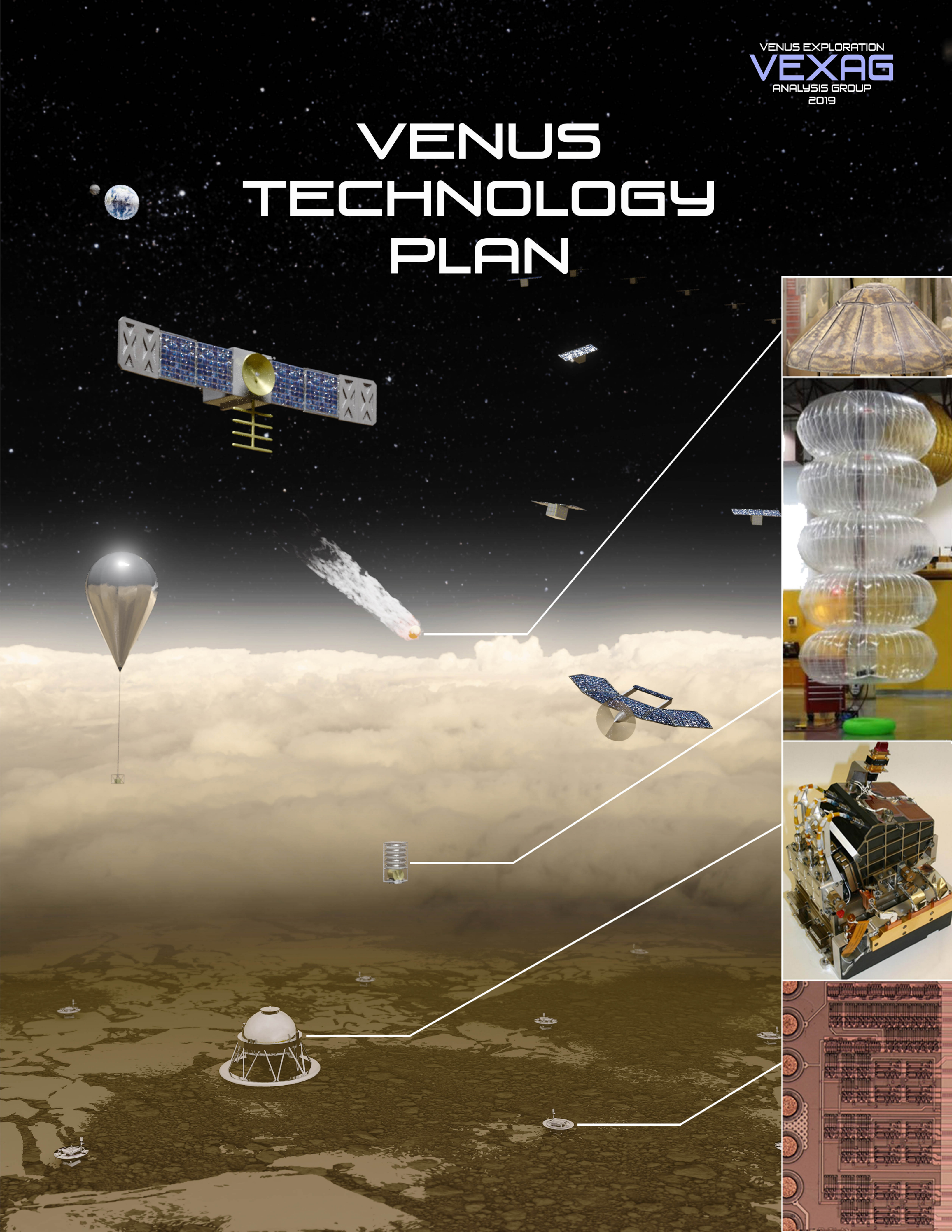
VENUS EXPLORATION
VEXAG
ANALYSIS GROUP
2019

VENUS TECHNOLOGY PLAN



At the VEXAG meeting in November 2017, it was resolved to update the scientific priorities and strategies for Venus exploration. To achieve this goal, three major documents were selected to be updated: (1) the Goals, Objectives and Investigations for Venus Exploration: (GOI) document, providing scientific priorities for Venus, (2) the Roadmap for Venus Exploration that is consistent with VEXAG priorities as well as Planetary Decadal Survey priorities, and (3) the Technology Plan for future Venus missions. Here we present the 2019 version of the VEXAG Technology Plan.

Prepared by the VEXAG Focus Group on Technology and Laboratory Instrumentation: Gary Hunter (Chair), Jeffery Balcerski, Samuel Clegg, James Cutts, Candace Gray, Noam Izenberg, Natasha Johnson, Tibor Kremic, Larry Matthies, Joseph O'Rourke, and Ethiraj Venkatapathy.

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VEXAG Charter. The Venus Exploration Analysis Group (VEXAG) 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 (PSD) in the Science Mission Directorate (SMD) 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 recommendations for the *NRC Decadal Survey* and the *Solar System Exploration Strategic Roadmap*.

1.0 Executive Summary

Venus exploration provides one of the most diverse sets of technical challenges in the solar system: an orbital environment allowing use of conventional orbiter platforms but with specialized instrumentation, an upper atmosphere with the most earthlike and accessible environment in the Solar System, and an extreme pressure/temperature environment on the surface.

This Technology Plan is simultaneously a status report, a development plan, and guiding document for the accompanying Goals, Investigations, and Objectives (O'Rourke et al., 2019) and Roadmap (Cutts et al., 2019) documents. The plan builds progressively from low to very high levels of maturity that could be accomplished over time with technology investments. Sections encompass both what is necessary for a single complete mission profile, and the broad array of technologies and components needed for wide range of mission proposals today and in the future. Needs for NASA investment arising from this study are summarized in Table 1.

Table 1. Major Needs Arising from This Study

Area	Needs
Entry Technology	Funding to ensure the entry technology capability does not atrophy
Subsystems	Development of high temperature electronics, sensors, and high-density power sources for the Venus environment with increasing capability
Aerial Platforms	A competitive program to determine which Variable Altitude balloons approach is most viable
In situ Instruments	Adaptation of flight-demonstrated technology and development of new instrument systems uniquely designed for the Venus environment
Communications and Infrastructure	Study of the feasibility of and methods for establishing a Venus communications and navigation infrastructure
Advanced Cooling	Investments in highly efficient mechanical thermal conversion and cooling devices
Descent and Landing	New concepts for adapting precision descent and landing hazard avoidance technologies to operate in Venus' dense atmosphere
Autonomy	Transitioning of automation and autonomous technologies to Venus-specific applications
Small platforms	Development of small platform concepts in addition to larger missions, as well as a new mission typedesigned around small platforms
Facilities and Infrastructure	Support of laboratory facilitiies and capabilities for instrument and flight systems, including critical technologies to avoid atrophy of capabilities
Modeling and Simulations	Establishment of a system science approach to Venus modeling
Unique Venus Technology	Continued and expanded support for programs such as HOTTech, and other technology development

While many of scientifically important missions to the second planet can be implemented with existing technology, some fundamental science questions can only be successfully answered with new mission paradigms. Some ambitious missions require investment in and maturation of new technologies, while other new technologies can leverage recent advances and commercial developments. An effective Venus exploration technology program includes a balance of investments in short-term missions and technology, enabling new paradigms and more ambitious future missions in the medium- and long-term. This *Venus Technology Plan* performs a detailed assessment of the maturity of the technologies needed to conduct missions to Venus.

2.0 Technology Plan Overview

Common components comprise all mission types: instruments, power, operations, and communications, varying significantly depending on the type of mission. Technology developments from exploration of other planets and other fields enhance the missions that can now be conducted on Venus. In the future, developments across a range of fields will also enable new types of missions. An energetic Venus exploration program would combine well-established technologies and mission concepts with new capabilities to address core Venus science questions from a combination of orbital, aerial, and landed platforms.

Table 2 presents the framework for assessing technologies for Venus exploration. Time frames in the second column map to those used throughout the Venus Exploration Documents, and assume investments required for development are made:

N is Near-term: 2020 to 2022: Represents "existing" technologies that are ready today or with limited development. Missions using these technologies can be proposed now with fully developed science rationale.

M is Mid-term: 2023 to 2032 - First Decade: Technology will be ready with moderate development. Mission concepts using these technologies can be proposed and executed during the period of the next Decadal Survey.

F is Far-term: 2033 to 2042+ - Second Decade: Science rationale exists for technology and these missions, concepts of operation, science instruments, and associated technology require additional time and resources for development. Moderate to high levels of investment are required, and as a result, missions are likely to be executed after the next Decadal Survey.

Table 2 shows a range of technology areas discussed in subsequent sections. Categories include systems technologies (Section 3) at the scale of the spacecraft/platform; Subsystems technologies (Section 4) for particularly important components of these systems; and Instruments (Section 5) to be tailored to Venus' unique conditions.

Table 3 describes possible Generic Mission Modes in the Near-, Mid-, and Far-term, with possible mission classes from 2020 to 2042 based on development progress from Table 2. Further discussion on the correlation between the GOI, Roadmap, and Technology Plan is in Appendix B. Table 4 color-codes the maturity of each technology relative to the Generic Mission Mode. An up arrow denotes a technology that has been notably advanced since the last Technology Plan. Lack of color-coding indicates that a technology is not applicable to that specific mission type. (Mobile Surface and Sample Return missions require significantly more technology development, and are thus far-term capabilities beyond the Decadal-after-next.)

For Near-term missions, technology maturity is very high (dark green).

For Mid-term missions, ready technologies need only limited (light green), or moderate (yellow) investment with defined pathways to achieve the generic missions described.

For Far-term missions, maturity ranges from being ready (green) to technology pathways nearing realization in that timeframe (yellow), to those needing basic research (red).

Table 4 shows a progression with increasing capabilites and increasingly complex missions. Near-term baseline missions could be proposed today, while new mission types and science could be proposed and flown in the next Decadal period with adequate technology development. Far-term Venus exploration will require, building from the Mid-Term, overcoming major technical challenges. Technology investment can surmount previous challenges of Venus exploration and enable new frontiers in Venus science and exploration.

Table 2. Framework for assessing technologies for Venus exploration

	Technology Area	Time Frame	Assessment
System Technologies	Aerobraking	N, M	Aerobraking is a mature technology and autonomous aerobraking can reduce the cost and risk while improve the time to achieve the desired orbit.
	Aerocapture	N, M	A large gap in aerocapture has been met with a nearly mature HEEET technology.
	Entry (Upper Atmosphere)	N,M	ADEPT with a sounding rocket sub-orbital flight test requires minimal additional development for enabling small and cube-sat missions to Venus.
	Descent and Deployment	M,F	Controlled descent of probes, drop-sondes, and aerial platforms in development for future use in atmospheric profiling. Incorporating guidance, with improved navigation, could enable more accurate targeting for these and lander systems.
	Landing	N,M,F	Hazard tolerance allows a wide range of near term missions. In the future, pin-point landing and hazard avoidance technologies will allow new mission scenarios.
	Entry, Descent, and Landing (EDL) Modeling & Simulation	N,M, F	Updates are needed for multiple modeling systems, including modeling for descent GNC pin-point landing and hazard avoidance.
	Aerial Platforms	N,M, F	Technology for near-term missions is mature. Technology investments are needed including new science instrumentation, and modeling tools to characterize the behavior of vehicles in the Venus environment. However, there are no technological show stoppers to impede the development of these capabilities.
	Atmospheric Entry Platforms	N,M, F	Methods to explore the atmosphere that are not aerial platforms include skimmers, probes, and sondes. These are advanced technologies, and future system may include targeted descent and surveying.
	Landed Platforms	N,M,F	Three classes of landed platform are envisioned involving increasing technical challenges: short duration containing analytical instruments (near term, current technology), long duration with sensors (mid term), and long durations with a complex instrument suite (far term). Significant advances have been made to enable longer term surface platforms.
	Orbiters	N,M,F	In general, orbiters are mature, capable, and can be adapted for different mission profiles. Potential technology enhancements include instrument advances, optical communications, and improved on-board computing.
	Mobile Platforms	F	Mobile systems would require a range of subsystems technology to allow, e.g., motion, power, cooling, and actuation, for extended periods. These are major challenges for mobile systems on the surface, but achieving these objectives with floating platforms may be more viable but also challenging.
	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. Atmospheric return missions are more feasible but significant challenges remain.
	Small Platforms	N, M, F	SmallSat, CubeSat and other small platform technology can make important contributions to Venus exploration. The development of small platform concepts as an addition to larger missions, as well as a new mission type or mission augmentation, is an integral part of a complete multistage Venus exploration program.
	Automation and Autonomy	M, F	Increasing capabilities for automation and autonomous decision-making combined with increasing computing power can change the way missions are conducted. Efforts to transition automation and autonomous technologies to Venus specific applications would enhance science delivered and mission success.
Subsystem Technologies	Power	M,F	Battery development is on-going for long-lived surface lander systems. Thermoelectric generators capable of operating in a 460 C environment are needed and maturing the capability of a mechanical converter (e.g., Stirling cycle) can be enabling for multiple mission types. Novel power concepts are also in development for future missions e.g., wind and other mechanical methods, solar power, or alternate chemical methods.
	Thermal Control	N,M,F	Extending lander life by a factor of 10 (to 25 hours) is feasible in the mid-term 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 have been advanced for simple platforms.
	Communications	N,M,F	Optical communications have advanced notably and are expected to ready to enhance future missions. Proximity communications are needed to enhance data return from all *in situ* missions including on-surface communications.
	Guidance, Navigation, and Control	M	Miniaturized low power systems are needed for localization and attitude knowledge on probes, aerial platforms, dropsondes and for pinpoint landing.
Instruments	Orbital Remote Sensing	N	Technology for implementing these missions is here today. Advances in radar and infrared techniques would be enhancing.
	Probe and Aerial Platforms	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 maturation of sensors that operate at Venus ambient. In far term, need totally new approaches for mobile laboratory.

Table 3. Generic Mission Modes descriptions for Near-, Mid-, and Far-term Missions

	Mission Mode	Generic Description
Near-Term	Orbiters- Fixed	Orbiters for investigations including surface, interior, atmospheric, and ionosphere
	Small Sat	A single small or cube sat conducting a focused science investigation
	Deep Probe	A probe characterizing the environment down to the surface
	Multiple Shallow Probes	Shallow probes or skimmers characterizing the upper-mid atmospheres
	Short Lived Large Lander	A short lived lander comprised of a conventional electronics instrument suite
	Aerial Platform Fixed	Aerial platforms with ability to operate in the atmosphere for sustained periods, but without flight control
Mid-Term	Advanced Orbiters	Highly complex orbiter systems with increasingly capable instrument array and limited ability to independently carry out and optimize investigations
	Multiple Deep Probes	Deep probes and sondes coordinated with aerial platform operations and each other
	Subsatellite/ Small Sat Platforms	Communication and observations systems able to provide a multiple scientific investigations as well as a communications and navigation infrastructure
	Aerial Platforms: Altitude Control Upper and Mid Cloud	Aerial platforms operating in mid and upper clouds with ability to control altitude
	Increased Duration Large Lander	A lander comprised of advanced thermal thermal protection extending life to 12 hours or more, and increasingly capable conventional electronics instrument suite
Far-term	Small Platform Lander- Long Duration	Small in situ platforms capable of operating at Venus ambient conditions to accomplish focused science investigations
	Advanced Orbiter /Smallsat Networks	An orbiter network composed of advanced orbiters and small sats providing coordinated science and mission communications support
	Aerial Platforms: Altitude Control All Cloud	Aerial platforms with ability to operate in the atmosphere for sustained periods throughout the various cloud altitudes
	Lander -Cooled Long Duration	A complex long-lived cooled landed systems with a suite of advanced earth-ambient temperature instruments
	Lander Network	A number of lander systems coordinated and linked in multiple scientific investigations, which are composed of a mixture of increasingly complex high temperature landers
	Mobile Surface	Mobile laboratory systems able to travel significant distances on the surface
	Sample Return Clouds	Sample recovery and return from the upper atmosphere
	Sample Return Surface	Sample recovery and return from the surface

Table 4. Mission modes and applicable technologies for Near-, Mid- and Far-term missions

	Mission Mode	Near-term Missions: Orbiters	Small Sat	Deep Probe	Multiple Shallow Probes	Short Lived Large Lander	Aerial Platform Fixed	Mid-Term Missions: Advanced Orbiters	Subsatellite/ Small Sat Platforms	Multiple Deep Probes and Sondes	Increased Duration Large Lander	Small Platform Lander-Long Duration	Aerial Platforms Altitude. Control Upper and Mid Cloud	Far-Term Missions: Advanced Orbiter /Smallsat Networks	Aerial Platforms Altitude Control All Cloud	Lander - Cooled, Long Duration	Lander Network-Long Duration	Mobile Surface	Sample Return Clouds	Sample Return Surface
System Technologies	Aerobraking																			
	Aerocapture																			
	Entry ⬆																			
	Descent and Deployment ⬆																			
	Landing																			
	Aerial Platforms																			
	Flight ⬆																			
	Landers ⬆																			
	Mobility																			
	Ascent Vehicle																			
	Small Platforms ⬆																			
	Automation and Autonomy ⬆																			
Subsystem Technologies	Energy Storage- Batteries ⬆																			
	Energy Generation- Solar ⬆																			
	Energy Generation - Radioisotope Power																			
	Energy Generation-Alternative Sources																			
	Thermal Control - Passive																			
	Thermal Control - Active																			
	High temperature mechanisms ⬆																			
	Moderate temperature electronics ⬆																			
	High temperature electronics ⬆																			
	Communications																			
	Guidance, Navigation, and Control			MM		MM	MM													
Instrument	Remote Sensing - Active																			
	Remote Sensing - Passive																			
	Remote Sensing - Surface																			
	Remote Sensing - Atmosphere																			
	In-Situ Aerial Platform and Probe																			
	In Situ Surface - Short Duration ⬆																			
	In Situ Surface - High Temperature Sensors																			
	In Situ Surface - Long Duration Mobile Lab																			

Color		⬆	(dark green)	MM	(light green)	(yellow)	(orange)	(red)
Title	Not applicable	Notable advancements since the last Rodamap	Very High. Ready for flight in this timeframe. Same as TRL 6	Mix of maturity. Some ready for flight, others at various maturity levels	Moderate to High. Limited development and testing still needed	Moderate. Active on-going R&D effort needed for readiness in this given timeframe	Moderate to Low. Significant R&D effort needed for readiness in this timeframe	Low. Major R&D effort needed with notable technical challenges
Description			Established for flight. May require resource commitment to maintain readiness or continuity of expertise		Defined transition to flight	Presently understood technical pathway to achieve capability by this timeframe	A viable foundation exists, but more than one technical pathway in consideration to achieve capability by this timeframe	It not clear how to achieve the targeted capability and basic research activities in multiple fields may be needed to achieve this capability by this timeframe

3.0 System-Level Capabilities

3.1 Aerobraking

Aerobraking technology uses atmospheric drag to modify the orbit of a spacecraft as it dips into the upper atmosphere of a planet. Information about density and winds is gleaned from spacecraft instruments such as an inertial measurement unit (IMU) during flight through the atmosphere. Aerobraking was used by the *Magellan* mission to lower the spacecraft orbit to a radar mapping configuration, and to circularize the orbit for gravity observations. ESA's *Venus Express* performed aerobraking maneuvers to characterize variability in the upper atmosphere. Multiple mars missions, e.g., the *Mars Reconnaissance Orbiter,* used aerobraking to obtain proper orbital timing and altitudes for science measurements while significantly reducing propellant requirements. The Mars *MAVEN* mission utilizes aerobraking techniques to raise its periapsis and lower its apoapsis to facilitate relays with Mars landers. Recent Mars spacecraft have been equipped with onboard algorithms that use periapsis timing estimation to provide automated orbital sequencing updates. Advances in onboard software, which include atmosphere and aerodynamic models as well as guidance and maneuver calculation algorithms, offer additional capabilities while ensuring aerobraking mission constraints are satisfied (Murri et al., 2010, Murri, 2013). Although aerobraking technology is now mature, spacecraft design (particularly solar panels) and orbital mechanics must be compatible with the Venusian heat and stresses generated.

3.2 Aerocapture

Aerocapture uses a deep pass through the upper atmosphere in one single orbit. A properly designed entry system with efficient thermal protection systems (TPS) protects the payload from mechanical and thermal loading arising from the single large velocity reduction during entry. Aerocapture has not yet been employed in planetary missions, but it could enable larger payloads to be quickly placed in orbit around Venus, especially those requiring orbits closer to the planet. Novel aerocapture approaches to achieve velocity reduction through drag modulation could enable small spacecraft missions in the near term. A scalable design could lead to middle and large class payloads that place an orbiter, allowing for single or multiple probe or balloon deployment. ADEPT technology (see below) combined with drag-modulated aerocapture is highly scaleable.

3.3. Entry (Upper Atmosphere)

Entry technologies need to be implemented for all mission modes in Table 3 except remote sensing missions. Although successful entry at Venus has been accomplished many times, some of the thermal protection technologies used in prior mission are no longer available. In addition, entry technologies are needed for single or multiple science instruments being proposed with cube-sat small spacecraft constructs. Even orbital missions using small spacecraft could be accomplished using both traditional rigid as well as novel deployable entry systems. Entry risks must be retired to realize potential missions of opportunity. This has been recognized by recent SMD funding of advances in entry system technology, including the following approaches:

3.3.1. 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 (Venkatapathy etal. 2012). Although successful in the past, this technological capability has atrophied. Raw materials are not readily available, so reproducing appropriate materials would require expensive revival of retired manufacturing processes and qualification of replacement materials. Thus, this solution is prone to premature obsolescence.

3.3.2. 3-D Woven Thermal Protection System: Heatshield for Extreme Entry Environment Techonology (HEEET) systems use 3-D woven materials infused with resin to withstand a broad range of entry environments, resulting in mass-efficient ablative thermal TPS. Two companies are capable of, and one has been certified to produce, flight-ready components for future Venus missions. The HEEET dual-layer system creates a robust and mass-efficient heat-shield compared to Carbon-Phenolic system. HEEET material has been tested at the arc jet Interacting Heating Facility (IHF) and can be tailored to 10's of gs rather than 100s of gs with Carbon Phenolic, enabling use of more sensitive optics in instruments. The HEEET project is now fully matured at TRL 6 due to technology investments.

3.3.3. Adaptable Deployable Entry and Placement Technology (ADEPT): This innovative approach involves protecting the payload during entry with a large deployed entry system to reduce the ballistic coefficient due to larger surface area. The ADEPT concept has the potential to provide significant payload mass capability compared to conventional rigid entry systems. Because the ADEPT configuration can be folded into a much smaller cross section during launch, it is well suited for delivery of small spacecraft to orbit, or for a secondary payload adapters where packaging is a constraint. The Hypersonic Inflatable Aerodynamic Decelerator (HIAD) (Bose et al., 2013) is an inflatable version of ADEPT that has been tested for Earth re-entry. The Venus Atmospheric Maneuverable Platform (VAMP) concept envisages using an inflatable structure for entry and flotation. ADEPT development for Venus is at TRL 5. Completion of ADEPT technology with a focus on secondary payload will enable small spacecraft aerocapture and entry missions.

It is critical that the SMD-PSD ensure the entry technology capability does not atrophy, and that periodic assessment and small investments be made to ensure HEEET and PICA continue to be available.

3.4. Descent and Deployment (from upper atmosphere to destination)

Descent/deployment capabilities are relevant to the same mission modes as those for entry. For probes, aerial platforms, and landers, rate of descent is controlled to stabilize vehicle attitude during passage to the surface through a progressively denser atmosphere. For probes and landed missions, velocity and attitude must be controlled during descent to provide time to sample different regions of the atmosphere, while limiting the dwell time at altitudes where the environment is harsh. This may require different sizes of parachutes or other aerodynamic structures. Special materials must be used to accommodate the high temperature acidic atmosphere, but these materials are available. For a landed mission with conventional electronics, the vehicle is brought quickly to the surface to minimize thermal input to the landing module. Maintaining attitude stability and minimizing jitter during descent are important for acquiring images with minimal motion blur. To date, all Venus descent systems studied/flown have been unguided, but incorporating guidance could enable more accurate targeting.

There is also a need to establish requirements for successful deployment of different aerial platforms. A successful balloon deployment/inflation test was conducted in the Earth's atmosphere during parachute descent (Hall et al., 2011) as a proxy for the Venus mid-cloud level. Descent velocity for a Venus airplane deployment depends on aircraft-specific design. Dropsondes deployed from an aerial platform could sample the atmosphere in multiple locations. Deep dropsondes can descend close to the surface relaying large amounts of high-resolution imaging data on potential landing sites. This technology requires further development for image generation.

3.5 Landing

By analyzing geomorphology data from previous missions (i.e., Magellan radar, Venera/VeGa lander imagery), models of the worst-case scenarios of slope have been developed to gain a better understanding of what types of terrain might be encountered. This method is meant for a semi-targeted landing in a broad region and will be the tool of choice for near-term landed missions. Hazard tolerance was the mode selected for the ViTaL study (Gilmore and Glaze, 2010) as well as for the recently proposed New Frontiers 2018 VICI Venus proposed lander mission (Glaze, 2017). Going forward, it should be feasible to draw on technologies developed by the Mars program and the STMD under the Autonomous Landing and Hazard Avoidance Technology (ALHAT) program. Considerations related to pinpoint landing and hazard avoidance include:

3.5.1. PinPoint Landing involves guiding the vehicle to a designated surface location by correlating its own images with prior orbital reconnaissance. This capability is TRL 8 for Mars and will be employed by Mars 2020. For Venus, the descent images could be acquired in the near infrared through windows near 1 μm (Helbert et al., 2014) and/or using radar. Using heterogeneous data sets like this has been studied and appears feasible (Ansar and Matthies, 2009). The control function would be quite different from landing on Mars and would use a steerable parachute or aerodynamic control surfaces. Steerable parachutes have been used on Earth in precision drops from aircraft for decades and have been studied for Mars. For Venus, it would be necessary to study how precise the ultimate landing could be.

3.5.2. Hazard Avoidance could be used independently or in combination with pin-point landing. It would acquire surface information (imaging, Light Detection and Ranging LIDAR, and radar) during the final stages of descent to identify areas of hazard and use onboard Guidance, navigation, and control (GN&C) capabilities to avoid them. These capabilities are beyond TRL 7 for lunar applications (Jiang et al. (2016). Hazard avoidance will be part of the *Mars 2020* lander using hazard maps generated on Earth. Hazard avoidance is now being studied for Europa, including onboard hazard detection. Analogous guidance and navigation capabilities have also reached a high level of maturity for navigating to the surface of primitive bodies. Rapid progress in miniaturization of high-performance processors, cameras, and inertial measurement units for Earth applications may be applicable for Venus descent and enable significant reduction in the avionics size and power consumption for guided descent.

3.6 Entry, Descent, and Landing (EDL) Modeling & Simulation (M&S)

EDL M&S capabilities are critically needed for implementation of all Venus mission modes designated in Table 3 except for remote sensing missions. Venus entry missions can leverage ongoing investments in aerosciences and material response modeling capabilities, but there are several unique aspects of the Venus environment that require dedicated development:

3.6.1 Aerothermal Models: Predicting the convective aerothermal environment during Venusian entry will rely on NASA tools such as Data-Parallel Line Relaxation (DPLR) code (Wright et al., 2009) and LAURA (Mazaheri et al., 2010). Those largely include models for Venus presently, although updates may be required, esp. for entry conditions encountering turbulent flow. Required updates are largely in-plan in the currently funded Entry Systems Modeling (ESM) Project (https://gameon.nasa.gov/projects-2/entry-systems-modeling/).

3.6.2 Shock Layer Radiation Models: Entry velocities are much higher than for Mars, which greatly increases the importance of shock layer radiation to overall heating levels. Databases in the NASA workhorse radiation codes NEQAIR (Cruden and Brandis, 2014) and HARA (Johnson et al., 2008) include relevant models for Venus shock layer heating, but are based on limited validation data. Required updates are not currently in-plan in the ESM Project.

3.6.3 Thermal Protection Material Response Models: Phenolic Impregnated Carbon Ablator (PICA) and HEEET are two heatshield TPS materials for future Venus entry missions. PICA has flown in CO_2 (Mars) and air environment and the thermal response model for PICA is flight validated. HEEET is a new material and the thermal response model developed is considered medium fidelity as ground tests are limited to testing in air and do not provide the ability to “test as we fly”. While the simulation tools allow for extrapolating from air testing to CO_2 (Venus), if the entry conditions are far beyond ground test conditions, then use of HEEET carries unknown risks. However, the thermal response models can be much improved for future use of HEEET if TPS flight data is obtained to develop high fidelity thermal response models to either reduce margin or identify areas of risks to mitigate them through better margin.

3.6.4 Descent Aerodynamics Models: At lower speeds, models are needed to ensure stable behavior of the entry vehicle before and after deployment of the parachute (or other aerodynamic structure). Required updates are largely in-plan in the ESM Project.

3.6.5 Flight Dynamics Models: Flight dynamics codes, such as the Program to Optimize Trajectories (POST) II (Powell et al., 2000), provide end-to-end simulation of the entire EDL sequence, including the impact of errors or dispersions. Current capability is likely largely sufficient for future mission needs.

3.6.6 Descent GN&C Models: Models and simulations are needed for pin-point landing and hazard avoidance, including performance of navigation sensors, hazard detection sensors, and the entire guidance, navigation, and control subsystem. Versions of such modeling and simulation capabilities have already been developed for guided descent for other planetary bodies, but such models must be updated to include relevant characteristics of Venus.

3.7 Aerial Platforms-Flight

A recent Venus Aerial Platform (VAP) Study (Cutts et al., 2018) examined the importance of mobility in the future exploration of Venus. Concepts examined range from fixed altitude platforms that are swept around Venus in the super-rotating flow, variable altitude platforms that can change altitude but have no other dimension of control, and platforms with some degree of three-dimensional control. The study found that variable altitude platforms preferably offer a significant increment in science over the fixed altitude platforms without the major increment in size, complexity, and associated low technology maturity of the platforms with lateral control. In addition, improvements in instruments, power, communications, and support capabilities for specific mission architectures are needed. There are multiple types of aerial platforms at different levels of maturity (Appendix B). They include a fixed-altitude (~55 km) super-pressure balloon (Hall and Yavrouian, 2013) as well as variable altitude platforms. The latter are referred to as aerobots because of their controllability; possibilities include pumped helium aerobots, pumped atmosphere aerobots, mechanical compression aerobots and phase change balloons.

Balloon navigation and autonomy require advances in satellite-based or on-board guidance and control. A program to determine which concepts are most suited to Venus operation while yielding the best scientific performance is needed. Superpressure balloons are a component of variable altitude balloons and represent a lower cost, lower risk alternative for a Venus mission.

3.8 Atmospheric Entry Platforms

Several atmospheric exploration methods are alternatives to sustained aerial platforms:

Skimmers are targeted vehicles with minimal thermal protection that enter and emerge from the atmosphere one or more times. The primary payload is typically a mass spectrometer or meteorological sensors. Sampled material analysis and data relay occur after the vehicle emerges from the atmosphere. Entry heating of the skimmer is modest, so TPS requirements can be relaxed and materials like PICA are quite adequate.

Probes are capable of surviving to surface contact, like Pioneer Venus. Possible payloads include a mass spectrometer, radiometer, nephelometer, etc. The high energy entry environment requires the use of HEEET technology.

Sondes with low mass can be deployed from an existing aerial platform. Sondes using conventional electronics as small as 5 kg can reach the surface of Venus and still remain operational. More advanced sondes would have the ability to navigate to surface features of interest in order to follow up survey investigations conducted with remote sensing.

3.9 Landers

3.9.1 Landers – Short and Increased Duration: Seven Soviet seven probes accomplished ~1-2 hour lifetimes with thermally insulated vehicles that maintained imaging sensors, communications systems, computers, and energy storage systems at temperatures below 100°C. The vehicles used insulated pressure vessels containing solid-liquid phase-change material (PCM) to extend surface lifetime. Improved passive thermal control allows survival on the surface of Venus for a period of hours with improved instrumentation. Concepts have been developed for deploying this type of small platform as a technology experiment, as a payload attached to a short-duration lander such as Venera-D (Zasova et al., 2019), or a platform that can be deployed in different configurations targeted for multiple types of science (NASA, 2017 and Grimm et al., 2018).

The lifetime of these landers could be increased to 20 to 25 hours using technologies such as PCMs employing the liquid-vapor transition in water and ammonia (Grimm et al., 2019). This would allow scientists to make decisions based on limited follow-up observations. These technologies should be considered for lander mission development.

3.9.2 Landers – Long Duration: Recently developed high temperature electronics, sensors, and other technologies have matured to a state where a simple long-life scientific probe would be feasible for Venus operations. The Long-Lived In-Situ Solar System Explorer (LLISSE) (Kremic et al., 2018a) could monitor conditions for up to one full Venus day, observing day to night cycles of illumination, surface winds, and temperatures, as well as short-term changes in atmospheric gases. Even small day-night temperature shifts at the surface may change certain chemical stability regions if the surface-atmosphere composition is very near the equilibrium chemistry of some constituents (Kremic et al., 2018b). The potential of a long-lived seismometer system on the surface of Venus has also been studied (Kremic et al., 2018b).

Bringing high temperature electronic circuits for sensors, data handling, communications, and power management to TRL 6 by 2019-2021 (Kremic et al., 2018b) would enable operation of such a long-lived lander. Because there is presently no viable low-power data storage, periodic transmission of data would be needed for long-term monitoring along with a coordinated orbiter to support lander telecom. High temperature technology development to improve power sources, develop low power memory, improve communications throughput, and support an in-situ camera system would enhance long-lived missions. Active cooling of a lander with Stirling power generation and refrigeration is also possible but likely in the far-term given the technical challenges and amount of radioisotope material needed.

Development of the high temperature electronics, sensors, and high density power sources designed for operating in the Venus environment with increasing levels of capability would be enabling for future missions.

3.10 Orbital Spacecraft

In general, orbiters are mature, capable, and can be adapted for different mission profiles. For example, an orbiter in a circular, low altitude, near-polar orbit can include high-resolution global imaging radar global coverage, or very high resolution in targeted regions, combined with global radar sounding. These orbiters can also perform global infrared mapping and acquire improved gravity data. An orbiter in an eccentric, long-period orbit would facilitate remote sensing (e.g., nadir and limb viewing) and include *in situ* sensors of the ionosphere and induced magnetosphere. Technology for implementing these missions is available now, although engineering challenges include thermal management for the low orbit and reducing the time needed to aerobrake into the circular orbit. Potential technology enhancements include optical communications and advanced onboard computing.

3.11 Mobility – Surface or near surface

Mobile platforms that operate on the surface or in the lower atmosphere could analyze surface compositional variations on a regional scale. They could 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. These systems include payload compartments maintaining temperatures at or below Earth ambient for imaging instruments. Currently, these high fidelity, visible imaging, and remote sensing infrared measurements require cooling. Operation at Venus surface temperatures would require high temperature sensor maturation. Other instruments may be operable in the range 150° to 200°C. Both power and cooling systems operable at Venus temperatures would need to be developed.

Concepts for floating platforms traversing the altitude range of the Venus surface and accessing all terrain types have been devised. Wheeled or legged vehicles require many mechanisms vulnerable to surface conditions. Issues of long-term near surface exposure to the corrosive conditions needs to be explored. Attaining a 10 to 100 km range would be challenging.

3.12 Ascent Vehicles

Venus Surface Sample Return (VSSR) is a long-range objective beyond 2043. Past studies of VSSR (Sweetser et al., 2003) have used architectures modeled on Mars Surface Sample Return. However, Venus sample return is significantly more challenging and is at a very low level of maturity, but will benefit from ongoing development of ascent vehicles for Mars.

3.13 Small Platforms

Rapid advances in spacecraft miniaturization have led to the development of CubeSats that create new opportunities for Venus exploration. The Venus Bridge Study (Grimm et al., 2018) concluded that SmallSat and CubeSat technologies for orbiters and various kinds of *in situ* vehicles (skimmers, probes, balloons and landers) and small platforms can make important contributions to Venus science (Grimm et al., 2018; Kremic et al., 2018). Technology is immature for some of these platforms, and any SmallSat at this stage is limited in size, weight, and power.

Propulsion systems enabling both injection on a Venus-crossing orbit and insertion into useful orbits or to Venus itself will be needed. Both ion propulsion and chemical propulsion systems, as well as aerocapture, are crucial. In addition, deployable antennas providing improved telecommunications links are highly desirable. Methods of achieving low cost for these missions without incurring a reliability penalty are needed. Small companies spearheading SmallSat and CubeSat development may be the key to small platforms fulfilling their potential.

Small simple lander platforms for extended surface operations periods may provide significant science return at greatly reduced costs. These lightweight systems could be delivered as a secondary launch from lunar missions, and may be deployed to the Venus surface from an aeroshell, balloons, or a lander. Investigations considered with these platforms range from meteorology, atmospheric chemistry, and seismology. **Development of small platform concepts as an addition to larger missions, as well as a new mission type or mission augmentation, is an integral part of a complete multistage Venus exploration program.**

3.14 Automation and Autonomy

Many aspects of Venus exploration are challenged by limited time and lack of human interactions during the mission. Machine-based intelligence can optimize science return by providing operation independent of human intervention. Automated systems can carry out set sequences of actions or make autonomous decisions with the capability for situational awareness, decision-making, and response. These advanced systems are rapidly increasing in capability and applicability and have great potential for Venus exploration, including 1) automated location of a desired surface target for image navigation and reduction of data volume, 2) altitude and mission control of a Venus balloon, and 3) autonomous lander operation on the surface. Autonomous systems can also collect and correlate data from the same phenomena observed from different vantage points on Venus to potentially identify events and patterns. Advances in automation and autonomy will broaden future Venus mission options. **Transitioning automation and autonomous technologies to Venus specific applications would enhance science delivered and mission success.**

Advanced automation, autonomy, and GN&C capabilities typically require advanced onboard computing capabilities, which must have minimal size, weight, and power (SWaP) consumption. Venus systems that face less extreme environments can be enhanced by advanced processors and other avionics. NASA's High-Performance Space Computing (HPSC) (Powell, 2018) is developing advanced computing systems useful for Venus aerial platforms and descent systems. Commercial-grade electronics may also offer improvements in performance and SWaP, such as processors developed for smart automobiles.

4.0 Subsystem Technologies

4.1 Power Subsystems

4.1.1. Energy Storage – Batteries: Many of the mission modes described in Table 3 could be implemented successfully with existing technology. Batteries for long-duration missions as well as work addressing requirements for missions such as LLISSE (Kremic et al., 2018a) are in development (Nguyen and Hunter, 2017). Batteries with high power density, reduced self-discharge, and rechargeability would expand mission capabilities. Secondary batteries may also handle peak loads accompanying a radioisotope power system.

4.1.2. 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/landers. For long-lived landers, the limited solar energy reaching the surface poses significant challenges to developing efficient energy converters that operate at these temperatures. The limited power return from standard solar cells at higher temperatures return has motivated exploration of other approaches (Landis and Haag, 2013). HOTTech program solar cell development supports concepts including low-altitude balloons (0 to ~20 km) as well as aerial platforms at high altitudes (Grandidier et al., 2018). Advances in solar power technology could be enabling for aerial platforms. Airplanes require efficient, lightweight, and acid-resistant panels clad on both sides of the deployable. Long-duration aerobots (balloons) need very lightweight, acid-resistant systems to minimize the payload mass.

4.1.3. Energy Generation – Radioisotope Power Source (RPS): Radioisotope power may play an important part for extended *in situ* Venus exploration. Applications include aerial platforms, which may spend considerable time on the nightside of Venus but would operate at moderate temperatures (-20° to 150°C), and lander missions with temperatures are up to 460° C. Given the recent selection of the *Dragonfly* mission and plans for Mars sample return, both of which rely upon RPS, availability of sufficient mass for additional missions is uncertain.

4.1.3.1. High Temperature Thermoelectric Converter: Both Mars *Curiosity* and *Mars 2020* use a Multi Mission Radioisotope Thermoelectric Generator (MMRTG). An enhanced version- the eMMRTG - is also under development. Either could be used for aerial platform missions. For surface operations, requalification or redesign would be needed to tolerate high temperatures because the cold end of the RPS is at Venus ambient. Efficiency of thermoelectric systems is low under these conditions and a more efficient RPS system is desirable.

4.1.3.2. Advanced Stirling Radioisotope Generator (ASRG): A highly efficient Stirling engine coupled with linear alternators would be able 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.

4.1.3.3. ASRG for High g and High T Conditions: For entry systems, the ASRG would need to be ruggedized. Lacking current development work, feasibility of this has not been assessed. For operation near the Venus surface, a version of the ASRG capable of operating with its cold end near ~500° C is needed. A design of a Stirling power/cooler for Venus was formulated (Sierra Lobo, 2012). Materials (Ritzert et al., 2011) and availability of radioisotope power units pose challenges.

While all three of these options are technically feasible, the qualification challenges associated with the use of radioactive sources are formidable.

4.1.4. Alternative Energy Sources: For long-duration operations deep within Venus' atmosphere, wind shear and temperature gradients can be exploited to harvest energy. A wind turbine concept (Kremic et al., 2018a) is being developed to provide up to ~0.4W (Landis et al., 2017). Additional energy sources include 'lithium candles' using ambient atmosphere as an oxidizer for a thermal engine, and clockwork power using gravity or buoyant forces to drive mechanical generators (Nguyen and Hunter, 2017; Oleson and Paul, 2016). Another approach (Bachelder et al., 2014) involves a reversible fluid balloon, cycling up and down using the Venus atmospheric temperature gradient as a heat engine while harvesting power with a rotor beneath the balloon. There are certainly other approaches that could be considered.

NASA should continue and expand support for programs such as HOTTech, and identify where joint sponsorship and dual use development can be leveraged that would result in new mission capabilities.

4.2 Thermal Control

4.2.1. Passive Thermal Control: Thermal control systems minimize heat transfer from the environment to the probe. They also 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 ~two hours on Venus. Contributing 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 heat leaks due to windows and cabling is an important part of the design process.

4.2.1.1. Large Landers: Technological readiness is very high for lifetimes of 2 to 3 hours. Liquid vapor PCMs (water or ammonia) may extend this by a factor of 10. PCM may also be coupled with a lithium getter to avoid the need to vent to the atmosphere.

4.2.1.2. Microprobes/Dropsondes: Thermal control technology advances will extend performance. Analyses for the Venus Aerial Platform study indicated that a streamlined vehicle as small as 5 kg could reach the surface and return surface images. Advances in insulation and phase change materials could extend the lifetime of such a vehicle.

4.2.1.3. Aerial Platforms: Aerial platforms could repeatedly descend to the base of the Venus clouds near 40 km, where temperatures approach 127º C. Passive cooling systems would be used repeatedly as the platform cycled to and from upper clouds (-23º C).

4.3 *Active Thermal Control*

An approach has been identified for a scalable, efficient, powered refrigeration/cooling system to maintain temperatures at operational levels for time periods as long as months (Kolowa et al., 2007). The current state of development of active thermal control technologies capable of operating in the Venus near-surface environment is low. At present, active coolers also need very high power, requiring that the efficiency of, e.g., a Stirling-type radioisotope generator be high. **Investments in advanced cooling technology are needed to enable future missions.**

4.4. Extreme Environment Technologies

4.4.1 High-Temperature Electronics:

4.4.1.1 Medium-Temperature Semiconductor-Based Electronics**:** Electronics stable at 200–300 °C are commercially available with a broad set of options. Their use with cooling systems in Venus surface missions would significantly reduce the required delta-T, and hence reduce the power required for long-duration surface missions vs. systems cooled to Earth-ambient temperatures. They could be used without cooling systems for aerial platforms operating at temperatures too high for conventional silicon electronics.

4.4.1.2. High Temperature – Silicon Carbide Semiconductor-based electronics: The first microcircuits of moderate complexity that have shown extended operation *in situ* in Venus simulated surface conditions (Neudeck et al., 2016) and for thousands of hours at 500°C in Earth air ovens (Spry et al., 2017) have recently been implements. These circuits can be up scaled in complexity. Circuits with near 200 transistors per chip operated for 60 days in simulated Venus surface conditions (Neudeck et al., 2018; Voosen, 2017). Development is ongoing to demonstrate circuits and materials (Lukco et al., 2018) to provide operations for a long-lived surface lander, including all aspects needed to conduct a simple mission: power management circuits, signal conditioning electronics for multiple sensors, conversion into digital signals, and communication of the data at up to 100 MHz in frequency. Proof-of-concept demonstration of these technologies is ongoing to provide a complete, although simple, operational system. These developments in high temperature electronics represent a paradigm shift for Venus surface operations, extending functionality from ~2 hours to months. However, these electronics are 1980's levels; these systems do not have internal memory and so data are broadcast periodically to an orbiter. While ROM and RAM high temperature memory is in development (Nguyen and Hunter 2017), decreased power consumption and increased storage is needed for some mission scenarios.

4.4.1.3. Other High Temperature Electronics: Carbon nanotube electron sources can operate as field emitters without the need for a heated cathode. This field is immature but shows potential for low-powered, high-temperature memory and logic devices with no temperature-dependent leakage currents (Manohara et al., 2010). In Gallium Nitride Electronics, high electron-mobility transistor devices with pinch-off values <2 V have been demonstrated at 500°C, and more advanced circuits are under development (Nguyen and

Hunter 2017). Substrates, passive components, and integration techniques (as well as packaging) require development and are at a lower level of maturity.

4.4.2 High-Temperature Mechanisms: Robotic mechanism technology enables short-duration (<1 Earth day) surface mission sample acquisition, drilling, and delivery. A general-purpose electromagnetic actuator (motor, feedback sensor and gearbox) has been tested in environmental chambers that operate at full Venus surface temperature and pressure.

For long duration (60+ days) surface and low atmosphere missions, even high-performance aerospace grade materials, coatings and lubricants need to be re-evaluated for compatibility with corrosive chemical species found in the near-surface atmosphere. Extended exposure to high ambient temperatures also causes over-aging of high strength metals. Ceramics offer a partial solution, but rigorous design and analysis methods need to be developed, and material formulations, processing steps, and test methods need to be standardized. A broad range of higher-level mechanisms are required for Venus, including the following:

4.4.2.1. High-temperature mechanisms for surface missions: Motors and encoders exist today that have operated for long periods at Venus surface temperatures. Many of the required mechanism components, materials, lubricants, etc. have been developed for operation at Venus temperatures. Significant materials development, along with testing and qualification for the full Venus environment is still required, especially at the system-level.

***4.4.2.2. High-temperature mechanisms for sample acquisition and storage*:** Sample handling and caching techniques need to be tested with the mechanisms and instruments for the full Venus surface environment, including control and fault algorithms.

4.4.2.3. High-temperature mechanisms for descent guidance and control. Guidance during descent will require mechanisms that can steer during at least some portion of the descent, facing temperature and corrosion challenges. This would be a relatively short-duration application, because Venus descent takes roughly less than one hour.

4.5 Communications

Communications for the “Trunk Line” between Venus and Earth, and among assets deployed to accomplish specific science activities will be required:

4.5.1 Communications for orbiters: Systems exist today for Venus orbiters to communicate with Earth at rates up to 10 Mb/s. Optical communications would enhance that data rate by at least a factor of 10. Component technologies developed for a Deep Space Optical Communications (DSOC) are now being integrated into the DSOC Flight Laser Transceiver (FLT) and ground-based receiver to enable photon-efficient communications. The DSOC payload is scheduled to launch in 2022 aboard the *Psyche* mission, reaching its destination in 2026. Optical communications could greatly enhance the capabilities of any future Venus mission involving radar imaging and interferometry provided an optical communications ground infrastructure is also developed.

4.5.2. Proximity Communications - probes, sondes and aerial platforms: For *in situ* atmospheric missions with direct-to-Earth communications, development of phased-array and other more efficient antennas would greatly enhance data return. The IRIS V2.1 Deep Space Transponder is targeted for Class-D space flight projects, utilizing COTS-grade components with minimal SWAP fully transponding at 3.8 W radio frequency output interoperable with NASA’s Deep Space Network and will be used on MarCO. This technology will be important for future SmallSat and CubeSat orbiters, small low-cost probes, and aerial platforms.

4.5.3. Communications on the Surface: Surface-to-orbit communications systems for long-duration surface missions are under development for long-lived landers. Communication frequencies up to ~100 MHz are planned by 2021, closely coupled with electronics development (Kremic et al., 2018a,b). Reduction of power needs for data transmission and increases in both frequency and data rates are areas of future development.

Studies of the feasibility of and methods for establishing a Venusian communications and navigation infrastructure are recommended.

4.6 *Guidance, Navigation, and Control*

Guidance, navigation, and control (GN&C) for orbital spacecraft present no unusual requirements. For *in-situ* elements, GN&C is needed for a range of motion planning, sensing, and vehicle control tasks. A recent assessment of these technologies for *in-situ* missions (Riedel and Aung, 2013; Quadrelli et al., 2013) concluded for Venus:

4.6.1. Landed Missions: Application of pin-point landing and hazard avoidance technologies would be important for safe landing of a mission to the Venus tesserae. Venus-unique needs include infrared sensors for imaging the surface during much of the descent phase, techniques for matching heterogeneous (infrared and radar imaging) data sets to support pin-point landing, and methods for achieving control authority in thick, hot atmospheres, including various forms of gliding decelerators. Work is required on hazard detection sensors that survive and operate in the Venus low-altitude thermal environment, and on methods to achieve control authority in the dense Venus atmosphere that are efficient.

4.6.2. Aerial Platforms: Knowledge of the position, velocity, and attitude (especially azimuth) of a platform is important for scientific objectives and high-gain communications. This is possible by radiometric tracking from Earth when aerial platforms are in line-of-site from Earth. Beyond line-of-sight for aerial platforms descending below the cloud deck, position estimation, possibilities include using radiometric measurements from orbiters (SmallSats and CubeSats), onboard registration of night-side images of the surface, and global radar maps of the surface created from orbiters (Ansar and Matthies, 2009). For attitude, tilt is readily measurable with inertial sensors, but azimuth is difficult to obtain within or below the cloud deck. Potential onboard solutions include radio direction-finding on signals from Earth or orbiters, and registration of surface imagery to global radar maps when the platform is below the clouds on the night side. Miniaturized onboard navigation grade IMUs could sustain position, velocity, and attitude after each external source measurement for at most a few hours.

4.6.3. Mobile Platforms on The Venus Surface or in the Lower Atmosphere: These classes of mobility platforms require position and heading knowledge to control their motion. Depending on the level of autonomy, they may also require onboard perception systems.

New concepts are needed for adapting precision descent and landing hazard avoidance technologies to operation in the dense, hot Venus atmosphere.

5.0 Instruments

5.1. Remote Sensing—Active

Radar was used on both NASA (Magellan) and Soviet-era Venera spacecraft to characterize the Venus surface. Improvements since that time enable much higher resolution images to be obtained. Since then, ESA Venus Express (Gilmore et al., 2015) and new laboratory data (Helbert et al., 2017) have demonstrated the ability of an orbiter to collect emissivity spectra and interpret rock type (Dyar et al., 2017) and oxidation (Dyar et al., 2018) through windows ca.

1 µm in Venus' CO_2-rich atmosphere. SmallSats and CubeSats will enable cross-links between pairs of spacecraft. The number of transects will increase as the square of the number of spacecraft making it possible to greatly increase atmospheric coverage.

5.2 Remote Sensing – Passive

Advances in techniques for passive remote sensing have been accompanied by progress in miniaturizing instrumentation. Seismic events couple to the atmosphere as infrasound, so the dissipation of the waves can be observed from space as they modulate electron densities and optical emission. In the dense atmosphere of Venus, seismic waves are coupled 60 times more efficiently than on Earth, making smaller quakes detectable. Infrared spectral imaging techniques could detect events on both the nightside and dayside of Venus. Probing the tenuous reaches of the upper atmosphere on Venus may now be possible using miniaturized submillimeter sensors.

5.3 Aerial Platform and Probe

Many instruments needed for atmospheric probes and higher-altitude aerial platforms that maintain internal temperatures well below Venus surface ambient are relatively mature. Needed advancements are engineering challenges specific to missions or measurements. Miniaturization of instruments would reduce mass, power, and volume for these applications. The Venus Aerial Platform study (Cutts et al., 2018) identified several of these categories of observation:

5.3.1. Atmospheric Composition: Mass spectroscopy is the standard method for precision measurements coupled with targeted measurements using a Tunable Laser Spectrometer (TSL*)*. Progress in development of Quadrupole Ion Trap Mass spectrometers (QITMS) could enable aerial platforms with small science payload capability to do high caliber science.

5.3.2. Cloud Particle Size and Composition: Comprehensive understanding of Venus' cloud-forming aerosols and their precursors remains elusive. Optical techniques for characterizing particle sizes can be coupled with mass spectrometry techniques for measuring particle composition, but no such hybrid instruments exist. Cloud composition may be critical to detection of life in Earth-like environments (Limaye et al., 2018). Several methods might be used for life detection, including mass spectrometers that can investigate multiple aspects of the cloud composition (Baines et al., 2018).

5.3.3. Atmospheric Structure: Not all techniques for measuring atmospheric structure are applicable to a floating or flying platform. Most critical are methods for measuring position and velocity of the platform so that the velocity of the winds can be inferred.

5.4.3. Aerial Platform Geophysics: The proximity of a platform to the surface and its atmospheric contact enable several important geophysical techniques: infrasound seismology, remnant magnetism, electromagnetic (EM) sounding and gravimetry. Miniaturized instruments are needed and where feasible be demonstrated in Earth analog experiments.

5.4 Landed Missions: Ambient Temperature Operation

Landed missions focus on elemental, mineralogical, and petrologic analysisof surface materials. Due to limited lifetimes on the surface, the speed of these measurements is vital. The Venus Science Priorities for Laboratory Measurements and Instrument Definition Workshop report (Kremic and Singh, 2015) suggests that miniaturization and increased sensitivity of heritage instruments, such as mass spectrometers, will be key. A new generation of mature optical instruments can undertake chemical analysis with fewer moving parts and lower power requirements than traditional approaches. But these instruments must be tested against harsh Venus conditions. Calibration of these instruments with Venus reference atmosphere chemistry and physical environment is needed, as are technical developments:

5.4.1. Measurements of Chemistry: Two techniques are feasible for measuring the composition of elements. X-ray fluorescence (XRF) was used by the APXS instrument on *Curiosity* and will be used by the Planetary Instrument for X-ray Lithochemistry (PIXL) on *Mars 2020* (Allwood et al., 2014). Laser-induced breakdown spectroscopy (LIBS) generates a plasma from the heat of a laser and performs its measurements at standoff distances. The LIBS analysis ablates material, also investigating the depth of surface weathering by probing below the rock surface. Both ChemCam on *Curiosity* and SuperCam on *Mars 2020* use this technology (Clegg et al., 2012, 2014; Maurice et al., 2012, Wiens et al., 2012), and are coupled with a Raman spectrometer. Venus LIBS is being studied by the Venus In Situ Compositional Investigation (VICI) (Glaze, 2017) to investigate near-surface atmospheric gradients that could affect the focus of the LIBS ablation laser.

5.4.2. Measurements of Mineralogy: Both x-ray diffraction (XRD) and Raman spectroscopy can measure mineralogy. XRD was used by CheMin on *Curiosity* (Bish et al., 2013); it currently requires sample collection and transport into the lander for analysis. The Venus Flagship Mission Study (Hall et al., 2009) 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. Raman analysis (Clegg et al., 2014; Sharma et al., 2010 and 2011) under Venus surface conditions is not affected by the supercritical atmosphere. It is used on *Mars 2020* by SuperCam and the Scanning Habitable Environments with Raman Luminescence for Organics and Chemicals (SHERLOC) (Beegle et al., 2014) instrument. Any of these techniques would be highly useful on Venus.

5.4.3. Fine-Scale Contextual Elemental and Mineralogical Analysis: Context for geochemical and mineralogical measurements is critically important, and can be provided by a microscopic imager analogous to the Mars Hand Lens Imager (MAHLI) instrument on *Curiosity*. The ability to do such measurements *in situ* is technologically challenging.

The adaptation of flight demonstrated technology to Venus applications and the development of new instrument systems uniquely targeted to the Venus environment should continue to be supported. Establishing and maintaining laboratory, modeling, and simulation capabilities is strongly recommended.

5.5 Landed Missions: High Temperature Operational

Long-duration measurements on the surface of Venus are challenging with existing technology. But focused investigations will likely be viable by the mid-2020's using small long-lived platforms with electronics and sensors designed to operate without thermal, chemical, or pressure protection. One SmallSat mission concept (Kremic et al., 2018b) proposes to deliver two landers to the surface of Venus for 120 days of operation. Active development of Venus surface-appropriate technology (e.g., a meteorology suite, ruggedized MEMS seismometer and heat flux sensor, as well as high bandwidth communications) would enhance the viability of such a mission.

Extending camera operation beyond the short-term would also require technology development because conventional camera systems are not viable under Venus conditions. A simple approach using the high temperature technology from *Viking* could be considered (Huck et al., 1975). A solid-state magnetometer that measures magnetic field induced changes in current within a SiC pn junction is also being considered (Cochrane et al., 2016, 2018). Both of these instruments would require novel approaches and sustained development.

5.6 Long Duration Mobile Laboratory

Most concepts for a long-duration surface laboratory have assumed that much of the instrumentation is contained in a protected temperature-controlled volume at near-Earth ambient with active cooling. Challenges for long-duration missions still apply e.g. increased mass/power, but are more difficult due to the power needed to operate instruments in constant listening modes.

Significant thermal control advancements enabling use of mature sensors or high-temperature electronics systems, sensors, and memory specific to those instruments are needed. The ability to reliably mobilize a platform on the Venus surface for a long period of time requires advances in motors using permanent magnets with high Curie temperatures, and windings resistant to the corrosive atmosphere. Less conventional approaches include wind-driven sails (Landis et al., 2017), balloon “bouncers” (Bachelder et al., 1999), or mechanical walkers (Landis and Mellott, 2007; Sauder et al., 2015). A near-surface floating laboratory could rise to high altitudes for cooling, or operate near the surface but at cooler temperatures, reducing demands on the cooling system or high temperature mechanisms. In either case, new sensors for imaging and geophysical measurements (magnetic fields, gravity and infrasound) would broaden science return.

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Appendix A
Reading Between The Venus Exploration Documents

The GOI, Roadmap, and Technology Plan are correlated documents with different purposes. This is illustrated in Table A.1, which correlates the Roadmap's primary scientific objectives (based on the GOI), with Technology Plan Table 2. The Roadmap is more specific on, *e.g.,* multiple types of orbiters or surface lander platforms, than the Technology Plan. Table A.1 shows that there is a general correlation in the science delivered between the Roadmap and Technology Plan for comparable missions/mission modes. The Technology Plan then goes beyond the roadmap in the far term to discuss enabled new types of missions, capabilities, and science.

Table A.1. Science Payload Capability of Roadmap correlation with Technology Plan Mission Modes

	Mission Mode	Generic Description	Example Roadmap Science Objectives
Near-Term	Orbiters	An orbiter using radar for surface mapping, and active remote sensing	Surface and Interior: Global and Targeted; Atmosphere and Ionosphere: Synoptic for for topography, emissivity, gravity, radar sounding, etc.
Near-Term	Aerial Platform Fixed	Aerial platforms with ability to operate in the atmosphere for sustained periods, but without flight control	Fix Altitude: Atmopsheric and Interior Investigations
Near-Term	Deep Probe	A probe characterizing the environment down to the surface	Classic entry probe or sonde: Broad suite of instruments includiing mass spectromenter, nepholometer, temperature, pressure, and surface imaging
Near-Term	Multiple Shallow Probes and Skimmer	Shallow probes characterizing the upper-mid atmospheres	Skimmer: Sampling the Venus atmosphere at a very high altitude and emerging from the atmosphere for sample analysis and data relay
Near-Term	Lander Short Lived	A short lived lander comprised of a conventional electronics instrument suite	3-5 hour lander: Broad suite of instruments focused on atmospheric and interior investigations
Mid-Term	Advanced Orbiters	Highly complex orbiter systems with broad instrument array and limited ability to independently carry out and optimize investigations	Atmosphere and Ionosphere: Optimized for atmospheric remote sensing and in situ sensors of the ionosphere and induced magnetosphere
Mid-Term	Subsatelite/ Small Sat Platforms	Communication and observations systems able to provide multiple scientific investigations as well as a communications and navigation instrastructure	Highly targeted investigations requiring tailored orbits. May also provide relay, navigation support, and synergistic science for surface and aerial platforms
Mid-Term	Aerial Platforms- Altitude Control Upper and Mid Cloud	Aerial platforms operating in mid and upper clouds with ability to control altitude	Variable Altitude: Atmopsheric and Interior Investigations below 60 km and ability to tolerate higher temperatures
Mid-Term	Increased Duration Large Lander	A lander comprised of advanced thermal thermal protection extending life to 12 hours or more, and increasingly capable conventional electronics instrument suite	12 hours lander: Advanced suite of instruments with interaction with earth to optimize science delivered.
Mid-Term	Small Platform Lander- Long Duration	Small in situ platforms capable of operating at Venus ambient conditions to accomplish focused science investigations	Temperature, wind, chemical species for extended durations

In particular, the Roadmap identified a range of specific platforms that embody the Generic Mission Modes described in the Technology Plan. These are specific categories of platforms for deploying investigations from orbit, from within the atmosphere, and on the surface that employ the capabilities in the Technology Plan for specific mission functions. **The Roadmap Mission Platforms are embodiments of the Generic Mission Modes of Technology Plan Table 2.** These include:

- Lander capabilities grouped as short-lived, long–lived, and advanced:
  - **Short-lived landers**: Patterned on the technologies used in past Soviet era lander missions but with improved instrumentation.
  - **Long-duration landers:** Use high temperature electronics capable of operating at 500°C, which are still under development and have never been used at Venus.
  - **The Advanced Lander**: Envisaged for the post decadal period would incorporate both kinds of capabilities with extensions to the useful lifetime of both as well as the progress in precision landing. In the post decadal period, the Roadmap envisages Advanced landers being developed that include part of the instrument payload implemented with conventional electronics that would function for up to an Earth day and part of it with high temperature electronics which would operate for up to a Venus years.

- Three types of platform for making measurements of no more than a few hours in the atmosphere:
  - **Skimmer:** A targeted vehicle with minimal thermal protection that enters and emerges from the atmosphere one or more times. The primary payload is a mass spectrometer but could also include meteorological sensors. Analysis of the sampled material and data relay would occur after the vehicle emerges from the atmosphere. The entry heating experienced by a skimmer is modest and consequently thermal protection system requirements can be relaxed and materials like PICA are quite adequate.
  - **Probe:** This is the classic (e.g., Pioneer Venus) probe capable of surviving to surface impact. Possible payloads include a mass spectrometer, radiometer, nephelometer, or other instruments for surface imaging and atmospheric studies. The high energy entry environment requires the use of HEEET technology discussed in Section 5.3.
  - **Sonde:** A low-mass sonde deployed from an aerial platform that has already entered and deployed in the atmosphere. Possible payloads are similar to those indicated for the Atmospheric Entry (Probe) mission but would be limited in mass. Analysis suggests that sondes using conventional electronics as small as 5 kg can reach the surface of Venus and still remain operational. More advanced sondes would have the ability to navigate to surface features of interest in order to follow up survey investigations conducted with remote sensing.
- Three categories of orbital spacecraft to conduct investigations:
  - **Orbiter – Surface and Interior:** The spacecraft is in a circular, low altitude, near polar orbit. Imaging radar could provide global coverage with high resolution, or very high resolution in targeted regions combined with global radar sounding. These orbiters could also perform global infrared mapping and acquire improved gravity data. The technology for implementing these missions is available now although engineering challenges include thermal management for the low orbit and reducing the time needed to aerobrake into the circular orbit. Potential technology enhancements include optical communications and advanced onboard computing.
  - **Orbiter -Atmosphere and ionosphere:** The spacecraft in an eccentric, long-period orbit. Extensive instrument suites would facilitate remote sensing (e.g., nadir and limb viewing) and in situ sensors of the ionosphere and induced magnetosphere. Typically, the spacecraft technology is less demanding than for investigations of the surface and interior and the data return requirements are typically less demanding. Advanced onboard computing would be an asset for performing event detection onboard (lightning, quakes, volcanic eruptions).
  - **Orbiter – SmallSat or CubeSat:** An orbiting SmallSat (or CubeSat), or multiple SmallSats to measure different locations at the same time. SmallSats may potentially host a wide variety of instruments. However, any single SmallSat is limited in size, weight, and power in comparison to conventional orbiters. Developments in miniaturization will be needed to fully exploit these capabilities. Access to Venus orbit could be enabled by advances in solar electric and chemical propulsion as well as aerocapture (Section 5.2).

Overall, the VEXAG "Roadmap for Venus Exploration" describes a program of Venus exploration featuring twelve mission modalities as presented in O'Rourke et al. (2019) in the Goals, Objectives, and Investigations document. Table A2 indicates those that are potentially useful to each GOI Investigation. VEXAG GOI is not designed to prescribe particular missions; the omnibus table is only intended as a general guide.

Table A3 examines the various Roadmap Platforms based on their technology maturity (similar to Table 4.3). **These Roadmap Platforms are deemed viable based on the Technology Plan and based on their technology maturity and timeframes considered.** The Venus Roadmap assumes a higher level of maturity required for mission consideration. For example, it requires enabling technologies to have advanced beyond the stage of basic research (i.e. invention required to be included), and it does not assume progressive technology development to enable a vision of future missions. Thus, Table A4 is a more conservative estimate of Technology Maturity than Table 4.3 above.

Table A.2 Mapping Between GOI And Roadmap Related To How Various Roadmap Missions Address GOI Science

VEXAG GOI			Roadmap Mission Modalities											
			Orbiter	Orbiter	Orbiter	Atmospheric Entry			Surface Platform			Aerial Platform		
Goal	Objective	Investigation	Surface/Interior	Atmosphere	SmallSat	Skimmer	Probe	Sonde	Short-lived	Long-lived (Pathfinder)	Long-lived (Advanced)	Fixed Altitude	Variable Altitude	Variable+ Altitude
			Near-term	Near-term	Near-term	Near-term	Near-term	Mid-term	Near-term	Mid-term	Far-term	Near-term	Mid-term	Far-term
I. Early evolution and potential habitability	Did Venus have liquid water?	I.A.HO. (1)	Blue	Yellow	Yellow				Blue		Blue			Blue
		I.A.RE. (1)	Blue						Blue		Blue	Yellow	Yellow	Yellow
		I.A.AL. (2)		Blue	Blue									
		I.A.MA. (3)		Yellow	Yellow				Yellow	Yellow	Yellow	Blue	Blue	Blue
	How does Venus inform pathways for planets?	I.B.IS. (1)				Blue	Blue	Blue	Blue		Blue	Blue	Blue	Blue
		I.B.LI. (1)	Blue	Yellow	Yellow					Yellow	Blue	Blue	Blue	Blue
		I.B.HF. (2)	Blue								Blue			
		I.B.CO. (2)	Blue							Yellow	Blue			
II. Atmospheric dynamics and composition	What drives global dynamics?	II.A.DD. (1)		Blue	Blue		Yellow	Yellow		Blue	Blue	Yellow	Yellow	Yellow
		II.A.UD. (1)		Blue	Blue	Yellow								
		II.A.MP. (2)		Blue	Yellow		Yellow	Yellow				Yellow	Blue	Blue
	What governs composition and radiative balance?	II.B.RB. (1)		Blue	Blue		Yellow	Yellow	Yellow	Blue	Blue	Blue	Blue	Blue
		II.B.IN. (1)		Blue	Yellow		Blue	Blue		Yellow	Yellow	Blue	Blue	Blue
		II.B.AE. (2)		Yellow	Yellow		Blue	Blue	Yellow	Yellow	Yellow	Blue	Blue	Blue
		II.B.UA. (2)		Blue	Blue		Yellow	Yellow				Yellow	Blue	Blue
		II.B.OG. (3)	Blue	Blue	Blue		Yellow	Yellow	Yellow	Yellow	Blue	Yellow	Blue	Blue
III. Geologic history and processes	What geologic processes shape the surface?	III.A.GH. (1)	Blue											Yellow
		III.A.GC. (1)	Yellow	Yellow	Yellow		Yellow	Yellow	Blue		Blue			Blue
		III.A.GA. (2)	Blue	Yellow	Yellow		Yellow	Yellow		Yellow	Blue	Yellow	Yellow	Yellow
		III.A.CR. (2)	Blue	Yellow	Yellow					Yellow	Blue	Blue	Blue	Blue
	Atmosphere and surface interactions?	III.B.LW. (1)	Yellow	Yellow	Yellow		Blue	Blue	Blue		Blue	Yellow	Yellow	Yellow
		III.B.GW. (2)	Blue	Blue	Blue				Yellow		Yellow	Yellow	Yellow	Yellow
		III.B.CI. (3)	Yellow	Yellow	Yellow		Blue	Blue	Blue	Yellow	Blue	Yellow	Yellow	Blue

Color Code	Meaning
Blue	**Vital:** Mission modality enables measurements that are vital (either alone or in combination) to completing the investigation.
Yellow	**Supporting:** Mission modality enables measurements that substantially contribute to completing the investigation.

Table A.3 Technology Maturity of technologies needs for Venus Roadmap Platforms.

	Roadmap Mission Modalities														
		Class	Orbiter - Surface and Interior		Orbiter Atmosph & ionosphere		Atmospheric Probes			Surface Platforms			Aerial Platform - Altitude Control		
Specific Technology Capability		Platform	Global	Target	Synoptic	SmallSa	Skimmer	Probe	Sonde	Short	Long	Advanced	Fixed	Var-1	Var-2
		Time Frame	Near	Mid	Near	Near	Near	Near	Mid	Near	Mid	Far	Near	Mid	Far
System Technologies	Aerobraking		Very High	Very High											
	Aerocapture														
	Entry ↑						Very High	Very High	Very High	Very High	Very High	Very High	Very High	Very High	Very High
	Descent and Deployment									Very High	Very High	Moderate			
	Landing									Very High	Very High	Moderate			
	Aerial Platforms ↑												High	Moderate	Moderate to Low
	Landers - Short Durations ↑									Very High		Moderate			
	Landers Long Duration ↑										Moderate	Moderate			
	Mobile Platform - Surface														
	Ascent Vehicle														
	Small Platforms/Cubesats ↑					High			High						
	Autonomy (Note 1) ↑		Very High	Very High	Very High	High	Very High	Very High	Moderate	Very High	High	Moderate	Very High	High	Moderate
Subsystem Technologies	Energy Storage- Batteries ↑		Very High	Very High	Very High	Very High	Very High	Very High	Very High	Very High	Moderate	Moderate to Low	Very High	Very High	High
	Energy Generation - Solar		Very High	Very High	Very High	Very High							Very High	High	Moderate
	Energy Generation - Radioisotope														
	Energy Generation-Alternative											Moderate			
	Thermal Control - Passive								Moderate	Very High			Very High	High	Moderate
	Thermal Control - Active														
	High temperature mechanisms ↑									Very High	High	High			
	High temperature electronics ↑										Moderate	Moderate to Low			
	Chemical Propulsion		Very High	Very High	Very High	Moderate									
	Solar Electric Propulsion		Very High	Very High	Very High	Moderate									
	Communications		Very High	Very High	Very High	Very High				Very High	Moderate	Moderate	High	Moderate	Moderate
	Guidance, Navigation, and Control		Very High	Very High	Very High	Very High				Very High	High	Moderate	High	Moderate	Moderate
Insutrument	Remote Sensing - Active		Very High	High	High	Moderate									
	Remote Sensing - Passive		Very High	High	High	High									
	In Situ Probe - Aerial Platform						Very High	Very High	High				Very High	High	Moderate
	In Situ Surface - Short Duration									High		Moderate			
	In Situ Surface - High Temperature										Moderate	Moderate to Low			
	In Situ Surface - Mobile Lab														
Platform	Maturity Assessment - Low End		Very High	Moderate	Very High	High	Very High	Very High	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate
	Maturity Assessment - High End		Very High	High	Very High	High	Very High	Very High	High	High	Moderate	Moderate to Low	High	Moderate	Moderate to Low

LEGEND	
(dark green)	Very High
(light green)	High
(yellow)	Moderate
(orange)	Moderate to Low
(red)	Low

Appendix B
Infrastructure Overview

1. **Ames Research Center (ARC) Arc Jet Interaction Heating Facility (IHF) Facility Enhancement:** The new 3" nozzle funded by SMD enhanced the NASA ARC IHF capability considerably and the capability allowed HEEET to be demonstrated for entry conditions ~ 5000 W/cm2 and > 5 atm. Missions (NF-4) that planned to use HEEET have opted to fly low entry flight path angle taking advantage of the mass efficiency of HEEET to achieve low entry g load. In order to verify/qualify HEEET design for future missions, it is necessary to have a slightly bigger (~ 4.5" dia.) nozzle. This will be the lowest cost to address future mission risks.
2. **Glenn Extreme Environment Rig (GEER):** The GEER vessel, operated by Glenn Research Center, has been operational since spring of 2015. This 0.8 m3 pressure vessel is capable of maintaining the physical and chemical conditions of the surface of Venus for an indefinite period of time, with continuous tests thus far of up to 80 days. Multiple user ports and a large hatch allow for accommodation of test articles ranging from 1 mm diameter geologic samples to complete instruments. Power and data feedthroughs have been custom developed to operate in the unique thermochemical environment, and a suite of candidate spacecraft component materials have been characterized for resistance to the Venus environment. Additionally, science investigations have used the vessel to recreate the surface conditions of Venus in order to study the unique behavior of surface-atmosphere interactions. GEER continues to gain new functional and analytic capability and is guided by annual reviews by an independent science advisory panel. GEER provides unmatched capability to mix and maintain an eight-component gas mixture in a large pressure vessel with precise thermal and chemical control.
3. **Goddard Flight Center:** A small Venus pressure test chamber, also known as VICI (Venus In-situ Chamber Investigations) available for testing of small components/instruments and running short-term experiments. The operating range of the chamber is room pressure to ~1380 psi (~96 bar), 25°C to 490°C, and the 'working' gas is typically CO_2. Gas mixtures that incorporate the three most abundant gases on Venus, CO_2, N_2, and SO_2, are also used depending on the experiment. The chamber interior or functional work volume is a five-inch diameter 316 stainless steel cylinder with approximately 11 inches of vertical space. Electrical/tubing feedthroughs and small sight windows are options that can be incorporated as needed into any particular test. There are pending plans to upgrade the chamber to a more resistant alloy.
4. **NASA JPL:** Multiple chambers exist of varying sizes and capabilities. 1) Venus Weathering Chamber. A 1.5 cm diameter by 15 cm long. chamber capable of exposing small material samples. Test conditions of up to 1000 °C and 1000 bars with mixtures of CO_2, N_2 and SO_2 gases are possible. 2) Small Venus Test Chamber. Provides a 10 cm diameter by 1.6 m long cylindrical working space using 460 °C, 92 bar CO_2 gas. An optional window facilitates optical experiments and pneumatic sample transfer experiments are accomodated. 3) Venus Materials Test Facility (VMTF). This chamber provides an 18 cm diameter by 56 cm tall cylindrical space suitable for a variety of testing purposes including testing of motors, drills and other electrical devices. It can provide 460 °C, 92 bar test conditions with CO_2 gas. 4) Large Venus Test Chamber (LVTC). A working space 31 cm in diameter and 2.4 m long. It can provide 460 °C, 92 bar test conditions with CO_2 gas. Supports full scale Venus drilling

and sample transfer experiments that include linear deployment of a drill assembly to the surface in addition to the drilling operation itself.

5. **Venus Optical Analysis Chamber:** Los Alamos National Laboratory has two – 2 m long, 110 mm diameter chambers that are capable of optically probing samples under 92 atm of supercritical CO_2 at 465ºC. These two chambers can be operated independently (2 m long path length) or together (4 m long path length). The chamber can be capped with sapphire, quartz or a steel plug on one or both ends of the chamber. It enables both active remote sensing with a laser as well as passive spectroscopy.

6. **Johns Hopkins APL:** The APL Venus Environment Chamber (AVEC) is a 0.7 L, portable, Inconel, vessel capable of maintaining conditions of 4000 psi at 500 C. Gases for the vessel are user-supplied and AVEC is expected to support the atmosphere of Venus and other planets. The vessel has a single feedthrough that is capable of supporting 2 and 4 wires for monitoring and operating active interior components, while physical conditions are monitored by a thermocouple (set in a 6” thermowell) and integrated pressure transducer.

Appendix C
Technology Highlights Since 2014

Venus Technology Roadmap presented in this document has notable differences from the previous version in 2014. Recent technology advancements have changed the landscape of Venus exploration and thus the Findings of this present Venus Technology Plan. In particular, Table A4 shows 2014 Findings and a 2019 State-of-The-Art Summary. This Table highlights that, although further development is needed due to the unique challenges of Venus exploration, advancements in Venus relevant technology in the last four years have been significant.

Table A4. 2014 Technology Plan Findings and 2018 Summary of the Present State-of-the-Art

2014 Finding	2019 State-of-the-Art Summary
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)….**This development needs the continued endorsement of the Planetary Science Division (PSD).**	HEEET is fully mature technology and ready for mission infusion. This closes a very large gap for Venus aerocapture, entry, descent and landed missions. ADEPT with a sounding rocket sub-orbital flight test requires minimal additional development for enabling small and cube-sat missions to Venus. See Section 3.3.2.
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. …. **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.**	Notable advancements have been made in moderately complex high temperature electronics with demonstration Venus simulated conditions for up to 60 days. These electronics are the foundation for development of a long-lived lander with an array of high temperature sensors intended for Venus surface operation for up to 120 days or more. See section 5.5.
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.***	Technology investments are needed including new science instrumentation and modeling tools to characterize the behavior of vehicles in the Venus environment. However, there are no technological show stoppers to impede the development of these capabilities. Flight tests using the Earth environments as an analog for Venus will be needed to optimize both the vehicles and science experiments. See section 3.7.
***In Situ* Instruments for Landed Missions:** Since the Planetary Science Decadal Survey in2011, 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	A workshop focused on instruments for Venus surface was conducted. Laser induced breakdown spectroscopy (LIBS) and Raman spectroscopy has been demonstrated. NASA awarded technology

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.***	development funding to the VICI New Frontiers 4 mission to mature the VEMCam (Raman and LIBS) instruments. See Section 5.4.
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.**	Development of three key enabling components of a Deep Space Optical Communications (DSOC) were developed 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. These technologies are now being integrated into a system scheduled to launch in 2022. See Section 4.4.
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 100ºC. 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 Tesserae 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 460ºC 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.***	Investments are presently on-going in battery and power technology with the objective of enabling small platform long-lived surface landers. Some advancements have been made in passive cooling approaches, but overall limited work has been done in advancing technologies such as Stirling cycle-engine to enable power and cooling since the 2014 Technology Plan. See Section 4.1
Advanced Descent and Landing: Lander missions for the mid-term would target the tesserae 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.***	Precision landing and hazard avoidance technologies have reached TRL 7 to 8 for missions to the Moon and Mars and are under development for Europa. These methods require significant further work for adaptation to the dense, hot atmosphere and long descent time at Venus. See Sections 3.5 and 3.6.