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WHITE PAPER TO THE NRC DECADAL SURVEY INNER PLANETS SUB–PANEL ON

TECHNOLOGIES FOR FUTURE VENUS EXPLORATION

by

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ABSTRACT

The purpose of this white paper is to provide an overview to the NRC Decadal Survey Inner Planets Sub–Panel on key technologies required for future Venus exploration missions. It covers both heritage technologies and identifies new technologies to enable future missions in all three mission classes. The technologies will focus on mission enabling and enhancing capabilities for in situ missions, because most orbiter related sub–systems are considered heritage technologies. This white paper draws heavily on the recently completed Venus Flagship Mission study that identified key technologies required to implement its Design Reference Mission and other important mission options. The highest priority technologies and capabilities for the Venus Flagship Design Reference mission consist of: surface sample acquisition and handling; mechanical implementation of a rotating pressure vessel; a rugged–terrain landing system; and a large scale environmental test chamber to test these technologies under relevant Venus–like conditions. Other longer–term Venus Flagship Mission options will require additional new capabilities, namely a Venus–specific Radioisotope Power System; active refrigeration, high temperature electronics and advanced thermal insulation. The white paper will also argue for a technology development program, since without it future Venus missions might not be achievable.

The primary purpose of this white paper is to provide relevant information to the NRC Decadal Survey Inner Planets Sub–Panel on Venus exploration related technologies. More detailed information is provided in the attachment, and in other reports including the Venus Flagship Mission study report [Hall et al., 2009]; the Extreme Environments Technologies for Solar System Exploration report [Kolawa et al., 2007]; the VEXAG Community white paper [VEXAG, 2007]; the Chapman Monograph chapter on Venus technologies [Cutts et al., 2007]; and the ESA Cosmic Vision EVE proposal [Chassefière et al., 2008].

Technologies discussed here are either based on existing capabilities, heritage technologies, or new technologies that can enable or enhance future missions. However, it should be noted that currently NASA does not have a dedicated technology development program to mature these capabilities. Sparse development activities at a number of NASA centers, targeting narrow research fields, using limited internal funding, is not sufficient and cannot form a coherent and coordinated program to address these issues. Furthermore, developments within industry are demand driven, where the requirements do not generally match the needs of the space industry. For example, demand for high temperature electronics that can operate on the surface of Venus is beyond the scope or development targets of any industry. Therefore, technology developments for exploring extreme environments — such as Venus — should be lead by NASA under a focused technology development program, in close collaboration with industry and academia to leverage their experiences in these fields. Furthermore, to enable a flagship class Venus mission by the second decade, a technology program to address key areas should start in the near future, since these developments are expected to have relatively long life cycles. Residuals from a well–crafted program could also benefit potential prior Discovery and New Frontiers mission, while cross cutting technologies (e.g., on high temperature mitigation) could be used on other planetary missions as well.

The chosen mission architectures and their mission elements are primary drivers for Venus technologies. These architectures can define large Flagship, medium New Frontiers and small Discovery class missions, with single elements or multiple elements. The recently completed Venus Flagship Mission study recommended a multi–element mission architecture for its Design Reference Mission (DRM), which is based on three science–driven platforms, namely on an orbiter, two cloud–level balloons, and two short–lived landers.

Since all of these platforms have been successfully used in the past for Venus exploration missions, this resulted in a very conservative approach to accomplish the mission's science goals. Consequently, the Venus Flagship DRM benefited from heritage technologies and, in turn, minimized the number of new technologies required for the implementation of this mission. This multi–element architecture also allows designers one to draw conclusions for technology needs for smaller (New Frontiers or Discovery class) missions, which would use similar mission elements. NASA's SSE Roadmap [NASA, 2006] and the VEXAG white paper on science [VEXAG, 2007] identified additional architectures, from the near surface Venus Mobile Explorer, to a Seismic Network, smaller New Frontiers class VISE [NRC, 2003] and Discovery class balloon missions [Balint & Baines, 2009], ultimately leading to a Venus Surface Sample Return mission.

Discovery and New Frontiers missions are not expected to include significant amount of new technologies and could be designed without them, although, if made available as part of a technology development program for a future flagship mission, they could benefit from it. For a flagship class mission, the Venus Flagship Mission study identified such broad–use key technologies that would require extensive development. For example, a sample acquisition and processing system for multiple samples that could operate under Venus surface conditions. The high temperature motors and actuators developed for sample acquisition system can be also used for the Venus Flagship Mission's pressure vessel rotation mechanism. The rugged terrain landing system needs to be developed in order to reliably access Tessera and other rugged areas on Venus. The pressure vessel, passive thermal control, and insulation for the short–lived lander (to be designed for 5 hrs) as well as technologies for mid–altitude balloons are considered to be mature. The capability to test and validate scientific measurements and to assess the survivability of all exposed sensors/instruments and lander components in Venus–like environment is critical to the mission success. This testing capability is mostly not available and needs to be developed.

Beside the Venus Flagship Mission architecture, other mission concepts were also assessed over the past few years. These included aerial mobility platforms capable of operating at distinct altitudes (e.g., near surface, mid–altitude and cloud level); long–lived landers; descent probes and drop sondes for atmospheric research; as well as a multi–element architecture in the form of a long–lived seismic network. Therefore, technologies developed to enable the Venus Flagship Mission could provide programmatic flexibility and enable these concepts if the flagship mission architecture is changed or if these concepts are flown later on.

The near–surface aerial mobility platforms will require the development and testing of materials for the lightweight pressure vessel as well as for a high temperature balloon system, likely in the form of metallic bellows. A suitable, low mass refrigeration system is critical for this mission concept. High and medium temperature electronics could provide significant benefits by reducing the temperature lift requirements on the refrigeration system.

Long–lived landers require similar critical technologies as low altitude balloons, but include also design solutions for safe landing. Long life (months or longer) will require new designs for pressure vessel potentially using new materials (e.g., beryllium or honeycomb structure based light weight designs). These static landers would also require a long–lived power source, such as a Venus–specific RPS coupled with an active refrigeration system. In addition, landers will require mechanical systems for robotic arms with an integrated high temperature sample acquisition system in order to acquire samples at different locations around the lander. Development of high, or even medium, temperature electronics and instruments is also crucial for reducing the refrigeration requirements.

An alternate form of long–lived lander is a seismic and meteorological station. A number of such stations can be envisioned to form a integrated network. Such stations may operate in Venus environment for extended periods of time with or without refrigeration depending on the availability of 460°C sensors and avionics. Although detailed performance requirements for these components will depend on the details of the selected architectures as well as on the science data acquisition scenarios, the general list of high temperature technologies will include high temperature sensors, power generation and storage, electronics for data acquisition and storage, power distribution and telecom. Maturing these technologies to the level where they can be used for Venus missions will require detailed planning and a significant long–term investment in technology development.

The summary table below lists the technologies that enable or enhance future Venus exploration mission. High priority technologies for the Venus Flagship Mission are highlighted in bold in a grayed cell, while new capabilities and enhancements to the VDRM are italicized in a lighter gray cell. Further information can be found in the references, and in the Appendix, which is posted with this white paper on the VEXAG website (**http://www.lpi.usra.edu/vexag/**)

Capability	Current State of the Art (TRL level)	Technology development needs to enable Venus missions	Benefits to future Venus missions
Pressure control	TRL 4–9 Titanium pressure vessel is space qualified; New lightweight materials need development.	Advanced materials (e.g., beryllium, honeycomb structures) could reduce structural mass.	Mass saving translates to higher payload mass fraction for the same entry mass.
Thermal control (passive)	TRL 4–9 Aerogels, MLI, PCM are space qualified, but not for high g–load entries and high temperatures.	High performance thermal insulation for Venus environment is required for mission lifetimes beyond Venera demonstrated lifetimes.	Improvements in passive thermal control could extend mission lifetime from ~2 hours to 5 hours or maybe more. (Beyond that active refrigeration and a power source is required.)
Surface sample acquisition and handling (VDRM)	TRL 2–3 Heritage Soviet–derived systems are not available off the shelf, but they demonstrate a feasible approach.	Surface sample acquisition system at high temperature and pressure conditions; Vacuum–driven sample transfer is demonstrated on Venera, but requires development for NASA.	Drilling, sample collection and sample handling are enabling for the Venus Flagship Mission.
Rotating pressure vessel (VDRM)	TRL 2 Rotating pressure vessel concept is powerful but technologically immature.	Full scale design and testing of a rotating pressure vessel with a driver motor and mounted sampling system.	It minimizes the external components, such as drill arms, actuators, motors, sampling systems; and the heat leakage from the outside through the number of windows required for panoramic imaging.
Rugged terrain landing (VDRM)	TRL 2 Russian landers provide proof of concept, however, these landed at benign surfaces and used a drag plate instead of parachutes.	Design and test a landing system that can account for a large variety of unknown landing hazards using parachutes.	Tessera and other rugged areas on Venus cannot be reliably accessed unless a properly engineered rugged terrain landing system is developed and tested.
Power storage	TRL 4 Demonstrated LiAl–FeS2, Na–S, and Na–metal chloride secondary batteries with specific energy in the 100–200 Wh/kg range; Short lived missions could use high TRL primary batteries.	Adapt high temperature cell and battery designs for space applications; Address stability of seals and terminals; Minimize the corrosion of current collectors at high temperatures; Optimize the electrolyte composition to improve performance and reliability.	High temperature batteries operating at Venus surface temperatures would make it possible to keep the power storage outside of the pressure vessel, thus reducing volume and thermal requirements for the pressure vessel.
Instruments (in situ) for the Venus Flagship Mission	TRL 2–9 Descent probe instrument heritage from Pioneer–Venus; New in situ contact instrument need development.	Several Venus Flagship Mission instruments, e.g., heat flux plate, XRD/XRF are at medium TRL; High–T seismometry and high–T meteorology are at low TRL; G–load tolerance during atmospheric entry should also be addressed.	In situ instruments are key drivers for Venus missions and are required for mission success.

Capability	Current State of the Art (TRL level)	Technology development needs to enable Venus missions	Benefits to future Venus missions
Power generation (new capabilities)	TRL 4 Demonstrated single Stirling convertor operation for 300 hours with a 850°C hot–side temperature and 90°C cold–side, 38% efficiency and 88 W power output with heat input equivalent to 1 GPHS module.	Cold side temperature must be raised from 90°C to 480°C with high conversion efficiency preserved (e.g., maintaining ΔT through increased hot end temperature, which would required materials or design development); Material testing, system development and validation for reliable operation in Venus surface environment.	Required for long life operation; Venus specific RPS with active cooling could enable long lived missions, operating for months; Low mass version could power near surface aerial mobility systems; It could power long lived seismometers and meteorology stations on the surface (117 days minimum).
Active refrigeration (new capabilities)	TRL 4 Cryocoolers are space qualified, but high temperature operation is not demonstrated at the system level.	Adopt Stirling conversion based coolers for Venus surface conditions; High efficiency duplex Stirling system must be produced that integrates the heat engine and refrigerator functions into a high efficiency and high reliability device; Refrigeration system should be coupled with the power source; Low mass and low vibration is desirable.	Almost every long–duration (~25 hrs+) in situ platform will require some amount of refrigeration to survive; Focus should be on radioisotope–based duplex systems that produce both refrigeration and electrical power; Low mass version would allow for near surface aerial mobility (metallic bellows); Low vibration version would enable a seismic network (on multiple landers) (117 days minimum); Extended mission life allows humans in the loop.
Advanced passive thermal control (enhancement to VDRM)	TRL 3–9 Venera and PV era insulation and phase change materials are mostly available.	Alternate insulation and phase change material technologies are needed to increase lander lifetimes beyond 2–5 hour operation.	Achievement of 12 to 24 hour lander lifetimes would enable humans–in–the–loop operation by ground controllers; Improved thermal insulation will decrease refrigeration requirements for truly long–term lander missions.
Testing facility (VDRM)	TRL 2-6 Two small Venus environment test chambers are operational at JPL; A small Venus test chamber setup is underway at GSFC; Proof of concept from Russian test chamber (decommissioned).	Large test chamber doesn't exist; Develop large Venus test chamber for full scale in situ elements (probe/lander) testing; Simulate transient atmospheric conditions; composition.	The 12.5 km anomaly on the Pioneer–Venus mission demonstrates the critical need for an environmental chamber using relevant atmospheric composition and conditions; It can test spacecraft components; validate and calibrate science instruments; test operating scenarios under realistic conditions.

Capability	Current State of the Art (TRL level)	Technology development needs to enable Venus missions	Benefits to future Venus missions
High–T and Medium–T components, sensors, and electronics (new capabilities)	TRL 2–4 Geophones could operate up to 260°C; High-temperature pressure, temperature, anemometers used on Venera/VEGA and Pioneer–Venus; Silicon based high–T components are designed for up to 350°C for the automotive and oil drilling industry; Limited number of components and integrated circuit capability demonstrated for SiC at 500°C; Limited electronics packaging at 500°C; Data storage, ADC, power converters, and other needed components never demonstrated.	High–temperature MEMS technology for seismometers could operate at surface temperatures; SiC and GaN high temperature sensors and electronics require development to operate at surface temperatures; Development of data acquisition, processing and storage capability, and packaging; Development of high–T power management; Demonstration of reliability and long life.	Long life on the surface is desirable (especially, for meteorology, seismometry); Sensors, actuators, instruments directly interfacing with the environment cannot be sufficiently protected, and therefore, high temperature components can enable operations and science measurements (e.g., long lived meteorology, seismometry) that otherwise cannot be achieved; High temperature data processing and storage, and power electronics results in a drastic reduction in refrigeration requirements, even at moderately high temperatures (>250°C); Low power dissipation at 300°C and long life reduces environmental tolerance requirements for components.
Upper atmosphere Balloons	TRL 5–7 Russian VEGA balloons successfully operated for 48 hrs over 20 year ago; Large super–pressure balloon have been built and tested at JPL and at CNES; Development for a mid–altitude balloon is underway at JAXA.	Cloud level balloons are considered mature, but further development, testing, verification and validation are required to address lifetime and reliability issues for a 30–day mission; Materials must tolerate high temperatures, corrosive environment (sulfuric acid droplets in clouds).	The Venus Flagship Mission balloons are designed for 30–days operation; An ASRG powered balloon mission could operate for months, circumnavigating the planet and continuously measure dynamics and atmospheric composition.
Near surface balloons	TRL 2–3 Metallic bellows proof–of–concept was built at JPL and tested at high temperatures.	Development is needed to build and test a metallic bellows system and test it under Venus surface pressure and temperature conditions; Near surface operation must address altitude change and surface access.	A near surface mobile platform could traverse hundreds of kilometers over a 90–day mission, image the surface at high resolution and periodically access the surface for sampling.
Descent probes and sondes	TRL 2–9 Pioneer–Venus probe heritage for large probes Microprobes have been designed but not yet tested.	Develop small drop sondes that could be released from a balloon platform (also work as ballast).	Drop sondes can enhance science by providing vertical slice measurements to complement balloon constant altitude measurements of the atmosphere.

Capability	Current State of the Art (TRL level)	Technology development needs to enable Venus missions	Benefits to future Venus missions
High–T Telecom	TRL 2 Demonstrated 2 GHz operation at 275°C using SiC; SiC and vacuum tube based oscillator demonstrated at ~500°C.	Development efforts should address SiC based RF components for transmitters; Miniaturized vacuum tube technology for power amplifiers; SiC based RF components for transmitters.	High temperature telecom on the surface would drastically reduce cooling requirements; It would enable long lifetime (117 days minimum); High data rate (~4.5 kbps) would support seismic operations; However, high temperature data storage at Venus surface temperature may represent a significant technology challenge.
Orbiter instruments and telecom	TRL 3–9 Magellan, Venus Express, Pioneer–Venus heritage; Venus Flagship Mission InSAR needs development.	Development is required for InSAR; passive infrared and millimeter spectroscopic techniques; and cloud LIDAR	InSAR is a key instruments on the Venus Flagship Mission; Ultra–fine resolution radar mapping and cloud LIDAR could provide high resolution science data on the surface and clouds, and highly desirable by science.
Atmospheric entry	TRL 5-9 Carbon-Phenolic (CP) used on Pioneer–Venus and Galileo probe; Provides heritage for use in steep entry flight path angle (EFPA) missions; Special rayon needed to make heritage CP; This rayon is out of production; Current arc jet capabilities are limited; Mars and Titan TPS, lower density, could be useful for lower EFPA.	1. Re-establish test capabilities; 2. Periodic verification of Industry capability to remanufacture heritage CP; 3. Establish alternate to heritage CP TPS, since heritage rayon is not made anywhere, anymore and current supply in hand is limited; 4. Assessment of lower density TPS be performed for shallow EFPA missions.	TPS is essential and enabler; High entry flight path angle (EFPA) entries result in high heat flux, pressure and g-loads; Limited supply of heritage CP enables unrestricted access to the planet; Lower density TPS can provide significant mass savings, but constrain the EFPA and thus the mission architecture.
Autonomy	TRL 4–6 Autonomous operation have been tested in previous missions (e.g., Pioneer–Venus probes), but at a lower complexity than required for a Venus Flagship Mission.	Develop and test reliable autonomous operation for a Venus surface mission, including control of the rotating pressure vessel; drill site selection; sample acquisition; instrument operations; reliable telecom.	Short lived missions (up to 5 hours) does not support humans in the loop; Autonomous operation is required for all science measurements and subsystem control.
Cross cutting technologies	See above	TPS; pressure vessel materials; passive thermal control (insulation; phase change materials).	These technologies can benefit a number of planetary missions, e.g., probes to Venus and deep probes to the Giant Planets.

Based on the information presented above, VEXAG recommends investments in key technologies to enable future Venus missions, including the development of a sample acquisition and handling system; a rotating pressure vessel; and a rugged terrain landing system. Building a test facility that could simulate Venus conditions between the surface and the cloud level is also recommended as

a high priority technology development item. Such a test chamber would be instrumental in the development and testing of new instruments and subsystems to be used on future Venus missions. A Venus Flagship Mission could be further enhanced by longer operating lifetimes on the surface. For this, development of a Venus specific Radioisotope Power System, coupled with active cooling, would be necessary. Development of high temperature tolerant components (e.g., sensors, actuators, and electronics) should be also considered, since these could provide new capabilities for proposed future Venus missions.

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APPENDIX: Extended Description of

TECHNOLOGIES FOR FUTURE VENUS EXPLORATION

Table of Contents

1. INTRODUCTION

The primary purpose of this document is to provide additional information to the NRC Decadal Survey Inner Planets Sub–Panel on Venus exploration related technologies. This overview draws from a number of sources, including two highly detailed reports, one on the Venus Flagship Mission study [Hall et al., 2009] and another on Extreme Environments Technologies for Solar System exploration [Kolawa et al., 2007]. It also references the VEXAG Community White Paper [VEXAG, 2007], the Chapman Monograph chapter on Venus technologies [Cutts et al., 2007], and the ESA Cosmic Vision EVE proposal [Chassefière et al., 2008].

Looking at historic Venus missions, conducting in–situ exploration of Venus, several conclusions can be drawn from the experience and technologies of Soviet and U.S. spacecraft. For example, it has been demonstrated that it is feasible to reach the surface of Venus and conduct scientific measurement in the Venus environment for time periods of the order of an hour or so, limited by the survivability in extreme environments and communication constraints related to those missions. The descent systems, such as probes or landers, require careful and in some cases creative designs, as well as the selection of materials that can not only survive but operate in these environments. During descent through an altitude of ~12.5 km there are certain atmospheric phenomena that can induce transient effects on the vehicle, which can have a serious impact on the subsequent execution of the mission (see 12.5 km anomaly on the Pioneer–Venus mission). The effects of long duration exposure to the environment in the lower atmosphere of Venus are unknown and more research is needed to understand the chemical and physical processes that may occur. Finally, some instruments can be operated while exposed to the Venus environment, but most of them must be contained in a temperature and pressure controlled vehicle.

The most recent assessment of Venus exploration related technologies was performed for the Venus Flagship Mission study [Hall et al., 2009], in which the proposed Venus Flagship Mission (also called as Venus Design Reference Mission or VDRM) manages to provide an outstanding science return with a multi–element mission architecture that requires limited development of new technologies. The surface sample acquisition and handling system, the rotating pressure vessel, and the rugged terrain landing system are the key areas where technology development is clearly needed for the two landers. In addition, there are sets of technologies (e.g., RPS with active cooling and high temperature electronics) that can either enhance the current Venus Flagship Mission or enable different and more ambitious alternate mission architectures. These technologies could also benefit potential future Discovery or New Frontiers class missions.

Success in accomplishing technology developments has a great influence on being able to conduct in situ missions, whether they are entry probes, landers or aerial platforms (targeting various altitude ranges). These technology developments are categorized as:

- Environmental–protection technologies providing isolation from extreme environments;
- Environmental tolerance for exposed components or systems; and
- Operations in extreme environments.

The first area includes technologies designed to protect spacecraft subsystems from the environment, including thermal protection systems (TPS) for hyper–velocity entry to mitigate extremely high peak–heat fluxes; as well as pressure and temperature control for the payload during in situ operations. The second area includes technologies needed for developing tolerance to the harsh conditions through "component hardening," for items such as electronics, electro–mechanical systems, and energy storage. Today's commercially available high–temperature electronics can operate up to only ~125°C, far below the temperatures for the Venus surface and near–surface environments. Development of temperature tolerance up to ~300°C, combined with a suitable thermal control would enable electronics to operate at or near the surface. The third area includes technologies for mobility, sample acquisition, and telecommunications systems.

Systems architecture selections will influence which technology developments are needed. In situ missions to Venus need a combination of technologies for high–temperature operations, including passive or active thermal control, pressure vessels, high–temperature electronics, energy storage, and high–temperature mechanisms. Venus landers with current technologies are limited to only a few hours of operation. Short–duration near surface and probe missions can operate with passive–thermal control. Long–lived near–surface missions may require active cooling to refrigerate the avionics and instruments, possibly powered by an internal power source, such as a Venus–specific Stirling Radioisotope Generator designed to operate in a relevant pressure and temperature environment. Improvements in pressure vessel materials would reduce mass, enabling additional payload (for an assumed constant entry mass). High–temperature sample acquisition systems will need environmental tolerance, as they interface directly with the environment. Also, materials research is needed for aerial mobility and parachute descent systems. For example, a Venus air–mobility platform employing metallic bellows would enable all axis control, long traverses, and surface access to multiple locations providing an advantage over static landers or rovers. An air–mobility platform enables in situ geological and geophysical investigations of the Venus surface over substantial distances.

2. EXTREME ENVIRONMENTS ON VENUS

Venus represents one of the most hostile environments in our Solar System. Its super–rotating atmosphere consists mainly of carbon dioxide (CO_2 ~96.5%) and nitrogen (N_2 ~3.5%), with small amounts of noble gases (e.g., He, Ne, Ar, Kr, Xe) and small amounts of reactive trace gases (e.g., SO_2, H_2O, CO, OCS, H_2S, HCl, SO, HF). The cloud layer contains aqueous sulfuric acid droplets at ~45 to ~70 km altitude. The zonal winds near the surface are ~1 m/s, increasing up to 120 m/s at an altitude of ~65 km, while the meridional winds vary between 0 m/s and ~15 m/s. Due to the greenhouse effect, the surface temperature reaches 460°C to 480°C. The average surface pressure can be as high as 92 bars. At conditions near the surface, the CO_2 becomes supercritical, which further complicates operations. In addition, electronics components and mechanical systems can fail under these supercritical CO_2 conditions due to alterations of materials by the environment. Therefore, mission and system architectures and their related technologies must address ways to mitigate these extreme–environmental conditions.

3. SYSTEMS ARCHITECTURES FOR MISSIONS TO EXTREME ENVIRONMENTS

Systems architectures for missions exploring the extreme environment of Venus may be categorized by (a) the isolation of sensitive materials from hazardous conditions; (b) the development of sensitive materials tolerant to hazardous conditions; and (c) the appropriate combinations of isolation and tolerance.

3.1 Environmental Isolation

One possible solution for extreme environment system architectures is to simply maintain all electronics and sensitive components in an environmentally controlled vessel. While this sounds feasible, the environmental protection is seldom complete or comes without cost. A good example is the active refrigeration needed for thermal isolation in hot environments. Such systems will require additional mass and power resources to maintain a heat sink. As a result, environmental isolation architectures typically require added resources and may not provide ideal solutions for all missions to extreme environments. Furthermore, in situ missions require certain components to be directly exposed to the environment (e.g., sample acquisition systems and sensors), making the implementation of this approach even more challenging.

3.2 Environmental Tolerance

The alternative extreme in missions to extreme environments is the development of hardware components that can reliably operate and survive in extreme temperature/pressure conditions, thus eliminating the need for environmental control. While this approach is ideal on a purely technological level, some of the key technologies would require a large investment to achieve the desired performance (e.g., avionics systems which would be capable of operating at ~500°C). Therefore, environmentally tolerant technologies may pose elegant solutions to some technology challenges (e.g., by removing the requirements for a pressure vessel and thermal management subsystem), but technology development may not be able to answer problems posed by fundamental physical limitations or impractical investment strategies.

3.3 Hybrid Systems

In hybrid architectures, hardened components would be exposed directly to the environment and components that cannot be hardened would be protected. Depending on the mission duration, passive or active cooling would be applied only for components that cannot be hardened to tolerate the Venus environment (e.g., CPUs and visible imagers), while high temperature tolerant components would be used where practical (e.g., for certain mechanisms and RF systems). Consequently, some temperature–sensitive components would be maintained inside an insulated thermal enclosure, while other more tolerant components would remain outside. This approach requires simpler and lighter thermal control, enabling more functionality with less cabling. In addition, this approach is also cost–effective if technologies are selected for systems engineering capabilities, as well as for tolerance.

For Venus landers, a hybrid architecture approach seems promising if technologies are appropriately sorted according to their suitability for environmental tolerance, versus the requirement for environmental protection. It is likely that thermal/pressure control zones will be required for sub–systems such as avionics, advanced instruments, and low temperature energy storage. On the other hand, sub–systems that dissipate most of the heat (e.g., telecom, power components) should be placed outside of the thermal control zone. In–situ sensors, drills, and sample acquisition mechanisms would also be fully exposed to the extreme environment. This approach was used on the two landers of the Venus Flagship Mission concept, where components inside the pressure vessel were temperature controlled with insulation and phase change materials, while the sample acquisition and handling system directly interfaced with the environment.

4. TECHNOLOGIES FOR SURFACE EXPLORATION

Although some Venus investigations can be accomplished from orbit using remote–sensing instruments, many key science questions can only be answered by in situ low–altitude and surface explorations of Venus. Short–duration missions that would tolerate these environments for up to a few hours can be accomplished with currently available technologies. Long–duration in situ missions, such as the Venus Mobile Explorer and the Venus Network concepts [VEXAG, 2007], are expected to operate for up to a year at or near the surface, but will require significant technology investments to achieve.

4.1 Existing Capabilities

For pressure and thermal control the Soviet Venera and VEGA missions used titanium pressure vessels surrounded by a rigid, porous, silicon–containing material that served as the outer thermal insulation. The Pioneer–Venus probes were also made out of titanium. Thermal control on short–lived missions can be addressed with passive aerogel and multi–layer insulation (MLI). The current state of the art aerogel has a density of approximately 20 kg/m^3.

Around the pressure vessel, multi–layer insulation (MLI) reduces the radiated heat flux between a hot and a cold boundary surface, thus preventing large heat leaks. It typically consists of closely spaced shields of Mylar (polyester) or Kapton (polyimide), coated on one or both sides with thin films of aluminum, silver or gold. MLI blankets often contain spacers, such as a coarse–netting material, to keep the layers properly separated. Inside the pressure vessel, phase change materials (PCMs) with high thermal inertia may be used to absorb the additional heat dissipated when the components are in operation, as was done on the Pioneer–Venus probes. Lithium salts, with a specific heat of 296 kJ/kg, were used inside the Soviet Venera and VEGA landers. The state of the art PCM is paraffin (C16H34) or a paraffin–like polymeric material that dissipates about 250 kJ/kg during its solid–to–liquid phase transition.

For sampling, the Venera drill was designed to first reach the surface 400 mm beneath its initial stowed position and then drill to a 30 mm depth. (In comparison, the requirement for the Venus Flagship Mission is to obtaining a sample from the weathered surface layer and another from 10 cm depth.) Although the Soviet drills were tested on harder rocks, on Venus it appears that they actually encountered softer material, like weathered basalt or perhaps compact ashy material, for which they drilled the full 30 mm in less than 2 minutes.

Attempts at soil analysis with the onboard sampling system on the Venus surface started with Venera 11 and 12, but proved unsuccessful due to failed pressure seals. The sampling systems of Venera 13, 14 and VEGA 1, 2 were improved and, with the exception of VEGA 1, the landers successfully performed their sampling and sample distribution tasks. An unexplained electrical shock to the VEGA 1 spacecraft prematurely initiated the deployment and operation of its drill system at 18 km altitude, instead of at touchdown. The Russian sampling systems (including support hardware) were about 26 kg, and consumed up to 90 W of peak power. The total length of the drill stem was about 40 cm, with a core diameter of about 16 mm. There was sufficient travel in the drill stroke to reach a surface (about 30 cm) and drill for 3 cm.

The system was capable of functioning at 500°C and consisted of a drill–based sampling assembly, a soil feed mechanism, a gas generator assembly for pyrotechnic devices, and a vacuum chamber. The system provided for straightforward, open loop, auger flight transport of sample cuttings to a vacuum based instrument chamber located inside the pressure vessel. The whole process of collection and analysis of the sample took a few minutes. This level of successful system implementation was only possible by extensive testing, conducted under conditions designed to simulate the Venus environment. The development took 2–3 years.

To benefit from flight heritage, an attempt should be made to acquire Russian high temperature (HT) motors used for the Venera/VEGA drill, since two years ago a survey of electric motors available anywhere in the world revealed that the maximum operating temperature is currently limited to 270°C. Today, however, for the purpose of supporting a landed Venus mission's drilling operation, a switch–reluctance electric motor has been shown at Honeybee Robotics to run indefinitely, drilling into chalks with no gear reduction at Venus temperatures. In addition, a brushless DC motor is not far behind in development and a switched reluctance motor has been demonstrated to operate at 500°C, while a high temperature bearingless motor is also under development.

4.2 Short–Lived Landers

The Venus Flagship Mission included two short–lived landers, operating on the surface for 5 hours in addition to their 1.5–hour descent science phase. These mission elements could be also envisioned as stand alone missions with moderate technology development needs, including sample acquisition, a rotating pressure vessel design, rugged terrain landing capabilities and targeted instrument technologies.

4.2.1. Pressure Control

Emerging pressure vessel materials should be designed to satisfy performance criteria, such as buckling, yielding, creep at a temperature of 500°C and to tolerate a pressure range of 100–150 atm over the anticipated lifetime of the mission. In addition, the pressure vessel material must be impermeable to gases, while retaining compatibility with the Venus chemical environment. Low thermal conductivity could be traded against better insulation. Other factors include: fracture toughness, heat capacity, and the thermal expansion coefficient. Candidate pressure vessel materials could include metallics (e.g., nickel–chromium alloys and beryllium), and composite materials (e.g., silicon carbide fiber reinforced titanium matrix or epoxy polymer matrix composites). A very important consideration in the selection of materials is its manufacturability into a spherical pressure vessel shell that needs to include windows and feedthroughs. Monolithic shells can be fabricated from titanium or beryllium, which has been the traditional manufacturing process for spacecraft landing on Venus' surface. Composite wrapped shells are commonly seen in pressure cylinders and the technology is well developed. These new pressure vessel materials would have a direct impact on the overall mass of the mission elements (e.g., landers, descent probes and low altitude balloons), exposed to high temperatures and pressures.

4.2.2. Thermal Control

Passive thermal control is suitable on short–lived near surface missions, e.g., on Venus Flagship Mission [Hall et al., 2009], VISE [NRC, 2003], and on descent probes. With a thermal conductivity approximately that of a gas at 0.1 W/mK, aerogel provides good insulation without convection. Possible next generation MLI insulating materials include a cocoon of high–temperature multi–insulation, manufactured by stacking and sewing together crinkled reflective metal–alloy foils, separated by ceramic fabric and/or insulated with xenon gas, although MLI only provides significant performance improvements when used in a high vacuum. In the more external part of a pressure vessel, metallic, ceramic or PBO (Poly–p–phenylenebenzobisoxazole) materials could be used directly, although they would need to be fabricated in layers thicker than films because films are too thin to provide insulation. Also, PBO is not acid resistant. While Kapton (a polyimide film by DuPont) is not suitable because it will not tolerate Venus surface temperatures, Aramid (a heat–resistant and strong synthetic fiber) or other polymers could in principle be combined with silica fabrics. For PCM materials, the need for low volumetric change limits the transformations to solid–liquid and solid–solid transitions. Also, a higher density PCM may be more appropriate, requiring smaller volume and less container or filler mass.

4.2.3. Surface Sample Acquisition and Handling

The Venus Flagship Mission concept baselined a rotary drill sample collection system, patterned off the successful Soviet Venera and VEGA missions in the [1970s and] 1980s. Implementation of a future drill system involves a two–step process: first, to recover, in some sense, the Soviet technology by designing and building new systems based on modern components and then measuring the performance of those designs with extensive testing under Venusian surface conditions. Second, there may be a need to engineer functional capabilities that the Soviet systems did not have in order to achieve the specific Venus Flagship Mission requirement to robustly drill down to a 10 cm depth in basaltic rock. Those additional functional capabilities are likely to include some combination of longer drill times, higher energy efficiency (energy per unit depth drilled) and feedback control.

4.2.3.1. High Temperature Electric Motors

High temperature (HT) motors will be needed for the Venus Flagship Mission sample acquisition system, especially for the high–duty–cycle motor actuating the drill shaft drive train. This motor shaft will likely see a higher number of revolutions, under load, than all other surface actuators combined. This central motor needs to withstand the internal heating from its power input in addition to the ambient temperatures of operation. Switch–reluctance and brushless DC electric motors for high temperature operations will require more testing and iterative development to optimize their mass and volume and their performance profiles. This long development process must be accomplished before these motors can be full up integrated into drilling system prototypes, capable of being tested in simulated Venus environments. [Landis 2006] reviews some technologies for high temperature motors.

4.2.3.2. Resolvers and Encoders

Building on the Venera/VEGA design heritage, the drill identified for the Venus Flagship Mission will require a drilling depth of 10 cm, with robustness afforded only by feedback control on the drill system. The feedback addresses jamming difficulties associated with varying chip removal rates and weight on bit issues that arise when drilling deep (2 to 10 cm) into strong and varying rock or into regolith that contain rock fragments larger than half the diameter of the drill stem. Recent experience with the Mars MER and Phoenix missions, and the MSL rock drill development demonstrate the utility of sophisticated drilling algorithms that can accommodate a wide range of rock and regolith physical properties and reliably achieve the desired drill depths. The set of physical challenges not only refers to a wide range of rock strengths and encountering small rocks in regolith targets, but also to very difficult rock drilling problems, such as engagement of the drill bit at an uneven or highly sloped rock surface or drilling through a hard spot in a soft rock or drilling into a crack in a hardened regolith target. For these drilling algorithms to work, the development of high–temperature resolvers (or encoders) that provide actuator output position knowledge will be required so as to foster the development of servo–controlled, fully autonomous drilling systems. Motor current sensing, sensor electronics, force and torque sensors, motor drivers, and motor electronics will all be required for high–temperature drilling systems and algorithms. Conventional encoders will not function at Venus surface temperatures, and magnetic fields associated with resolver operations will drift with elevated temperatures. This drift over time at high temperatures is not yet well understood. New types of high–temperature resolvers are under development; however, the comprehensive development, characterization, and testing of high–temperature resolvers composed of new materials packaged in sampler prototypes, and drilling into strong basalts at Venus surface conditions, will be required to implement feedback control on a Venus drilling system. Though basic boring can be accomplished without feedback, the feedback system will increase probability of achieving the desired 10 cm depth in any type of rock.

4.2.3.3. Lubrication, Bearings and Other High Temperature Drive Train Elements

Conventional bearings will not function for very long at Venus surface temperatures, but bearings made of silicon carbide and races made of Stellite (a specialty steel) have been demonstrated to operate for relatively long time periods at Venus temperatures. However, the frictional profiles and operational lifetimes of these materials remain uncertain. Employing dry lubricants, such as tungsten disulphide, on gear components has been shown to work for short periods on bearings and spur gears at Venus surface temperatures, although much more research and development is required to analyze the wear performance of tungsten disulphide on planetary gears and other drive train elements under stress, such as harmonic drives. Additionally, aerospace component suppliers claim that proprietary coatings could enable long–duration electromechanical component operations at Venus temperatures. These coatings should be investigated and tested as candidates leading to the development of longer–lasting, high–temperature drive trains. Drill system support and positional/surface placement mechanisms might benefit from the development of a high–temperature brake. A high–temperature brake might not be too difficult to envision, but almost nothing is currently known about how any frictional brake might perform in a Venus surface environment.

4.2.3.4. Drill Bits Tailored to Work at Venus

On Mars, sharp diamond–cutting elements on the MER Rock Abrasion Tool did wear at rates that are significantly lower than when operated in the Earth's environment on rocks of similar strength. The mechanism responsible for this unusual mechanical behavior is not well understood, but might be related to the lack of moisture on Mars. Although there is some high temperature boring at Earth for geothermal wells, we know even less about how drill bits of any material will perform when cutting into regolith or strong rock at high temperatures and surrounded by the supercritical carbon dioxide atmosphere of Venus. A very significant research and development, including a chamber–testing program, will be required to produce reliable and efficient long–lasting drill bits.

4.2.3.5. Vacuum/Low Pressure Tanks Sample Transfer Technology

The Soviet sample transfer system was based on gas transport of rock pieces and shavings from the drill to an internal chamber driven by the high atmospheric pressure on the surface. It is a conceptually simple approach and worked reliably on the Venera and VEGA missions. Nevertheless, it will be necessary to develop, build a prototype, and conduct extensive testing to validate a robust design for a future Venus flagship mission.

4.2.3.6. Sample Acquisition Prototype & Algorithm Development

Drill and sample acquisition prototype testing should proceed beyond just the drill subsystem to the development of drill testing that simulates all of the key elements (e.g., drilling from the drill mounting and articulation hardware; and from a lander or lander mock–up). Prototypes of primary and support hardware in the sampling chain, including analytical instruments, should be integrated together to allow for end–to–end tests in a Venus–simulated environment. This end–to–end testing means (a) autonomous drilling into a variety of targets from a lander (or high–fidelity lander mock–up), (b) transferring acquired samples to a sample processor (if needed), and (c) moving the (processed) samples from the high–pressure environment of Venus to the low–pressure instrument–staging area inside the pressure vessel, where (d) the samples are provided precisely to working versions of the analytical instrumentation while (e) measurements are taken. Along this hardware–based development path, drilling algorithms matched to the drill, its motors, drill bits, the environment, and a range of targets must be developed and refined during the end–to–end testing program.

4.2.3.7. Proposed Sample Acquisition System Development Plan

High–temperature motor development in support of a Venus mission is underway and approaching TRL 6 for switch reluctance motors and TRL 5 for brushless DC motors. However, the development of reliable actuators capable of operating under load at Venus surface temperatures and pressures will be crucial to the acquisition and distribution to instruments of high–quality samples. Also, high–temperature actuators will be enabling (for rock drilling and for other electromechanical mission elements operating at 460°C). The development of high–temperature motors for a flagship–class mission to Venus must achieve a very comprehensive TRL 6, far in excess of the current development status, so as to be suitable for insertion into the design of a flight system.

For lubricants, bearings, electromechanical drive train components, brakes, and resolvers, the comprehensive development of high–temperature (and pressure) versions of all these elements are as crucial as the development of high–temperature actuators. All of these additional elements are needed to develop full–up, high–performing drilling systems and sample transport elements, such as carousels and transport tubes. Developmental work in the Venus mission context has only just begun in the area of resolvers and bearings. Almost no work has been performed on high–temperature lubricants and key drive–train components, such as planetary gear heads and harmonic drives. Only one lubricant has been significantly tested at Venus temperatures. Other candidate lubricants (and coatings) will need to be evaluated in the drive train and bearing context at Venus temperatures and pressures. The vacuum–based sample–transfer technology might be developed somewhat independently of the drilling prototype, as its interface can be defined well enough for later add on and integration. All elements of a future Venus sample acquisition, processing, and distribution system will need long development tracks, which then leads sequentially to the long development and testing of full drilling prototypes (along with prototypes of any articulating mount and the sample–transport subsystems). Beginning this development as soon as possible will leave the greatest possible time margin for completion of these difficult tasks (many of them sequential in nature); beginning development in the near term might lend a great deal of benefit along the way to precursor Discovery and New Frontiers missions.

4.2.4. Rotating Pressure Vessel of the Venus Flagship Mission

A novel feature for the Venus Flagship Mission landers is the rotating pressure vessel, which provides two major advantages: (1) it enables the otherwise fixed drill system to access an extended area around (i.e., an over 3 m long strip under) the lander; and (2) simultaneously it simplifies the process of obtaining panoramic images. For these, a single panoramic camera looking out horizontally through a single window and a drill imager looking downward could be used. The Venus Flagship Mission design for the rotating pressure vessel is at a conceptual level, and no known prototyping activity has yet occurred. Therefore, the rotating pressure vessel requires technology development in which the requirements are related to those for drilling and actuation systems.

The rotation system must operate at Venus surface temperatures, driven by an electric motor and gearbox that provides low rotation speeds (<1 revolution per minute). Motor, bearing and lubrication technology used by drills will, in principle, suffice for rotating the pressure vessel, although customized for its loads and rotation speed. If this design option remains for the Venus Flagship Mission, prototypes will need to be constructed and tested for the Venusian surface environment to validate it. This validation will need to include testing for the high entry vehicle deceleration rates (g–loads) that could load the pressure vessel bearing to a very large extent.

4.2.5. Rugged Terrain Landing System

The Venus Flagship Mission consists of two landers, targeting different landing locations. The Tessera region is expected to be more rugged than the relatively flat plains, targeted by the Venera and VEGA landers. A robust landing configuration should avoid (a) landing on a rock that impacts and damage the bottom of the lander/pressure vessel; (b) landing on a steep slope causing a tip–over hazard; (c) landing in a telecom obstructed orientation. A suitable design requires development and testing.

4.2.6. Power Storage for Short Lived Missions

For the Venus Flagship Mission concept primary batteries were placed inside the pressure vessel, where the temperature–controlled environment didn't necessitate high temperature batteries over the 5 hours surface operation.

However, high temperature batteries could be placed outside of the pressure vessel, thus reducing the vessel's volume, mass and thermal management requirements.

While not fully developed, several battery chemistries were created and qualified, which could operate at or above 400°C. Lithium and sodium batteries under development allow stable energy storage at ambient temperatures. It means that no significant energy loss is expected after integration of the power subsystem and during the cruise to Venus. These batteries could be operated in a temperature range of 325 to 480°C. Similarly, lithium–sulfur batteries could operate in the range of 350–400°C. Practical energy densities in the range of 100–150 Wh/kg are reported on the optimized couple Li/FeS_2 batteries. Sodium–sulfur (Na/S_2) batteries have a similar operating temperature range and practical energy density of ~100 Wh/kg. Further details on energy storage can be found in [Mondt et al., 2004], [Kolawa et al., 2007], and [Harrison and Landis 2008].

4.2.7. Instrument Technologies for the Venus Flagship Mission

The Venus Flagship Mission study identified a strawman payload addressing key science objectives and investigations. Some of the proposed instruments are protected inside the pressure vessel and are at relatively high TRLs (TRL 4/5/6), while others require focused technology development to operate directly in the extreme environment of Venus. Two examples for instruments requiring technology development are the heat flux plate and the X–ray diffraction/X–ray fluorescence (XRD/XRF) instrument. Descriptions of the other Venus Flagship Mission strawman payload elements are provided in [Hall et al., 2009].

4.2.7.1. Venus Heat Flux Plate

To measure heat flow on Venus with an accuracy of ±5 mW/m^2, ultra–tall carbon nanotubes (CNTs) in the height range of 10 mm to 25 mm were considered to establish tight thermal contact between heat flux plate and the rough surfaces of Venusian rocks. A joint JPL–Caltech team has developed a process to grow 10 to 25 mm tall CNTs on different substrates. Further technology development is needed to achieve (i) reproducible ultra–tall CNT growth on large area substrates, (ii) enhanced adhesion of CNTs to the substrates, and (iii) increased compliance property of CNTs to achieve conformability to surfaces with roughness on the order of 1 to 2 cm. Enhanced adhesion to the plate surface is important to ensure non–flaking of CNTs during measurement.

4.2.7.2. CNT X–ray Tubes for XRD/XRF Instrument on Venus

X–ray diffraction/X–ray fluorescence (XRD/XRF) instruments for definitive mineralogy on Venus can greatly benefit from CNT field emitters. JPL has developed an architecture of multi–walled carbon nanotube (MWNT) bundles that has delivered the highest reported current densities at low electric fields (~10 to 15 A/cm^2 at ~5 to 10 V/μm over a 100–μm diameter area). Based on this architecture, application specific electron sources have been developed for miniature X–ray tubes that operate at lower acceleration voltages (10 to 20 kV with Cu or Co–target), and are capable of increased photon flux (10^7 to 10^{12} Photons/s) that allow faster data collection rates (limited only by the detector speed) on the order of minutes as opposed to hours. CNT emitter based X–ray tubes weigh less than 50 g and together with a custom–designed high–voltage power supply can weigh less than 1 kg, and can have significant impact on sensitivity, resolution, and power consumption of XRD/XRF instruments.

While basic CNT X–ray tube concept has been demonstrated, technology development is still needed to transition this development into a usable X–ray tube that has the capability to focus an X–ray beam to a spot size of 50– to 100–μm diameter. Integrating the CNT X–ray tube with collimators is a challenge. Producing an X–ray tube that is ready for integration with an XRD/XRF instrument needs a stand–alone vacuum packaged component that has beam position and beam energy tenability. The beam tailoring optics that can be monolithically integrated with CNT electron emitters needs to be designed such that photon flux on the order of 10^{12} to 10^{14}/s can be produced from a small area source (100– to 200–μm diameter). X–ray production efficiency exponentially decreases as the acceleration voltage is decreased. Hence the current density from the CNT source needs to be increased correspondingly to maintain the necessary photon flux. This optimization, while easily explained in theory, needs careful designing of the CNT array source to keep the electrostatic screening effect to a minimum. Even here, enhanced adhesion of CNT arrays to the substrate is necessary to withstand high field operation. This will be a common development between the heat flux plate and the XRD/XRF instrument.

4.3 Long–lived Landers

A Venus surface mission on the order of 5 hours or less precludes the possibility of having a 'human in the loop' for directing scientific investigations. A desirable goal of ~24 hours would permit at least a limited form of human interaction with the spacecraft. Other high priority science investigations, such as seismic measurements and long time monitoring of the environment requires surface operation from several months to a year or more. Long surface operation can't be achieved with technologies discussed for short–lived landers and would require additional focused enabling or enhancing technologies, as discussed below.

4.3.1. Thermal Management for Long–lived Landers

Mission lifetime can be extended with a suitable thermal management design. For shorter mission passive thermal control would suffice, while for long–lived missions active cooling could be used.

4.3.1.1. Passive Thermal Control

Mission lifetime increase from a few hours to ~24 hours could be still within the realm of possibility using passive thermal management to absorb thermal energy from electronics generated and leaked in sources. However, this would require technology development for phase change materials, such as lithium nitrate trihydrate ($LiNO_3$–$3H_2O$) or a water based heat absorption / vapor venting system. Water could be also introduced to the pressure vessel's insulation layers, which could freeze during the cruise phase and then absorb heat from the Venus environment, while changing from solid ice to water and vapor phases. This could maintains a layer within the insulation below 305°C for a time period (e.g., for 24 hours or longer if the temperature tolerance for the electronics could be increased from the typical 125°C to 300°C). Other passive options include the concepts of a Lithium metal matrix (contained in an exterior vessel and mixed with the water vapor exiting the pressure vessel), or a Lithium shell within the insulation layer exterior to the pressure vessel.

4.3.1.2. Active Thermal Control – Refrigeration

The ability to actively refrigerate instruments and electronics fundamentally changes the nature of any long–lived mission, including landers, low altitude mobile platforms, or independent in situ instruments. Such a refrigeration system would have two main components: a power source and a refrigeration system that uses the power source to pump heat from the payload back out into the environment. A specially designed Radioisotope Power System (RPS) is the only realistic long–lived power source for the surface of Venus. A high efficiency RPS would be needed to jointly power the payload as well as the refrigeration system. The most mature and highest efficiency options for Venus are the Stirling convertor based refrigeration systems. These require either an electrical power input or direct pneumatic coupling with a Stirling heat engine, in what is known as duplex operation.

There is considerable technical maturity in the field of Stirling heat engines and refrigerators that can serve as the foundation for the development of refrigerators for Venus. However, substantial technology development is still required given the extreme temperature and pressure environment of the Venus surface. The most significant technical challenges are: (a) combining a Stirling heat engine and refrigerator into a long–lived duplex system with at least two stages of cooling, (b) achieving high thermodynamic efficiency that would keep the GPHS module (and correspondingly the ^{238}Pu) requirements at a manageable and affordable amount, (c) creating a complete system design with the multi–stage refrigerator that is integrated into the Venus platform (lander, rover, balloon), and (d) addressing issues arising from the potential electromagnetic or mechanical vibration byproducts of the Stirling–convertor–based power source and refrigerator that could interfere with scientific instruments. (In particular, there is a concern that the mechanical vibration of the machine could interfere with seismometry measurements if the Stirling convertor is not physically decoupled from the seismometer.)

The performance of the refrigerator could be improved using a multi–stage system, where multiple refrigerators would operate in series, such that the heat rejected by one refrigerator is collected and pumped to a higher temperature by the next one. (This would require a nested pressure vessel design.) A multi–stage system would provide a major improvement to the thermodynamic efficiency, translating to greatly reduced plutonium requirements. Furthermore, using low–power components with reduced heat dissipation from the payload and improved thermal insulation could further reduce the refrigeration requirements on the mission element, thus further reducing the plutonium requirement, refrigeration system mass and volume.

4.3.2. Power Systems for Long–lived Landers

Venus exploration missions pose significant challenges for energy storage systems. Many concepts for Venus surface missions (landers and seismic/meteorological stations) require mass– and volume–efficient energy storage systems that can operate at temperatures as high as 480°C. Venus atmospheric exploration missions (aerial platforms, atmospheric probes) likewise require energy storage systems that can operate at 50 to 480°C, depending on the altitudes. Since the mass and volume of the batteries increase linearly with the mission duration, internal power generation in the form of a Venus specific Radioisotope Power System (RPS) could become an enabling option for long–lived missions, especially when coupled with active refrigeration. Power systems for long–lived landers could be powered by stored energy (in combination with a power source), photovoltaic arrays, or radioisotope systems. Each of these options has advantages and disadvantages. While the technology exists to make solar cells that can operate in the high–temperature environment of the Venus surface, these cells have a low effective efficiency, due to the high temperature, the low light levels below the clouds, and the spectral shift due to atmospheric scattering [Landis and Vo 2009].

4.3.2.1. Power Storage – High–T Batteries

High temperature batteries could be placed outside the pressure vessel, thus reducing its mass and volume requirements. The major issues that need to be addressed before rechargeable batteries could be considered for Venus missions include: adapting cell and battery designs for high–temperature space applications, ensuring the stability of seals and terminals, minimizing the corrosion of current collectors at high temperatures, determining the effects of zero gravity upon performance, improving the safety, and optimizing the electrolyte composition to improve conductivity and reliability. High–T (300 to 600°C) rechargeable batteries were designed to be rechargeable, but can also function in the primary battery mode. They have a projected specific energy between 200 and 500 Wh/kg and some of versions could operate up to 500°C. Chemical composition examples include a) $LiAl–FeS_2$, b) Na–S, and c) Na–metal chloride. However, these are only projected performance values and high temperature batteries are currently at a low TRL, with no ongoing development effort. Further details on these batteries are given in [Kolawa et al., 2007], [Mondt et al., 2004], [Hall et al., 2009], and [Harrison and Landis 2008].

4.3.2.2. Power Generation – Venus Specific RPS

Radioisotope power systems are capable of providing continuous power for potential future Venus surface missions. Although NASA is currently developing two types of Radioisotope Power Systems (RPS), namely the Multi Mission Radioisotope Thermoelectric Generator (MMRTG) and the Advanced Stirling Radioisotope Generator (ASRG) [Dyson, 2009], these were not designed for the extreme environments of Venus, although they could operate satisfactorily in the cloud level at ~55 km altitude, where the pressure and temperature conditions are Earth–like. Near the surface, RPSs must tolerate high pressure, temperature, and corrosion. Therefore, for most of the considered mission architectures operating near or at the surface, a Venus specific RPS will likely need to be coupled with active refrigeration.

MMRTGs and ASRGs use static and dynamic power conversions, respectively. Since dynamic conversion is about four times more efficient than static conversion, the ASRG requires about the quarter of the ^{238}Pu compared to the MMRTG, while generating the same amount of electric power and rejecting proportionately less waste heat. This excess heat on a long–lived Venus in situ exploration platform would have undesirable impacts at various mission phases. For example, during the cruise phase the in situ elements would be encapsulated inside an aeroshell, requiring removal of the RPS generated waste heat. Near or on the surface of Venus the high temperature of the environment would reduce the temperature difference between the hot and cold sides of the RPS, and with it the efficiency of the power conversion process. For these reasons a long–lived Venus surface mission require an RPS using dynamic power conversion.

To validate a Stirling–based RPS in the Venus surface environment, the cold end temperature has to be raised from the current 90°C to 480°C, with an expected decrease in overall thermodynamic conversion efficiency. An increase in conversion efficiency could be achieved by increasing the hot end temperature beyond 850°C to as much as 1200°C, thus maintaining a high temperature difference between the hot and cold sides. However, this will require further development for the hot–end material. NASA GRC conducted initial development of advanced materials (refractory metal alloys and ceramics) specifically for high–temperature Stirling applications. Although not fully mature at the present time, these advanced materials have the capability of operating at temperatures in the range of 1100 to 1200°C. Tradeoffs between the maximum operating temperature and the required development and risk need to be investigated in terms of long–term thermal stability, outgassing, and synergistic effects. For example, the combined effects of radiation, temperature, and aging over time need to be assessed.

Identifying the appropriate size for the RPS is also an important issue, in light of science goals and exploration objectives. Static landers, for example, may require more power than aerial mobility platforms, but they are less mass and volume constrained. An aerial platform, such as the Venus Mobile Explorer concept, would traverse using a metallic bellows system. This limits the suspended mass for the gondola, which accommodates the power and refrigeration systems. Therefore, future RPS technology development for a Venus RPS with active refrigeration should reflect science drivers and related mission architectures. A potential long–lived Venus flagship mission could also contribute to the demands on the plutonium inventory. Therefore, future mission studies on alternative Venus mission architectures should assess plutonium needs and work with NASA HQ to be included in ^{238}Pu production and allocation plans.

4.3.3. High Temperature Components

High temperature components for Venus exploration include sensors, electronics, telecom components and instruments, as will be discussed below.

4.3.3.1. High–T Sensors

A range of sensors applicable to Venus missions has been and continues to be developed for a variety of target applications, including high temperature aerospace and industrial applications. Sensor development includes high–temperature positioners, accelerometers, pressure sensors, thin film sensors, and chemical sensors. These sensors are typically silicon carbide (SiC) or gallium nitride (GaN) based, in support of high temperature operations.

Conventional Si–based *pressure sensors* are temperature limited, while devices such as SiC–based pressure sensors have a much wider operating temperature range. Progress has been made in both SiC–based pressure sensor micromachining and packaging, and were demonstrated to operate for over 130 hours at 600°C, with a projected 5,000 hours at 500°C, and have been demonstrated multiple times in engine environments at pressures up to 500 psi (34.5 bar). Research efforts are geared towards integrating three functionalities in a Micro–Electro–Mechanical Systems (MEMS) structure: a pressure sensor, an anemometer, and a temperature differential sensor. GaN sensor technologies for pressure and temperature measurements can offer several unique capabilities although, at the present time, they are not as mature as SiC sensors. AlxGa1–xN/GaN heterostructure based GaN microsensors provide robustness in wide ranges of temperature and pressure (a few K to >800 K, 0 to >10 Kbar) high sensitivity, and the reliable and reproducible sensor fabrication.

High temperature *physical sensors*, including those for strain, temperature, heat flux, and surface flow, are required for surface measurements in propulsion system research at temperatures up to 1100°C, well beyond the Venus environment. These sensors are microfabricated and have been placed at variety of high temperature materials and complex surfaces. Measurement requirements for these sensors are usually as simple as voltage or current. A multifunctional sensor, such as that already demonstrated at 700°C and patented, could integrate into one "smart" sensor, resulting in the design of individual gauges that measure strain magnitudes and direction, heat flux, surface temperature, and flow speed and direction. Thus, in one sensor system, a range of physical parameters regarding the environment could be measured under Venus relevant conditions.

The development of MEMS–based *chemical (micro)sensors* to measure emissions in high temperature, harsh environments has been on–going for engine emission monitoring applications, and could be adopted for Venus applications, where each sensor would be designed to be selective to the chemical species of interest intending to provide direct measurement of the chemical species. Sensors composed of Schottky diodes, electrochemical cells, and resistors composed of a variety of harsh environment materials are used to detect a range of species with sensor operating temperatures ranging from 500–700°C. GaN–based micro chemical sensors have been recently developed for in situ chemical species detection and monitoring in extreme environments. Electrical signals characteristic of chemical analytes (H_2, CO, NO, NO_2, acetylene, etc.) have been measured with GaN HEMT (high electron mobility transistor) sensors at the sensor temperatures as high as 400°C. For operations at higher temperatures (>500°C), GaN MOS (metal oxide semiconductor) HEMT sensors would be necessary in order to avoid the burn–out of Schottky gate electrode and prevent high gate–leakage current. GaN HEMT sensors are most sensitive to the chemical species with strong dipole moments. High selectivity detection of organophosphate compounds compared to common organic solvents has been reported. High sensitivity detection of caustic gases (HCl, Cl_2 & NH_3), which is not possible with Si–based sensors, has been recently demonstrated with GaN HEMT sensors, indicating reliable operation of GaN micro chemical sensors in caustic environments such as in Venus.

4.3.3.2. High–T Electronics

Currently available electronic systems for Venus missions would depend predominantly on silicon–based Very Large Scale Integrated (VLSI) CMOS circuits, which need to be maintained through passive or active cooling in an Earth–like environment, and rated to operate up to 125°C, but selective number of Si CMOS components are also available in High Temperature Silicon–On–Insulator CMOS (HTCMOS). These latter components include: microcontroller, static random access memory, analog multiplexer, crystal clock, linear regulator, operational amplifier and are able to operate at temperatures as high as 300°C. At temperatures above 300°C only discrete wide bandgap semiconductor devices (diodes and transistors) are available that are fabricated using Silicon Carbide (SiC), Gallium Nitride (GaN), or Gallium Arsenide (GaAs) semiconductors. Commercial versions of these transistors are generally not optimized for operation at 500°C for extended period of time. However, development, fabrication and optimization of SiC devices for high temperature operation was successfully demonstrated at NASA Glenn Research Center (GRC) in 2007 on a small scale integrated high temperature SiC circuits (including packaging) over thousands of hours at 500°C. In support of the NASA Aeronautics program [Neudeck, 2008], GRC has produced a 500°C SiC based differential amplifier, an inverting amplifier, a NOR gate, and NOT gate.

An alternative approach to solid–state devices is the use of thermionic vacuum devices (vacuum transistors), which are well–suited for extreme temperatures because they require high internal temperatures (700–800°C) in order to operate. They are also low–noise, linear devices, with electrical performance parameters that are virtually independent of temperature. Recently JPL demonstrated an extremely small vacuum transistor made with Carbon Nano Tube (CNT) that operated at 700°C. The low–noise, temperature–insensitive properties of the vacuum tube transistors, including the CNT based versions, make them ideally suited for telecommunications applications.

Capacitors have proven to be significantly more challenging. General–purpose ceramic capacitors often tend to exhibit wide variations in capacitance with increases in temperature, due to changes in the dielectric constant.

Due to the high temperatures of the Venus ambient environment, issues such as the degradation of materials with temperature, stresses resulting from coefficient of thermal expansion (CTE) mismatch, and creep become significant. At Venus temperatures, polymers for printed circuit boards and adhesives are no longer an option due to degradation. Ceramic substrates, such as alumina or aluminum nitride, can be used for high temperature hybrid circuits, but it is critical that the substrates are designed using high temperature trace materials. Die attach materials need to have a melting temperatures that are only slightly greater than the target environment to avoid exposing the device to further temperature extremes. Finally, wirebond material selection must take into account die metallization and substrate metallization to minimize the formation of brittle intermetallics.

Electronics operating at 300°C will greatly reduce the mass of the cooling system needed for Venus missions. However, the available menu of commercial 300°C circuits is barely adequate for building a 300°C electronic instrument. A larger and more sophisticated menu of integrated circuits (ICs) capable of operating at this temperature will enhance our ability to design sophisticated systems. Also, the significant leakage current of these circuits at 300°C is a major power drain that would limit the battery life. High temperature circuits fabricated on advanced ultra thin SOI CMOS technology can have an order of magnitude lower leakage current, which would minimize this problem.

High temperature memory would be necessary to maximize the data return of in–situ data systems. That is, while continuous data transmission can provide data when the transmitter is in sight of the orbiter, high temperature data storage is necessary if it is determined than no data can be lost from planetary in–situ devices (e.g., from the seismometer). The prospects of high temperature data storage using current SiC technology (even the most advanced) are daunting. This in part is due to the fact that metal–oxide–semiconductor (MOS) circuits commonly available in silicon and central to present memory storage are not available in SiC or in other high temperature semiconductor technologies.

High temperature motors and actuators will need high temperature power electronics for drive and control of actuators as well as for precision analog electronics for interface with sensors (i.e., position sensors). None of the above circuits are currently available. Also, the lack of complementary transistors makes it extremely difficult to realize the circuit power reduction achieved in Si based CMOS technologies in wide–bandgap semiconductors. Significant work has been done, for example, on high power SiC devices or high temperature SiC transistors, but not on devices that are both high temperature and high power. Absence of complementary devices seems to also impact both traditional and CNT based versions of thermionic vacuum devices.

Two approaches are suggested regarding the advancement of high temperature electronics and data processing. The first is to use the simpler circuits presently available in SiC to create state machines and control devices, which can be used for Venus applications. A fundamental point related to electronics and communication development at ~500°C is that due to the low maturity of SiC electronic materials, a direct transfer of Si based approaches to SiC is problematic. Second, the maturation of high temperature electronics using a variety approaches to the comparable maturity of silicon is highly desirable. These developments would have to be of the complete system; not only of the electronic materials themselves, but device contacts, interfaces, packaging, and related communication technology.

Furthermore, a standard methodology for testing and assessing the reliability of high temperature circuits for Venus application needs to be developed. This methodology needs to establish procedures for accelerated life tests that factor in both the upper operating limits temperature of the electronic devices and the specifics of Venus environment, such as its atmospheric chemistry and pressure.

4.3.3.3. High–T Telecommunications

Only limited work has been done in developing long range, high power, and high temperature transmitters for Venus applications. Absence of high frequency passive and active radio frequency (RF) components seems to be a major issue limiting the progress in this area. While high temperature SiC transmitters could be designed using an array of low power SiC RF amplifiers together with passive power combiners, SiC transistors have been demonstrated to work up to an ambient temperature of ~200°C, while retaining ~30% of their room temperature gain. (It should be noted that SiC components could operate at 500°C and 1 GHz for extended periods of time using alternate circuit designs and advanced packaging/contact technology.) Alternatively, a mechanical resonant cavity based oscillator could be used to provide stable power–temperature performance at 500°C, but at a mass penalty. Short–range, low–power, high–temperature transmitters are also at an early stage of maturity with SiC transistors operating up to 275°C at 1 GHz, while high temperature pressure sensors at 400°C integrated with a 30MHz oscillator/transmitter has been demonstrated. Other work has shown a loop antenna integrated within the oscillator enabled the wireless transmission of the pressure to distances of 1 m. Overall, any of these designs would be significantly challenged as–is to provide viable operation on Venus.

Preliminary results in high temperature communication technology are only providing a limited proof of concept for long–life, high temperature communication systems for Venus missions. Based on the current state of the art and the mission requirements, further development of high temperature transmitters and corresponding RF components for this purpose are required. These developments are central to any high temperature instrument or sensors system designed to operate in Venus environment.

Significant improvements to RF components are achievable, but would require concentrated development. For example, although MHz frequency transmission is viable, the SiC transistors developed by NASA GRC and used for 500°C demonstrating circuits will have to be completely redesigned to improve their RF properties and their operating frequency to several GHz. At the current time, this appears to be the most viable option for improved transmitter performance. In addition, the passive components required to construct oscillators and amplifiers must be developed to the same level of reliability. Lastly, packaging of the circuits is required. While ongoing development in the Aeronautics program will help, it will not be a complete solution to Venus specific problems.

In parallel, the same type of development is necessary for other promising types of transmitter technologies. Vacuum tubes or GaN semiconductor technologies can either provide an alternative to or complement existing SiC technologies. Combinations of SiC–GaN semiconductor material systems are already being explored for their advantages in communication applications.

4.3.4. High Temperature Instruments

The options to technologically realize a seismometer and meteorological network on the surface of Venus and secure their long–term operation from 117 days to 1 year include (a) the use a refrigerated pressure vessel; (b) the use components that can fully and reliably operate in Venus surface environment without thermal control including high temperature sensors, high temperature electronics and telecom system, and high temperature power sources and batteries; (c) and the development of a hybrid system using both refrigeration and environmentally hardened components. The use of high temperature components would enable the optimization of the refrigeration system to minimize its power and mass, and refrigeration can protect components that can't operate at Venus surface temperature and pressure.

4.3.4.1. High–T Seismometry

There is currently a technical void with respect to seismometers and geophones which can exceed an operating temperature of 260°C. The primary barrier to the development of such high temperature seismometers is the lack of available materials which can be used to fabricate a sensor structure capable of exhibiting the appropriate sensitivity to seismic events and surviving high–temperature conditions. For example, typical geophones employ ferrite materials, which demagnetize at high temperatures. This could be resolved by using a high temperature variable inductor coil that could measure a change in the inductance. This approach is viable using presently available high temperature sensors and circuitry, and is potentially capable of providing significant Venus seismometry data in the higher frequency range, however, packaging and robustness issues would need to be addressed. The development of a seismic instrument, which measures across the complete frequency range, is a significant technical challenge for a longer–term development. Given on–going advancements in high temperature Micro–Electro–Mechanical Systems (MEMS) technology, such a broad range measurement device is achievable; the corresponding electronics and communication technologies for a more complex system would be very challenging.

Adopting a full spectrum Mars–based seismometer design still remains technically challenging and equals to developing high temperature semiconductors to the capability of silicon–based technology. Therefore, a more complex high temperature seismic instrument would require great development efforts or a hybrid system with a power source and refrigeration system for long–lived operation. While it may be possible to build systems that operate at Venus surface temperatures and thereby avoid the need for active refrigeration, such systems will need to include data storage and handling functionality unless gaps can be tolerated in the data due to a temporary lack of telecom availability when either the orbital relay or the Earth is not visible from the seismometer.

4.3.4.2. High–T Meteorology

Obtaining an understanding of the day–to–day Venus ground ambient metrology/atmospheric conditions, using a high temperature weather station, requires a basic measurement system that includes temperature, wind flow and pressure. Some general specifications for such sensors include: 1) operation at 500°C, 2) measure pressure of 92± 0.1 bars with 10 Hz to 100 mHz frequency response, 3) measure temperature from 450°C to 500°C with 1°C resolution, 4) measure wind speeds from 0.3 to 1.0 m/s with 0.03 m/s resolution, and 5) measure gas species variations with time. To achieve this would require a hybrid system with high temperature sensors interfacing with the environment, and thermally protected components inside the pressure vessel, including suitably connected data handling and telecom systems.

5. TECHNOLOGIES FOR AERIAL AND SURFACE MOBILITY

Balloons provide unique, long–term exploration platforms from which to address such fundamental issues as the origin, formation, evolution, chemistry, and dynamics of Venus and its dense atmosphere.

5.1 Existing Capabilities

In 1985 the USSR's twin VEGA balloons successfully pioneered the use of aerial platforms to explore planets, but payload mass restrictions prevented their measuring abundances of diagnostic chemicals or noble gases. The VEGA balloons had a 6.9 kg payload suspended 12 meters below a fluoropolymer–coated Teflon fabric balloon, floated in the most active layer of the Venus three–tiered cloud system at ~54 km altitude, where they experienced Earth–like pressure and temperature conditions. The tether and straps between gondola compartments were made of a nylon–6 type material called kapron (note: not Kapton, which is a polyimide film developed by DuPont, and can remain stable in a wide range of temperatures, from –273°C to +400°C). The deployment system included bottles of compressed helium and a 35 square meter parachute that was used during the balloons inflation process, which took ~230 seconds to complete and was controlled with barometric sensors. The batteries' lifetime of 48 hours limited the mission duration to 47 hours, during which time data was transmitted back to Earth. One–way Doppler and very long baseline interferometry (VLBI) were used to track the motion of the balloon from Earth to provide the wind velocity in the clouds. The tracking was done by a 6–station network on Soviet territory, and by a global network of 12 stations organized by France and the NASA Deep Space Network. Both VEGA 1 and VEGA 2 balloons survived for 47 hours, and traveled over 10,000 km until depletion of the batteries.

In addition VEGA, ongoing activities include the development of a superpressure Venus balloon at JPL; tests at ESA as part of the Cosmic Vision program; and plans by JAXA to launch a mid–altitude Venus balloon after 2016.

5.2 Cloud Level Balloons

There is renewed interest in balloons for Venus; mission concept have been proposed in the US, Europe and Japan. High altitude balloons at ~55 km experience Earth–like conditions (~30°C and ~0.5 bar). Therefore, the balloon material selection is not affected by extreme pressure and temperature conditions. However, the balloon material still has to tolerate the sulfuric acid droplets in the clouds, and the balloon should be designed to limit the helium leak rate. A prototype high altitude balloon has been built at JPL in 2006 in support of a Discovery proposal targeting Venus. This type of balloon would inflate after atmospheric entry, and during its lifetime would be protected from the environment by a layer of Teflon film. Therefore, the inflation system represents an important technology item.

Long duration balloons (i.e., 30 days or more) could circumnavigate Venus multiple times while drifting poleward and potentially reach the polar vortices, where they will be swept down towards the polar surface obtaining dynamical and chemical measurements until the balloons will ultimately be destroyed under the increasingly extreme conditions with altitude decrease. Long lifetime, coupled with a suitable power and telecom system would allow for much greater data volume than available from a battery powered short lived mission. Long balloon lifetime would require further improvements to the balloon design to minimize leaks (at the seams) and to have better resistance to the sulfuric acid droplets in the clouds.

As was done by the VEGA balloons, both local dynamics and planet–scale atmospheric circulation can be investigated via radio–tracking of the balloon from Earth. Today's improved interferometric and Doppler tracking together with well–calibrated onboard pressure sensors can yield knowledge of all three components of balloon velocity an order of magnitude more accurately than achieved by VEGA, that is, better than 10 cm/s on time scales of a minute in the vertical and an hour in the horizontal. Furthermore, the new, highly miniaturized instrument technologies of the 21st century would allow such measurements to be made.

High altitude balloons could be designed to cycle between altitudes, as described in [Chassefiere et al., 2008] [Balint & Baines, 2009] [Kazuhisa & Yamada, 2008] . For this concept, the balloon is filled with a buoyancy fluid that changes phase from a liquid to a gas depending on the balloon's altitude (and with it the ambient temperature), which results in stable cycling as the fluid evaporates and re–condenses. For Venus, the likely buoyancy fluid is a mixture of helium and water, with the water undergoing the phase change during flight. Large altitude excursions between 60 km and the surface at Venus are not possible due to the lack of a single balloon material that could tolerate the environment throughout the altitude cycles. Material issues would limit the cycling balloon to a minimum altitude of ~10 km. In turn, high peak–to–peak amplitude cycles near the surface could benefit the thermal management of the payload, where at the balloon's maximum ascent altitude the payload could be cooled down. Venus cycling balloons are at low technology maturity, including both material and thermal design related issues.

5.3 Mid–Altitude Balloons

At mid– to low–altitudes, the dense atmosphere of Venus may provide higher buoyancy for aerial platforms, and higher aerodynamic resistance for controlled descent of probes suspended under a parachute. Finding a single balloon material that could withstand the high temperature and pressure at these altitudes is challenging. Based on NASA studies, one of the polymer film materials known to work at Venus surface temperatures of 480°C is Poly–p–phenylenebenzobisoxazole (PBO). However, there is no experience with making gas–tight seams, needed for balloon construction involving initially flat sheets of material. An additional problem is that PBO requires a special coating for protection from the atmospheric sulfuric acid droplets. While Teflon (a polytetrafluoroethylene (PTFE) by DuPont) is acid resistant, it may not survive the near surface portion of the mission, since it becomes brittle at high temperatures, and its compatibility with PBO should be assessed. Zylon (representing a range of thermoset polyurethane synthetic polymer materials manufactured by the Toyobo Corporation) is one of the strongest synthetic fibers in the world. Its high tensile strength and heat resistance could make it perfect for balloons that have to survive the harsh conditions on Venus. However, the sulfuric acid droplets could corrode Zylon. In addition to materials issues, mid–altitude balloons will require low mass, pressure and thermal management systems, or high temperature electronics and telecom systems that could operate in this environment.

5.4 Surface Sample Return Related Aerial Mobility

A proposed Venus Surface Sample Return (VSSR) mission would require a balloon to lift the sample from the surface, carrying an ascent vehicle (a rocket) to an altitude of ~60 km. This rocket would then fire to take the sample into Venus orbit from which it would rendezvous with an Earth return spacecraft. Launching the sample from the surface directly to orbit is prohibitive, due to the high atmospheric density and thus the aerodynamic drag. Without the availability of suitable single balloon material, the most promising solution is a multi–balloon system [Kerzhanovich et al., 2005], where in the first stage a metal balloon would lift the sample from the surface to an altitude of ~10 km. Next the helium would be transferred to a second balloon made from Teflon–coated Kapton film, carrying the payload and the rocket to the ~60 km launch altitude. A proof–of–concept metal bellows balloon was successfully tested at the Jet Propulsion Laboratory for inflation and leakage at 460°C, but there are still significant technical challenges in the areas of deployment and inflation, optimization for low mass, altitude control, and validation of leak–free operation.

5.5 Near Surface Aerial Platforms

For near surface mobility, inflatable balloons with available polymer balloon materials and adhesives do not work due to high surface temperatures (~460°C). Provided a VSSR–type large altitude traverse were not required, then a metal balloon alone – made of thin sheets of stainless steel or other suitable allow – would suffice at near surface altitudes. As envisioned for the Venus Mobile Explorer mission concept, a metal balloon could fly at an altitude of up to ~5 km (driven by surface imaging), performing aerial reconnaissance over long ground tracks and potentially doing other scientific investigations. Passive thermal control could suffice for a mission duration of several hours. A low–mass version of an active refrigeration system, coupled with radioisotope–generated electrical power, could enable a mission of very long duration, limited only by the leakage of helium buoyancy gas from the metal balloon. This concept would also require significant onboard autonomy functionality for flight controls, hazard detection and avoidance and science data collection. It would also benefit from a miniaturized payload, light pressure vessel and thermal insulation. An onboard imager would generate high data volumes, which in turn would require a challenging telecom system design in this environment.

5.6 Descent Probes and Drop Sondes

Drop sondes or descent probes are short lived missions elements, but they have to operate in an increasingly harsh environment, where the temperature and pressure rise with altitude decrease, the clouds contain corrosive sulfuric acid droplets, and below ~12.5 km altitude the predominantly carbon dioxide atmosphere becomes supercritical. Depending on the sondes or probes payload and duration of operation, the combination of different design architectures and technologies will be needed to achieve the desired life and performance. The size of these elements could also vary from a few hundred grams – as described in the ESA Cosmic Vision EVE proposal – to hundreds of kilograms (e.g., the Pioneer–Venus large probe was 315 kg). Sondes and probes could be released directly from orbit, or dropped from a balloon, in which chase the balloon could provide a high data rate relay telecom link between the sonde and an orbiter. Landers can also be instrumented for descent science, but the technology impact of mitigating surface operation bounds the technology requirements of the probes. Therefore, for short–lived probes and sondes a combination of passive thermal control and conventional space electronics and telecom can be used. In order to reduce the mass penalty of this thermal control design, moderate temperature silicon–on–insulator (SOI) electronics could be used for data processing and communication. For probes with simple payloads (temperature, pressure and other basic sensors), high temperature sensors, electronics, and batteries can be used providing system survivability during descent. The benefit of this approach would be a significant mass reduction and longer life (limited by battery life).

When considering mission architectures with a large number of simultaneously descending probes, the communication infrastructure would have to take into account the labeling and identification of the signals and data from each sonde or probe, and a suitable orbiter relay telecom support, since direct–to–Earth communication from in situ might not be feasible.

5.7 Surface Mobility with Rovers

Surface rovers represent a particular technology challenge for Venus exploration, since mobility introduces one of the highest power requirements to this type of mission element. The rover would require light versions of all technologies listed under the short–lived and long–lived static landers, including a lightweight, small volume, and high efficiency RPS with active cooling. Therefore, especially if it turns out that the rover could only transverse a few kilometers, science drivers should be weighted against technology development needs and alternative mission architectures before recommending a surface rover.

6. TECHNOLOGIES FOR LAUNCHERS, ORBITERS & ATMOSPHERIC ENTRY

6.1 Existing Capabilities

Based on flight heritage from Mariner, Magellan, Pioneer–Venus, Venera/VEGA, and Venus Express, much of the technologies associated with launch vehicles, orbiters, flyby spacecraft, and entry technologies can be handled with existing technology capabilities.

A key technology area for future Venus missions is transportation, the ways and means of getting spacecraft to Venus. This can be achieved with existing launch vehicles for most of the missions, although the VSSR mission might require a larger launch vehicle than those currently available. Solar electric propulsion (SEP) might be used on smaller orbiter mission, although these missions could be achieved using conventional launch vehicles. High– and mid–altitude balloons could use aerobraking first to achieve safe atmospheric entry conditions. As aerobraking was demonstrated originally on Magellan and was then used by the Mars Odyssey and Mars Reconnaissance Orbiter missions, it does not require significant technology development. The Venus Flagship Mission baselined aerobraking to achieve a circular orbit for the science mission phase from an elliptical orbit which supported the relay telecom phase. For the VME mission, development of advanced chemical propulsion launch vehicles would deliver higher mass than that currently available with existing propulsion systems. For multi–element missions, such as the Venus Flagship Mission concept, S–band proximity communications could support high data rates between the in situ elements and the orbiter. Furthermore, the orbiter could generate large amounts of science data that in turn would require high data rates from the relay orbiter to Earth (in Ka/X–band).

6.2 Atmospheric Entry

Hypervelocity atmospheric entry produces extreme heating (measured as heat flux in kW/cm^2)

through both convective and radiative processes. Relatively very high heat flux encountered during Venus entry requires ablative thermal protection systems (TPS) that allow only a small fraction of the heat to penetrate conductively, and are designed to reject the majority of the heat through re-radiation and ablation. Because of the high gravity field and dense CO_2 atmosphere of Venus, it is a more challenging target for entries than Mars or Earth. Three parameters are key in entry system design: peak heat flux, integrated heatflux, which is a function of duration and peak pressure. The challenge for entry system is to provide thermal protection without catastrophic failure, since TPS is a single point failure system, and with the lowest TPS mass fraction possible. Heritage carbon–phenolic TPS has been demonstrated for missions ranging from 5 to 30 kW/cm^2, requiring mass fractions ranging from 12% for Venus missions to as high as 50% to 70% for missions to Saturn and Jupiter, where the heat fluxes are significantly higher. For a Pioneer–Venus type steep entry heritage carbon–phenolic could be used, but there is limited supply of out of production raw material, a special rayon, in hand and establishing an alternate is critical. However, entry with shallow flight path angles – required for low g–load tolerant RPSs – would experience much lower peak heat flux and pressure, potentially allowing the use of lighter ablative materials, thus increasing payload mass fraction for the same delivered mass. Due to the slow rotation of Venus, the planetary entry is not limited by the approach trajectory option, resulting in equally feasible prograde and retrograde entries.

6.3 Telecom for High Data Rates and Volumes

A very–high resolution radar system produces such high data volumes that the chief technological problem is related to bandwidth. Optical telecommunication is one solution to this problem. The Venus Laser Transceiver (VLT) option is an optical transceiver for Venus orbiter–to–Earth telecommunications, to achieve a greater than 10–fold data volume return, compared to Ka–band communications. The VLT is based upon the 50–cm aperture Mars Laser Optical Transceiver to be flown during a pre–2020 pathfinder mission, supporting data rates above 100 Mbps from 1 AU. Further details on this system are given in the Venus Flagship Mission study report [Hall et al., 2009].

6.4 Orbiter Instruments

For orbital missions, the dense atmosphere, preventing the use of imagers in the visual range, blocks much of the electromagnetic spectrum. Radar imaging deployed on Magellan has provided a global map of Venus, but advances in radar technology could provide improved topographic maps and potentially detection of surface changes using Interferometric Synthetic Aperture Radar (InSAR). Advances in passive infrared and millimeter spectroscopic techniques enable more effective probing of this part of the planet. Details on other proposed orbiter instruments are provided in the Venus Flagship Mission study report [Hall et al., 2009].

6.4.1. Orbiter Interferometric Synthetic Aperture Radar (InSAR)

InSAR provides comprehensive measurements of the topology and topography of the Venusian surface. It has the capability to operate in an interferometric mode to produce high–resolution topographic information at a posting of 50 m/pixel and as a standalone imager to extremely high–resolution data of local areas at 6 m/pixel. The InSAR proposed for the Venus Flagship Mission concept included two 4–m × 4–m antennas that are separated by 9 m on booms, with one antenna used to transmit the radar signal and both used to receive the reflected echoes. The observing geometry from the 230–km circular polar orbit is offset from the nadir by about 30 – 35 degrees, allowing for range and Doppler processing that yields radar images from the two received datasets. The image strip parallels the flight path of the spacecraft and is approximately 10 km wide to permit overlap with subsequent orbit tracks as Venus slowly rotates. At a resolution of 50 m per pixel, it requires 1.8×10^{11} pixels to cover the entire planet, or 7.2×10^{14} bits of science data at ~4,000 bits per pixel. The Venus Flagship Mission is designed to return 3 × 10^{14} bits of InSAR data over the course of the mission, allowing for approximately 40% of the planet to be mapped at this resolution and correspondingly less at higher resolutions. Therefore, these InSAR measurements should be supported by a suitable telecom system, and making the measurements would require tight pointing control, knowledge, and stability.

6.4.2. *Global and Targeted Ultra–Fine Resolution Radar Mapping*

A rough estimate for a 6–m resolution global image map of Venus, which has a surface area of 4.6 × 10^{14} m^2, would require ~1.8 Pbits of raw downlinked data, and a global 50–m resolution DEM would require 0.7 Pbits, over ~1800 hours of total instrument operation, distributed through at least one Venus rotation cycle. Even finer radar image resolution (down to the 1 to 2 meter scale) can be achieved for perhaps a few percent of the surface, through well demonstrated spotlight–mode synthetic aperture techniques, which require the spacecraft to track a particular location on the ground for periods of order 10 seconds. Beyond the science benefits, these types of measurements could help with landing site selection for future missions, including a Venus Surface Sample Return (VSSR) mission.

6.4.3. *Cloud LIDAR*

A multi–wavelength LIDAR instrument is capable of measuring the cloud topography from orbit with higher precision than achieved by instruments on Venus Express. While the laser wavelength of 1032 nm used by the instrument on MESSENGER is not well suited for the Venus atmosphere, it is expected that a LIDAR optimized for its atmospheric wavelength window would work. Furthermore, multiple LIDAR wavelengths would enable learning more about the cloud microphysics on a global scale at altitudes not accessible to entry probe or balloon borne observations.

7. TESTING FACILITY – VENUS ENVIRONMENT TEST CHAMBER

The electrical anomalies experienced by all four Pioneer–Venus Probes, starting at ~12.5 km above the surface, resulted in partial loss of science data below that altitude. While multiple options were considered, the most likely reason for the failures were contributed to condensation of conductive vapors on the external sensors in the deep atmosphere, leading to shorted electrical circuits. Other theories included chemical interactions of atmospheric constituents with the probe and sensors, such as reaction of residual sulfuric acid from the clouds with harness or sensor materials or supercritical CO_2 driven oxidation of titanium parts or polymers; and probe charging followed by electrical breakdown of the atmosphere, leading to sparks that could possibly ignite probe external fires.

The anomaly experienced by the Venus descent probes points to the need to simulate the Venus environment as accurately as possible. The Pioneer–Venus probes were tested in nitrogen at temperatures up to 500°C and pressures up to 100 bars. They were never tested under these conditions in a carbon dioxide environment, because it was assumed that both carbon dioxide and nitrogen are chemically inert, and consequently the substitution of carbon dioxide by nitrogen was acceptable. Recent work on the properties of carbon dioxide at high pressures and temperatures, when it enters a supercritical state, indicate that these assumptions are not correct. Therefore, testing in a relevant environment is imperative.

Consequently, drills, support mechanisms, sample processing, and distribution and contingency sampling elements outfitted with high–temperature motors, resolvers, bearings, lubricants, brakes, and high–temperature drive trains will need to be designed, built, and extensively tested in a terrestrial setting as well as inside a Venus chamber at pressure and temperature. This prototype testing must include extensive strong rock and regolith drilling (at relevant temperatures and pressures) so as to fully characterize the complex systems reaction produced by the environment and drilling loads generated from a wide range of targets. This requirement would have an impact on the sizing of the Venus environment test chamber.

In addition to the technologies for future Venus exploration, new laboratory measurements could help to maximize the science return from current and future Venus missions. These measurements could be divided into two categories: Category 1 are laboratory data necessary for retrieving Venus system variables from calibrated instrument data, and Category 2 are laboratory data necessary for characterizing fundamental Venus processes based on newly revealed Venus system variables.

The required conditions for laboratory measurements and component testing would necessitate a Venus Environment Test Chamber design that would target four basic physical regimes with seamless transition. These are: (1) the atmosphere above the clouds, in which the temperature and pressure conditions are similar to those in the terrestrial atmosphere; (2) the sulfuric–acid–laced cloud layer; (3) the atmosphere below the clouds, in which the temperature and pressure range is unique for solar system exploration; and (4) the super–heated surface and near surface environments where the ground is ~460°C and the atmosphere is supercritical CO_2. The Venus Environmental Test Facility would simulate pressure, temperature, and atmospheric composition as a function of altitude. Details on the science benefits of such a test facility is given in the VEXAG white paper [VEXAG, 2007].

While facilities for laboratory investigations at extreme Venus temperature and pressure conditions could be small and devoted to particular investigations, larger chambers for spacecraft and instrument testing under Venus conditions could enable laboratory investigations, if these chambers were available to the general scientific community.

8. CROSS CUTTING TECHNOLOGIES – VENUS VS. GIANT PLANETS

Understanding Solar System formation requires in situ measurements of Giant Planets atmospheric composition. Deep entry probes to Jupiter and Saturn are proposed to measure atmospheric constituents and dynamics down to about 100 bars. At this pressure elevation on Jupiter and Saturn the pressure and temperature conditions are similar to those at the surface of Venus. Therefore, many of the technologies are directly relevant between Jupiter, Saturn and Venus entry probe technologies. For example, atmospheric descent to the surface of Venus takes about 1–1.5 hours, while reaching 100 bars at the Giant Planets would take ~70 minutes (driven by telecom and trajectory constraints for the latter). Consequently, pressure vessel and thermal management technologies and probe instrumentation would be similar between them.

9. CONCLUSIONS

Potential in situ exploration mission architectures could range from smaller high altitude balloons and descent probes to large long–lived mobile near–surface missions. These could be implemented as single element simple architectures in the Discovery and New Frontiers mission classes, or in a higher complexity flagship mission, such as the Venus Flagship Mission, Venus Mobile Explorer, and Venus Network, leading towards a future Venus Surface Sample Return mission. The success of the Mars Exploration Rovers has demonstrated that long–lived mobile in–situ vehicles can provide substantially improved science returns (which is in line with the 2006 SSE Roadmap recommended Venus Mobile Explorer concept), while the Venus Design Reference Mission study highlighted the benefits of a multi–element architecture with moderate new technology needs.

Mission elements on these potential future in situ missions must be tailored for atmospheric and surface conditions. This necessitates new technologies and capabilities for tolerating and in some cases exploiting the severe environmental conditions of Venus. In general, in situ missions to Venus would benefit from a number of technologies for high temperatures, including active thermal cooling, pressure vessels, high–temperature electronics, energy storage, and high–temperature mechanisms, driven by the chosen mission architecture.

Surface missions to Venus encounter particular challenges, because they need to operate in extremely harsh environments (~480°C and ~90 bars) and prior to reaching the surface, a lander would face the additional hurdle of passing through the extremely corrosive sulfuric acid clouds at higher altitudes. For short–duration in situ missions passive thermal control approaches may be adequate, but very long–duration missions would require active cooling to "refrigerate" the thermally controlled avionics and instruments. High temperature sample acquisition is an enabling technology for all surface missions. Even short missions require hardened sample acquisition systems because of the necessary environmental exposure, although the exposure duration will determine the technology requirements. Accordingly, refrigeration technology would be needed for long duration missions, involving anything beyond the science that could be provided with current communications systems. Furthermore, certain functions will remain impractical for implementation at high Venus surface temperature and pressure. This group includes components such as most scientific sensors and microprocessors.

Current state–of–practice technologies do not support long lived in situ Venus missions. Advances in thermal control, electronics, sensors, actuators, materials, power storage, power generation and other technologies are expected to enable these potential future missions. Systems architectures could be key in establishing which technologies will enable systems exposed to the environment, and which technologies will require consistent protection. Sample acquisition systems will clearly require environmental tolerance and appropriate systems engineering, since they openly interface with the environment. On the other hand, for certain sensors and microprocessors it will remain impractical to increase tolerance levels, thus these will need to remain in a protected environment. Materials research will continue to play an important role in developing technologies for aerial mobility. Balloons are envisioned as possible modes of exploration for Venus, but the environmental constraints must be addressed.

Balloon missions need to address material issues, including temperature and corrosion. Balloons operating at cloud levels are at relatively high TRL, but the technology required to implement a lower altitude (<50 km) Venus balloon is not mature and faces four main challenges, related to materials, high temperatures (requiring thermal management), power and mass limitations.

A summary of the technologies required to operate on the surface of Venus is given in Table 1, while the recommended technology development priorities for Venus exploration in light of the Venus Flagship Mission study are summarized in Table 2. It should be noted that these technologies could be also beneficial to future New Frontiers and Discovery class mission concepts.

To address these challenges, an early program of systems analysis would be important to define the best approach and to determine realistic technology performance goals. This could advance the findings of the Venus Flagship Mission study and open up the mission architecture trade space, in case elements of the Venus DRM are implemented in smaller Discovery and New Frontiers missions, resulting in a reassessment of the Venus Flagship Mission architecture. Development of these new capabilities may require substantial technology investments. Thus, a credible long–range technology investment strategy could animate a set of early missions, some of which would permit validation of technologies needed for follow on missions. It is expected that a Venus Environment Test Chamber would play an important role in developing and testing new technologies and capabilities to enable these future missions.

Table 1: Summary of technologies for the surface exploration of Venus [Hall et al., 2009]

Capability	Requirements	State of the art (TRL level)	Development focus
Refrigeration	– long life in Venus environment (months) – high efficiency – capable of ~3kW total heat rejection – suitable for integration with lander and low altitude balloon pressure vessels – minimized mechanical vibration	TRL~3 – high temperature operation not demonstrated at the system level	– Stirling machines need to be adopted for Venus environment – duplex Stirling machine must be produced that integrates the heat engine and refrigerator functions into a high efficiency and high reliability device.
High–temperature power system	– long life in Venus environment – high conversion efficiency – low mass	TRL~4 – demonstrated single Stirling convertor for 300 hours operation with a 850°C hot–end temperature and 90°C cold–end, 38% efficiency and 88 W power output with heat input equivalent to 1 GPHS module.	– cold end operation needs to be raised from 90°C to 480°C with high conversion efficiency preserved – material testing, system development and validation for reliable operation in Venus surface environment.
High–temperature energy storage	– long life in Venus environment (117 days min.) – high specific energy - rechargeable and primary batteries	TRL 4 – demonstrated LiAl–FeS_2, Na–S, and Na–metal chloride secondary batteries with specific energy in the 100–200 Wh/kg range	– adapt cell and battery designs for space applications – stability of seals and terminals – minimize the corrosion of current collectors at high temperatures – optimize the electrolyte composition to improve performance and reliability
High–temperature sensors	– long life in Venus environment (117 days min.) Seismometers: – 0.3 mHz to 10 Hz frequency range – 10^{-8} to 10^{-9} $msec^{-2}Hz^{-1/2}$ amplitude sensitivity Other sensors: – pressure, temperature, wind speed, gas species variation in time	TRL 2–6 – geophones operating up to 260 °C – high–temperature pressure, temperature, and anemometers used on Venera/VEGA and Pioneer	– high–temperature MEMS technology for seismometers – SiC and GaN high temperature sensors
High–temperature electronics (500 °C)	– long life at Venus environment (117 days min.) – data acquisition, processing, and storage capability – power management	TRL 2–3 – limited integrated circuit capability demonstrated – limited electronics packaging – data storage, ADC, power converters, and other needed components never demonstrated	– SiC–based electronics – GaN–based and miniaturized vacuum electronics – high–temperature electronic packaging, passive components – reliability, long life

Capability	Requirements	State of the art (TRL level)	Development focus
Medium–temperature electronics (300 °C)	– low power dissipation at 300°C – long life and reliability	TRL 4 – medium temperature components developed for automotive and oil drilling industry	– HTSOICMOS electronic components – low power – test, validation, and reliability
High–temperature telecom	– long life at Venus environment (117 days min.) – high data rate (~4.5 kbs)	TRL 2 – demonstrated 2 GHz operation at 275°C using SiC – SiC and vacuum tube based oscillator demonstrated at ~500°C	– SiC based RF components for transmitters – miniaturized vacuum tube technology for power amplifiers – SiC based RF components for transmitters

Table 2: Venus Technology Development Priorities [Hall et al., 2009]

	Technologies for the Venus Flagship Mission	Comments
1	Surface sample acquisition system at high temperature and pressure conditions	Drilling, sample collection and sample handling are enabling for the Design Reference Mission. Heritage Soviet–derived systems are not available off the shelf, but they demonstrate a feasible approach.
2	Lander technologies for rotating pressure vessel and rugged terrain survivability	Rotating pressure vessel concept is powerful but technologically immature. Tessera and other rugged areas on Venus cannot be reliably accessed unless a properly engineered rugged terrain landing system is provided.
3	Venus–like environmental test chamber	This capability is critical for testing and validation of science measurements as well as for testing of components and systems for their survivability in Venus environment
	New capabilities	Comments
4	Refrigeration for the Venus surface environment	Almost every long duration (beyond 25 hrs), in situ platform will require some amount of refrigeration to survive. Focus should be on radioisotope–based duplex systems that produce both refrigeration and electrical power.
5	High temperature sensors and electronics, including telecom systems	Refrigeration requirements can be drastically reduced if electronics can operate at elevated temperatures. While a Venus ambient 460°C capability would be most desirable for telecom, data processing/storage, and power electronics, a major reduction in refrigeration loads could be realized already with moderate temperature operation (>250°C).
	Enhancement to the current Venus Flagship Mission design	Comments
6	Extension of lander life through advanced thermal control	Human intervention during the lander operation on the surface of Venus is not possible unless lander life is extended to at least 24 hrs.

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