate optical communications on a planetary mission. This is particularly relevant to the radar missions.
2) *Proximity Communications- probes, sondes and aerial platforms:* Communications systems also exist for atmospheric, or short duration surface, missions supported by a relay orbiter. Application of the Mars relay link communication protocols would enable better 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 will require significant research and development. Close proximity (2m, wired or wireless) high-temperature communication systems have been demonstrated for 24 days. Lifetimes need to be extended for long duration applications.

6.9 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 Section 5.5, the application of Pin point Landing and Hazard avoidance technologies* will 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 and 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 (IMU) to achieve real-time and onboard autonomous navigation is applicable. 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 which 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 Surface or in 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 sections: 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. A variety of techniques have been used for characterizing the atmosphere as exemplified by ESA Venus Express. Some early work exploring specific orbital penetrating instruments other than radar is ongoing.

7.2 In Situ – Probe and aerial platform

Many instruments needed for a variety of atmospheric probes, 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, since payloads are also mass, power and volume constrained in these applications particularly, miniaturization of instruments would have a great deal of payoff

7.3 In situ – Short duration landed missions

A primary focus of these missions is to carry out 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 Fluorescence***: This technique measures 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 (**CheMin) instrument on the Curiosity rover employs this technique and worked successfully but took 27 hours of integration time to analyze the mineralogy of a sample, [24]. The STDT for the Venus Flagship Mission 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.
2) ***Laser Induced Breakdown (LIBS/Raman):*** For the Venus 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 required bringing a sample inside the pressure vessel. The LIBS mode is degraded by the Venus environment but the Raman mode is not affected significantly. The instrument also ablates material which may help in investigating the depth of surface weathering.
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 soils sampel as they are viewed microscopically. As the Mars 2020 Science Definition Team [26]looked

at the requirements for that mission they recognized the importance for geologic objectives 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 this 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, Moon and Mars, geophysicists have to take account of diurnal or seasonal variations in making the measurement and it requires measures in a bore hole acquired 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 and from a short duration lander.

For seismic studies of the interior of Venus measurements must be made over a long time baseline. Some work is being funded by NASA 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 Lognonne[27] 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 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 Mars like 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 ambient. 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 may be needed.

8.0 FINDINGS

The following findings are preliminary. They have been updated based on feedback on the Venus Technology Forum of November 19, 2013 but are subject to further revision before this plan is considered complete.

1. **Entry Technology:** The thermal protection system (TPS) technology for missions involving entry into the Venus atmosphere has not been used for many decades and as a result 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) with the goal of reaching TRL 5/6. These developments will 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.

2. **Testing Facilities:** Testing facilities are important to the development of advanced TPS materials such as 3D Woven TPS and also for investigating and validating the performance of new technologies for operating deep in the Venus atmosphere. A number of facilities capable of high temperature and high pressure operations have been developed and these need to be equipped with diagnostics equipment. Larger facilities may be needed as we progress in technology development of long duration operations on the Venus surface.
3. **Landers – Short Duration:** The technology for missions with lifetimes of 2 to 3 hours called for in the VER is available now. Technologies with the promise of extending lifetimes by a factor of 10 are looking increasingly promising. Maturation of these technologies could greatly increase the capabilities of Venus surface missions and enable the operations team to respond to information from the lander while it is still operating.
4. **Landers – Long Duration**: Advances in high temperature electronics may enable long duration missions on the surface of Venus operating for periods of up to a year where the sensors and all other components operate at Venus ambient. However, the types of measurement that can be made from these vehicles will be limited.
5. **Stirling Cycle Technology**: To achieve the long term objective of Mission Modes that operate on or near the surface of Venus for months at a time, highly efficient thermal conversion and cooling devices are needed but are currently at a very low level of maturity. Mechanical devices typified by the Stirling cycle-engines developed for the ASRG are required for this. While radioisotope power systems of lower efficiency using thermocouple converters may satisfy many NASA, Stirling system are irreplaceable for the mobile laboratory.
6. **Aerial Platforms:** After more than a decade of development, the technology for deploying balloon payloads approaching 100Kg 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 atmosphere and with the ability to modify altitude are much less mature and need development. A buoyant vehicle, operating close to the Venus surface, is one option for the Regional Mobility Mission Mode called for in the VER but requires major development.
7. **In Situ Instruments:** Since the last Venus technology assessment performed in support of the Planetary Science Decadal Survey in 2011, there has been significant progress in instruments for surface geology and geochemistry. The utility of 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 At this stage, the best approach for pursuing the scientific objectives defined by the GOI team are not clear and a workshop focused on this topic is desirable.

9.0 ADDITIONAL WORK PLANNED

This Venus Technology Plan is a work in progress with a completion date targeted for the spring of 2014. This version has been prepared for distribution at the time of the Fall American Geophysical Union (AGU) meeting. The following revisions are anticipated in the near term.

1) **Alignment with Companion documents**: The companion Exploration Roadmap and Goals, Objectives and Investigations documents have been developed in parallel and while there has been communication between the teams we still need to refine the alignment of the content of the three documents.

2) **Funding of technologies:** The current version of the Technology Plan indicates those technologies that need work to be ready for missions but does not indicate if that work is funded.
3) **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 may need special attention if they are critical to implementing high priority missions. The current version of Technology Plan does not identify these technologies separately

REFERENCES

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[1] Venus Goals Objectives and Investigations Document – VEXAG Review Draft, Nov 19, 2013

[2] Venus Exploration Roadmap, VEXAG Review Draft team, Nov 19, 2013

[3] Vision and Voyages for Planetary Science in the Decade 2013-2022, National Research Council, 2011

[4] Solar System Exploration Roadmap, by NASA's Planetary Science Division, 2006

[5] Extreme Environments Technologies for Future Space Missions, JPL D-32832, 2007

[6] Technology Perspectives in the Future Exploration of Venus by James A. Cutts, Tibor S. Balint, Eric Chassefiere and Elizabeth A. Kolawa, GEOPHYSICAL MONOGRAPH SERIES, VOL. 176, PP. 207-225, 2007

[7] Venus Flagship Mission Study, Report of the Venus Science and Definition Team, Task Order NMO710851 17, April 2009

[8] Technologies for future Venus exploration, White Paper to the Planetary Science Decadal Survey, Tibor S Balint, James A. Cutts, Mark Bullock, James Garvin, Stephen Gorevan, Jeffery Hall, Peter Hughes, Gary Hunter, Satish Khanna, Elizabeth Kolawa, Viktor Kerzhanovich and Ethiraj Venkatapathy, September 2009

[9] "Adaptive Deployable Entry and Placement Technology (ADEPT)," E. Venkatapathy, P. Wercinski, K. Hamm, B. Yount, D. Prabhu, B. Smith, J. Arnold, A. Makino, P. Gage and K. Peterson, International Planetary Probe Workshop, Toulouse, Fr., June, 2012.

[10] *Smith et al, 2013 IEEE, " Venus In Situ Explorer Mission Design using a Mechanically Deployed Aerodynamic Decelerator")IEEE, 2013*

[11] Technology Development for a Long duration, Mid-Cloud Level Venus Balloon," *Advances in Space Research* by J. L. Hall, A. H. Yavrouian, V. V. Kerzhanovich, T. Fredrickson, C. Sandy, Michael T. Pauken, Eric A. Kulczycki, Gerald J. Walsh, M. Said, S. Day (2011). ", Vol. 48, No. 7, pp. 1238-1247, October, 2011.

[12] Autonomous Landing and Hazard Avoidance Technology (ALHAT) – Technology Demonstration Mission http://www.nasa.gov/mission_pages/tdm/alhat/index.html

[13] Jeffery L. Hall and Andre H. Yavrouian, "Pinhole Effects on Venus Superpressure Balloon Lifetime", AIAA Paper 2013-1292, presented at the 2013 Balloon Systems Conference, Daytona Beach, FL., March 26-28, 2013.

[14] Technology Development for a Long duration, Mid-Cloud Level Venus Balloon," *Advances in Space Research* by J. L. Hall, A. H. Yavrouian, V. V. Kerzhanovich, T. Fredrickson, C. Sandy, Michael T. Pauken, Eric A. Kulczycki, Gerald J. Walsh, M. Said, S. Day (2011). ", Vol. 48, No. 7, pp. 1238-1247, October, 2011.

[15] Science and Technology Interchange Meeting on the Venus Upper Atmosphere at Glenn Research Center, Jan 2013 (http://www.lpi.usra.edu/vexag/Venus_UA_STIM_Agenda.pdfworkshop)

[16] Comparison of Aerial Platform Options for Investigating the Unknown Ultraviolet Absorber on Venus by James Cutts and Patricia Beauchamp, International Planetary Probe Workshop (IPPW-10), 2013

[17] Novel Architecture for a LongLife, Lightweight Venus Lander by D. Bugby, S. Seghi, E. Kroliczek, and M. Pauken Citation: AIP Conference Proceedings **1103**, 39 (2009);

[18] Venus Surface Sample Return: A Weighty High_Pressure challenge by Ted Sweetser, Jonathan Cameron, Gun-Shing Chen, Jim Cutts,Bob Gershman, Martha S. Gilmore, Jeffrey L. Hall, Viktor Kerzhanovich,Angus McRonald, Erik Nilsen, Walt Petrick, David Rodgers, Carl Sauer, Brian Wilcox, Andre Yavrouian, Wayne Zimmerman, American Astronautical Society, 2001.

[19] Extreme Environments Technologies for Future Space Missions, JPL D-32832, pages 236-237, 2007.

[20] Carbon nanotube-based digital vacuum electronics and miniature instrumentation for space exploration by

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H. Manohara, R. Toda, R.H. Lin, A. Liao, M. Mojarradi, Proceedings of SPIE Vol. 7594, 2010.

[21] Guidance Navigations and Control Assessment for Future Planetary Science Missions: Part III Surface Guidance Navigation and Control, by Marco Quadrelli and Michael McHenry, JPL D-78106, April 2013.

[22] Monocular Vision for Long-Term MAV Navigation: A Compendium, by Stephan Weiss_, Markus W. Achtelik_, Simon Lynen, Michael C. Achtelik, Laurent Kneip, Margarita Chli and Roland Siegwart, Journal of Field Robotics, 30(5), Sept/Oct 2013.

[23] Multi-Modal Image Registration for Localization in Titan's Atmosphere by Adnan Ansar and Larry Matthies, IEEE/RSJ International Conference on Intelligent Robots and Systems, October 2009.

[24] X-ray Diffraction Results from Mars Science Laboratory: Mineralogy of Rocknest at Gale Crater by D.L.Bish et al Science Vol 341, 2013

[25] Raman and Laser-Induced Breakdown Spectroscopy (LIBS) remote chemical analysis under Venus Atmospheric pressure by S.M. Clegg, S.K.Sharma, A.K. Misra et al, 43rd Lunar and Planetary Science Conference 2012,

[26] Report of the Mars 2020 Science Definition Team by J. Mustard et. Al. July 1, 2013.

[27] Detecting atmospheric perturbations produced by Venus quakes, by Raphael Garcia, Philippe Lognonné and Xavier Bonnin, Geophysical Research Letters, Vol 32, L16205, 2005