Technology Perspectives in the Future Exploration of Venus

James A. Cutts[1], Tibor S. Balint[1], Eric Chassefiere[2], Elizabeth A. Kolawa[1]

Science goals to understand the origin, history and environment of Venus have been driving international space exploration missions for over 40 years. Today, Venus is still identified as a high priority science target in NASA's Solar System Exploration Roadmap, and clearly fits scientific objectives of ESA's Cosmic Vision Program in addition to the ongoing Venus Express mission, while JAXA is planning to launch its own Venus Climate Orbiter. Technology readiness has often been the pivotal factor in mission prioritization. Missions in all classes—small, medium or large—could be designed as orbiters with remote sensing capabilities, however, the desire for scientific advancements beyond our current knowledge point to in-situ exploration of Venus at the surface and lower atmosphere, involving probes, landers, and aerial platforms. High altitude balloons could circumnavigate Venus repeatedly; deep probes could operate for extended periods utilizing thermal protection technologies, pressure vessel designs and advancements in high temperature electronics. In situ missions lasting for over an Earth day could employ a specially designed dynamic Stirling Radioisotope Generator (SRG) power system, that could provide both electric power and active thermal control to the spacecraft. An air mobility platform, possibly employing metallic bellows, could allow for all axis control, long traversing and surface access at multiple desired locations, thus providing an advantage over static lander or rover based architectures. Sample return missions are also featured in all planetary roadmaps. The Venus exploration plans over the next three decades are anticipated to greatly contribute to our understanding of this planet, which subsequently would advance our overall knowledge about Solar System history and habitability.

1. INTRODUCTION

Science objectives for Venus exploration are considered key to answer questions about Solar System formation and habitability. Venus, a member of the inner triad, is one of the first planets to be visited by spacecraft. Over the past 40 years, more than 20 missions succeeded in exploring it, through flybys, orbiters, probes or landers, not counting failed attempts. Past missions included the Magellan and Pioneer-Venus missions by the US; the Venera Program missions by the USSR; and the USSR Vega missions with extensive international cooperation.

From a US perspective, in 2003, the National Research Council (NRC) published an Integrated Exploration Strategy for the study of the Solar System, called the Decadal Survey [NRC, 2003]. It identified three criteria in establishing NASA mission priorities: scientific merit, opportunity (e.g. favorable budgetary or orbital configurations), and technology readiness. It also identified Venus as a high priority science target. In response to the NRC recommendation, the 2006 NASA Solar System Exploration Roadmap [NASA, 2006] included a number of potential Venus missions, rang-

[1] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA.

[2] Service d'Aéronomie/ Pôle Système Solaire de l'IPSL, Service d'Aéronomie, Université P & M Curie, Paris, France.

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ing through all mission classes from small (Discovery), to medium (New Frontiers) and to large (Flagship) missions. From a European perspective, ESA's Venus Express orbiter is currently performing scientific investigations through remote sensing measurements. Future exploration of the Solar System, including Venus, will be addressed through the Cosmic Vision Program [ESA, 2006], for which the Announcement of Opportunity (AO) is expected by the end of 2006. From JAXA, the Venus Climate Orbiter, also known as Planet-C, is planned for launch in 2010 [Imamura et al., 2006].

This chapter addresses technology perspectives for the future exploration of Venus, by first discussing the extreme environmental conditions, followed by mission architectures and technology needs.

2. EXTREME ENVIRONMENTS ON VENUS

Understanding the formation of our Solar System and answering questions about habitability require a focused exploration program. At the target destinations, however, we have to deal with extreme conditions, such as high temperatures combined with high pressures; extreme cold; high radiation; and thermal-cycling. 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 is composed of aqueous sulfuric acid droplets at ~45 to ~70 km attitude. The zonal winds near the surface are ~1 m/s, increasing up to 120 m/s at an altitude of ~65 km. The greenhouse effect results in very high surface temperatures, ~460°C to 480°C, while the surface pressure can reach as high as ~92 bars. At these conditions near the surface, the CO_2 becomes supercritical, which can further complicate missions planned to explore these regions. Therefore, mission architectures and related technologies must address ways to mitigate these environmental conditions.

3. MISSION ARCHITECTURES FOR VENUS EXPLORATION

Venus exploration is clearly an important element of the Solar System Exploration program for national and international space agencies. Parallel exploration strategies address both orbital and in situ explorations of Venus. In this section we provide a brief historical overview of previous Venus exploration missions, and then outline various candidate mission architectures planned for the next three decades by the space agencies, concluding with discussion of additional mission architectures currently not in the roadmaps.

3.1. Brief Overview of Historical and Ongoing Missions

The Soviet space agency executed a highly successful program for Venus exploration, reaching the surface with multiple landers. NASA's Pioneer-Venus multi-probe mission also performed in-situ exploration of the planet, while the Vega missions were conducted through international partnership under the leadership of the Soviet space agency. The major mission characteristics are summarized in Table 1.

Venus landers have historically been designed with spacecraft subsystems operating within conventional temperature ranges and protected passively inside pressure vessels. The success of this thermal design approach depends on its capability to both exclude the exterior heat and to absorb the heat generated internally by the operating electronics. The pressure vessel also requires a minimum number of ports, windows, and exterior connections in order to minimize the number of potential thermal leaks. Beside the protected components, the Venera 13 and 14 landers, as well as the Vega landers, included a sample acquisition system with sample processing that operated in the Venus environment throughout the collection of multiple samples. Designs used on these historic missions would not be compatible with some of the proposed missions requiring controlled, multiple sample acquisition and processing, since the acquisition system would need to be placed outside the vessel, operating in the Venus environment.

3.1.1. Pioneer-Venus Multiprobes. To date, NASA's in situ Venus exploration program involved only the Pioneer-Venus Multiprobe mission, which sequentially deployed four atmospheric probes from the same Multi Probe bus. The probes were launched as a cluster on a single craft in 1978, while the orbiter was launched ten weeks earlier. Three of the 94 kg Small Probes were identical (including 61 kg pressure vessels and 33 kg deceleration modules), while the fourth probe, known as the Large Probe, was 302 kg (including a 193 kg pressure vessel and a 109 kg deceleration module). These probes were not designed to carry out surface observations, but were equipped to survive the descent to the surface with thermal controls, other than phase change materials.

Pioneer Small Probes: Three of the probes were identical 0.47 m diameter spherical pressure vessels, housed inside a 0.76 m aeroshell that did not separate from the probe during descent. The pressure vessel was machined from Titanium with a heat shield of carbon phenolic, and filled with Xenon to reduce the heat flow through the walls to the instruments. The instruments were mounted on heat-absorbing Beryllium

Table 1. Summary of historical Venus in situ missions

Missions	Launch	Module Mass (kg)	Descent (min)	Surface (min)	Design	Comments
Venera 3	1965	337			80°C, 5 bar	Entered Venus atmosphere
Venera 4	1967	380	93		300°C, 20 bar	Stopped transmitting at 25 km (battery)
Venera 5	1969	405	53		300°C, 20 bar	Stopped transmitting at ~20 km (320°C, 27 bar)
Venera 6	1969	405	51		300°C, 25 bar	Stopped transmitting at ~20 km (320°C, 27 bar)
Venera 7	1970	500	35	23	540°C, 150 bar	Parachute failure, rough landing, landed on the side
Venera 8	1972	495	55	50	490°C, 100 bar	Performed as designed
Venera 9	1975	1560 (660)	20+55	53	490°C, 100 bar	Orbiter out of the radio range
Venera 10	1975	1560 (660)	20+55	65	490°C, 100 bar	Orbiter out of the radio range
Venera 11	1978	1600 (760)	60	95	490°C, 100 bar	Transmission stopped
Venera 12	1978	1600 (760)	60	110	490°C, 100 bar	Transmission stopped
Venera 13	1981	1600 (760)	55	127	490°C, 100 bar	Transmission stopped
Venera 14	1981	1600 (760)	55	57	490°C, 100 bar	Transmission stopped

Missions	Launch	Module Mass (kg)	Descent (min)	Surface (min)	Design	Comments
Vega 1 lander	1984	750	60	20	490°C, 100 bar	Loss of contact after 20 min Transmission
Vega 2 lander	1984	750	60	56	490°C, 100 bar	Flyby out of range

Missions	Launch	Module Mass (kg)	Flight (hrs)	Design	Comments
Vega 1 balloon	1984	21 kg incl. 6.9 kg gondola	48	Designed to operate at 54-55 km altitude where temp. is about 40°C and press. About 0.5-1 bar	Transmission stopped after batteries were exhausted and balloon reached a day side
Vega 2 balloon	1984	Same	48	Same as Vega 1 balloon	Same as Vega 1 balloon

shelves. The interior of the vessel was protected from external heat by a thick 61-layer blanket of metallized Kapton insulation lining, while the exterior was covered by low emittance coating. The small probes did not carry a parachute, instead used aerodynamic braking during the descent to the surface. The housing doors for the three instruments opened at 70 km above the surface, in a controlled manner, using an actuation mechanism with adequate torque to overcome aerodynamic forces resulting from the descent of the probes through the atmosphere. The small probes were each targeted at different parts of the planet and were named accordingly (North, Day, Night). Following the 53 to 56 minutes descent, only the Day Probe survived landing with its antenna pointed towards Earth, and continued sending radio signals for 67 minutes after impact. The electrical anomalies experienced by all four Pioneer Venus Probes resulted in partial loss of science data below that altitude. This so called "12.5 km anomaly" [Seiff et al., 1993]—manifesting in electrical failures—is further discussed in the "Testing for Extreme Environments" section.

Pioneer Large Probe: The Pioneer Venus large probe had a diameter of 1.42 m, with a 0.78 m diameter Titanium pressure vessel, filled with Nitrogen. After deceleration from initial atmospheric entry at about 11.5 km/s near the equator on the Venus night side, a parachute was deployed at 47 km altitude. The sealed spherical pressure vessel was encased in a nose cone and aft protective cover and contained seven science experiments. The vessel was lined with 41 layers of a dimpled and flat metallized kapton insulation blanket (with a ~2.5 cm total thickness), used 37 kg of beryllium for two equipment mounting shelves acting as a heat sink, and with the outside covered with low emittance coating. Electrical heaters helped remove the condensates from the two sapphire science instrument windows. For the infrared radiometer the prime and backup windows were fabricated from 200 and 31 carats natural diamond stones, and sealed using a preloaded system of a graphoil sealing surface with anviloy and inconel alloys. The Large Probe took 54 minutes to descend through the atmosphere and did not survive the landing.

3.1.2. The Venera Program. The former Soviet Union carried out an extensive program over two decades as they successfully delivered landers, labeled sequentially as “Venera”. (Venera is Russian for Venus.) These missions conducted a range of measurements through the upper atmosphere, atmosphere, and on the surface. Among the 10 successful landings the Venera 13 lander survived for 127 minutes after reaching the surface of Venus in 1982. These landers used a hermetically sealed pressure vessel with a phase change material (starting with Venera-8), as well as more traditional thermal insulation both inside and outside. The pressure vessel, containing all of the instrumentation and electronics, was mounted on a ring-shaped landing platform and was topped by an antenna. Another breakthrough was the development of a lightweight honeycomb composite outside insulator that was able to withstand high temperatures and pressures. These new materials resulted in a large mass savings. On Venera 9 and 10, some of the sensors designed to study clouds and atmosphere during descent, specifically nephelometers and spectrometer sensors, were mounted outside of the pressure vessel with their own insulation and PCM for thermal protection. The spectrometer sensors were connected to spectrometer through fiber optic pipes to view upward and downward. The temperature, pressure, and density sensors were designed to operate and survive in Venusian environment. The platinum temperature sensors were enameled to protect them from chemical corrosion and from the absorption of gas into metal.

3.1.3. The Vega Landers and Balloons. Two Vega missions were executed under international partnership, led by the Russian Space Research Institute (IKI). The complex mission architecture called for an orbiter that released a lander and a balloon at Venus prior to continuing on to rendezvous with Comet Halley. The two spacecraft, Vega 1and Vega 2, were launched on December 15 and December 21, 1984, respectively. Arriving at Venus in June 1985, each spacecraft deployed a 1500 kg descent module towards Venus and the main spacecraft were then retargeted for a Comet Halley encounter in March 1986. The descent modules split into two parts, a lander and a balloon package, and entered into the atmosphere of Venus on June 11 and June 15, respectively. Both landers reached the surface of Venus and returned data about the atmosphere of Venus and soil composition data was obtained by Vega 2(the soil acquisition device failed on Vega 1). The Vega 1lander survived for 20 minutes and the Vega 2 lander transmitted data for 56 minutes. The two balloons performed 4 science experiments, while the two landers executed 9 experiments. (While they were designed to perform 12 experiments, the temperature and pressure units and the soil device failed on Vega 1, and the mass spectrometer failed on Vega 2.) The Vega balloons were designed to deploy and float high in the atmospheric clouds where the temperature was near Earth ambient. However, the balloon materials had to be tolerant of the corrosive effects of concentrated sulfuric acid and other chemical agents present in the clouds and to ultraviolet radiation. In addition, the balloon materials as well as deployment system had to survive for months folded up and exposed to vacuum during cruise to Venus. The Vega balloons had a 6.9 kg payload suspended 12 meters below a fluoropolymer-coated Teflon fabric balloon, floating in the most active layer of the Venus three-tiered cloud system at ~54 km altitude. The tether and straps between gondola compartments were made of nylon-6 type of material called kapron. The deployment system included bottles of compressed helium and a 35 square meter parachute that was used during the filling of the balloons with helium. The filling process took about 230 sec 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 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 1and Vega 2balloons survived for 47 hours, and traveled over 10,000 km until depletion of the batteries.

3.1.4. Flyby and Orbiter Missions. The US Mariner 2 mission was launched in 1962 and verified the planet’s high temperatures. In 1974 Mariner 10 (US) bound for Mercury, flew by Venus (2/5/74), and tracked global atmospheric circulation with visible and violet imagery. The Pioneer-Venus Orbiter (U.S.) radar mapped Venus (12/78), and dropped four probes through the Venusian clouds, as discussed above. The most recent US Venus orbiter mission, Magellan was launched in 1989. It arrived at Venus in 1990 and mapped 98% of the planet. The mission ended in 1994. ESA's Venus Express was launched in 2005, as a follow on Mars Express. Scientific investigations during its 500-day nominal missions in Venus orbit aim to enhance our knowledge of the composition, circulation and evolution of the atmosphere of the planet. The surface properties of Venus and the interaction between the atmosphere and the surface will be examined and evidence of volcanic activity will be also explored. NASA's MESSENGER spacecraft will fly past Venus twice, in October 2006 and June 2007. During the first Venus flyby very limited observations were made since the spacecraft was in solar conjunction. The science opportunity during the second flyby could include taking representative sets of VIS and IR image mosaics as a practice for the Mercury flybys. Other measurements could cover atmospheric profiles, the exosphere of Venus on departure, observation of acceleration of energetic charged particles at the bow shock of Venus, and measurements of the magnetic field before, during and after the flyby.

3.1.5. Lessons Learned from Historic In Situ Missions. Looking at historic missions, several conclusions can be drawn from the experience of Soviet and U.S. spacecraft, conducting in-situ exploration of Venus. For example, 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 communication issues and the extreme environment. 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 the 12.5 km level 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. The effects of long duration exposure in the lower atmosphere of Venus are unknown and more research is needed to understand the chemical and physical processes that 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.

3.2. Mission Architecture Options for the Future Exploration of Venus

Technology readiness has often been the pivotal factor in mission prioritization. In particular, the technology challenges may account in significant part for the lack of new Venus in situ NASA missions and the slow pace of exploration over the past decade. While missions in all classes could be designed as orbiters with remote sensing capabilities, the desire for scientific advancements beyond our current knowledge point to in-situ exploration of Venus. The specific technology needs, such as high temperature electronics, requires the understanding of the planned mission architectures. Therefore, the various exploration strategies are bounded by relevant mission architectures.

Mission architectures for Venus exploration could include orbiters, high and low altitude balloons, microprobes, entry probes, long lived landers or mobile explorers, sample return and network missions. Some of these architectures are proposed by various space agencies, while other are included for completeness. Typically, these missions are optimized to reach the best balance between key trade space options, such as science objectives, programmatics, mission architectures and technologies. Driven by programmatic considerations, the missions can be also categorized by their size, namely small, medium or large. Moving from smaller to larger missions the science returns and mission complexities are expected to increase. At Venus, the harshness of the environment amplifies with the depth in the atmosphere. Thus, the technology challenges to enable these missions are predominantly influenced by two factors, the distance from the surface and the time spent in that environment. The various mission architectures described here reflect the increasing requirements for tolerating these extreme conditions, while in the next section we discuss the relevant system architecture approaches and technologies planned to enable these missions.

3.2.1. Proposed Roadmap Mission Architectures. Space agency roadmaps identified Venus exploration missions in all mission classes from small to large. While the descriptions below will not detail science objectives, they will provide generic mission architecture elements and technology drivers.

Orbiters and Flybys. Based on simple architectures, these types of missions can be designed with or without in situ elements. Due to the closeness to the Sun, they can be powered by solar panels. From orbit only remote sensing observations are available. However, they can act as telecommunication relays between in situ elements and Earth. Examples for flyby and orbiter missions include the MESSENGER spacecraft and the Venus Express and Venus Climate Orbiter orbiters.

High Altitude Balloon. Balloon platforms are of high interest for studying the atmosphere and in a limited way the surface. By staying above the clouds at 60 to 65 km from the surface, the pressures and temperature conditions are Earth-like (0.1 to 1 bar, and -50 to -70°C), providing simplicity to this architecture. At this altitude the temperature and pressure conditions would not require extreme environment technologies. The potentially solar powered payload could address optical, contact and analytical measurements, devoted to the characterization of clouds; chemical sensors to measure atmospheric composition at cloud level; and electromagnetic wave analyzers to monitor the electromagnetic activity of the planet below the ionosphere. A balloon could be deployed from an orbiter or flyby spacecraft, or by direct atmospheric entry. After entry the payload would release the aeroshell and inflate the balloon at an appropriate altitude, then drift in the super rotating atmosphere with limited mobility. A balloon could also serve as a carrier to deploy microprobes. An ESA study described a platform, consisting of a gondola and balloon with a floating mass of 32 kg, including 8 kg of science instruments and microprobes. While the balloon circumnavigate Venus at an equilibrium floating altitude of ~55 km and analyze the middle cloud layer, it would also release 15 drop-sondes at scientifically interesting locations. For inflation gas, hydrogen, helium and ammonia could be considered, however, hydrogen is preferred for its overall system mass efficiency. Various high altitude balloon concepts are studied and proposed by both NASA and ESA, targeting small to medium class missions.

Microprobes. To understand the composition and dynamics of the atmosphere, it is important to obtain atmospheric measurements of the vertical structure down to the surface of Venus. Due to inhomogeneity, these observations should be performed at multiple locations, requiring multiple descent probes. An ESA proposed multi-probe mission would utilize 10 to 50 microprobes, deployed in short separation intervals of ~5 minutes, obtaining atmospheric profiles at both the day and night sides. The microprobes would communicate with the balloon, reducing the high power requirements for the telecom system on the probes. The collected data would be relayed to Earth from the balloon. Each of the 100 grams microprobes would carry a core payload of miniaturized sensors, encased inside an evacuated glass sphere, and based on commercial off the shelf (COTS) technology. The probe descent would be monitored from the balloon by a probe returned “ping” signal, and could be used for trajectory reconstruction. Initial estimates indicate that the probes could operate down to altitudes of 10–20 km, however, this requires further detailed thermal analysis, since at these altitudes the temperature reaches about 300 to 400°C. (In comparison, the temperature limit for COTS and military components is around +85°C and +125°C, respectively. Therefore, a suitable thermal management system on the microprobes would likely increase their mass above the current estimates.) An ESA funded study determined that an accompanying balloon subsystem, floating at an altitude of ~65 km, would weight less than 1.5 kg. The concept is proposed by ESA as part of a small to medium class mission. [Chassefière et al., 2006]

Low Altitude Balloons. At a 10 km altitude 2 cubic meter pressurized balloon could carry up to 100 kg of total payload. The Lavoisier project was submitted to ESA [Chassefière et al., 2000], as a follow up to and in the spirit of the balloon deployed at cloud level by the Soviet Vega mission in 1986. It is composed of a descent probe, for detailed atmosphere composition analysis, and of a network of 3 balloons. In the Lavoisier concept, each balloon probe is made of a gondola, protected by a thermal shield during the entry phase. Balloons have a complex and variable thermal environment during their operational phase. All the parts that can withstand this environment are not thermally protected in order to reduce the size of the temperature-controlled area. This is the case in particular for the hardware components of the telecom subsystem and for the batteries. The temperature controlled area is designed to keep all the thermally sensitive equipments below 40°C. Taking into account the limited power resources, a concept of a passive thermal cocoon made of concentric layers of PCM (Phase Change Materials) has been validated for the balloon probes. The concept of the gondola consists of a spherical cocoon with a series of concentric layers having the following characteristics (from the outer edge to the inner edge): insulating layer, liquid water layer, insulating layer, paraffin layer, inner compartment with the payload. The thermal shield would absorb the thermal flux during atmospheric entry and probe descent from the upper atmosphere down to the altitude measurement. The shield concept could be based on the technology used for the Huygens probe front shield sub-system. At an altitude of about 20 km, the thermal shield would be released, and the 2 m^3 balloon deployed from the gondola, then inflated with helium. This would stabilize the gondola at the measurement altitude of 10 km for about 20 hours. Following the balloon deflation, the gondola would descend to the surface for a 2 hours surface operation, completing the mission. Additional issues related to the balloon material that could tolerate high temperatures at these altitudes, is discussed in Section 5.7.2.

Entry Probes. Probes are simple and can utilize flight heritage from US and Soviet missions discussed above. They would have limited lifetimes of 1 to 2 hours, while descending from an altitude of ~80 km to the surface. Surface access and science return are expected to be limited. In the concept proposed for ESA’s Lavoisier mission [Chassefière et al., 2000], a scientific payload of 15 kg would operate during the descent. Optical instruments would be expected to survive soft landing and continue operating for some time, similarly to the Huygens probe. Recent ESA discussions identified a potential multiprobe mission to Venus, with up to 4 probes descending to the surface. One probe would enter the night side and three the day side, at the equator, mid latitude and the pole. This architecture requires a trajectory design for the flyby spacecraft and the three entry probes, addressing telecommunication strategies. Entry probe concepts are proposed by ESA for small to medium class missions. [Chassefière et al., 2006]

Short Lived Lander. In the Decadal Survey the Venus In Situ Explorer (VISE) mission concept was envisioned by the NRC as a balloon mission that would study Venus' atmospheric composition in detail and descend briefly to the surface to acquire samples that could be then analyzed at a higher altitude, where the temperature is less extreme. This medium class (New Frontiers) missions would perform compositional and isotopic measurements of the surface and atmosphere of Venus [NASA, 2006]. The duration of surface operation could range from a few minutes up to several hours on the surface of Venus, acquiring and characterizing a core sample to study the mineralogy of the surface. Short lived landers offer simplicity and flight heritage from Soviet missions. However, the science return would be limited and the platform would not allow for mobility. Concepts are proposed by both ESA and NASA for a medium class missions.

Long Lived Mobile Explorer. Venus Mobile Explorer (VME), proposed in NASA's SSE Roadmap [NASA, 2006], is proposed as a second decade Flagship class mission with a launch date as early as 2025. VME would explore and characterize the surface with a wheeled or aerial vehicle and would further acquire and characterize a core sample. It would need to operate in the Venus surface environment for up to 90 Earth days. After passing through the sulfuric acid clouds discussed previously, these missions are envisioned to require sample acquisition from about 10–20 cm depth and in situ sensing. Of even greater interest to the scientific community are long-term (1 year or longer) missions. In this case, robust active refrigeration, coupled with a long lived radioisotope power system, would be critical for the more fragile subsystems. Rovers could provide good surface and subsurface access for sampling and seismic measurements, but limited traversing over the mission lifetime. An aerial platform could offer all axes mobility, go-to capability, good traversing and surface mapping at high resolution imaging from near the surface, but also involves significant technology challenges to mitigate the extreme environment. The entire project, from start to end-of-mission, could be accomplished in 6–7 years, including a surface stay time of days or weeks (although certain enabling technologies, such as the radioisotope power system with active cooling may require additional development time).

Atmospheric Sample Return. This architecture supports in-situ chemical and isotopic measurements of the upper atmosphere of Venus. Understanding the distribution of isotopes in the Solar System, such as those of oxygen, sulfur and noble gases, we require very high precision measurements up to 0.01%. Since current mass spectrometers available for in situ exploration have a sensitivity of about 1%, it is desirable to return the collected samples and conduct laboratory investigations on them using highly sensitive Earth based instruments. The preferred, and likely the simplest, concept for atmospheric sample return consists of a sample collection flyby pass through the upper atmosphere of Venus (130 km). The bus would be equipped with a collector coupled with a cryogenic device. The collected samples would be returned to Earth on a free return ballistic trajectory. The concept is under consideration by ESA for a small to medium mission.

Surface Sample Return. A Venus Sample Return is considered to be a very difficult mission that would certainly follow a successful Mars Sample Return and an effective Venus Mobile Explorer mission. As for Mars, answers to detailed questions about the past suitability of Venus for the origin and sustenance of life can only be answered by bringing samples back to terrestrial laboratories. These include definitive interpretations of the petrology and mineralogy of crustal samples over scales from the regional to the microscopic and determinations of the C, O, S and H isotopic abundances in the crust and lower atmosphere. The implementation challenge lies not so much with Venus environmental issues (although they are not trivial) as it does with the mission energetics. There would need to be a buoyant ascent stage to collect the sample either from the surface or from another vehicle (deployed to the surface and back into the atmosphere) and then carried to an altitude from which atmospheric density is low enough for a launch to be feasible. At this point the propulsion needed is equivalent to an inner planet mission starting at Earth's surface. Needless to say, even with a very small sample return payload the buoyant stage would only be capable of reaching Venus orbit, where another Earth Return Vehicle would have to be waiting to rendezvous with the ascent stage, to transfer the sample for a return flight to Earth. Sample recovery at Earth would be similar to the proposed Mars sample return concept with a direct entry to a suitable recovery site. Advanced airborne systems and high-energy in-space propulsion are key capabilities needed for this mission. Although it is recommended in the Decadal Survey, the Venus Surface Sample Return (VSSR) mission is beyond the planning timeframe of the roadmaps, therefore, it may not require technology development within the next ten years. However, it is important to see the progression from short-term to longer-term missions and on to sample return in order to understand the importance of various technologies, particularly high temperature sample acquisition.

3.2.2. Additional Mission Architectures. The following mission concepts are currently not in agency roadmaps, but included here for completeness.

Mid Altitude Balloon. Due to the large pressure and the Archimedes buoyant force, Venus balloons could transport substantial scientific payloads, although harsh environmental conditions at mid altitudes (p>50 bars, T>400°C) the concepts might prove to be too difficult to implement. At about 35 to 45 km from the surface the balloons would be below the cloud layer, but still too far from the surface for high resolution remote sensing measurements or surface access. For example, due to the high atmospheric opacity, only low altitude balloons below 10 km, with a resulting visibility over 10%, would be able to perform efficient visual and infra-red sounding of the surface and near-surface atmosphere. The sulfuric acid droplets in the clouds would introduce material challenges, and the reduced solar availability could make power generation difficult. This would limit mission lifetime, and the concept is currently not in any of the roadmaps.

Long Lived Lander. This concept provides good surface access for both sample acquisition and seismic measurements, but it would face the same challenges as those encountered by static Soviet landers under the Venera program. Furthermore, the long mission duration would necessitate and internal power source, such as a radioisotope power system, with active cooling to the instruments and subsystems. Static landers, by definition, do not provide mobility. For long lived in situ explorations mobile platforms provide a scientifically more rewarding architectures, therefore, static landers are currently not considered in the roadmaps.

Network Missions. These network mission architectures could be considered for balloons and seismic measurements. They would have similar characteristics to single missions of the same type with an added benefit of allowing access to multiple in situ sampling or measurement locations. The multiple elements would provide redundancy, but introduce additional mission architecture and technology challenges with deployments, communications, and issues related to extreme environments. The cost for these architectures would also be significantly higher than for single missions. Consequently, these concepts are currently not in any of the roadmaps.

4. SYSTEMS ARCHITECTURES FOR MISSIONS TO EXTREME ENVIRONMENTS

Systems architectures for extreme environments may be categorized by the isolation of sensitive materials from hazardous conditions; development of sensitive materials tolerant to hazardous conditions; and appropriate combinations of isolation and tolerance.

4.1. 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 difficult.

4.2. 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 are 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.

4.3. Hybrid Systems

In a hybrid architecture, hardened components would be exposed directly to the environment and not hardened components 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. The integration of isolation and tolerance to form a hybrid system is illustrated in Plate 1.

For Venus landers, a hybrid architecture is 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.

5. TECHNOLOGIES FOR FUTURE EXPLORATION OF VENUS

Technology needs depend strongly on mission goals and mission architectures. The principal challenge, where new technology may play a role, is observation and access to the surface and lower atmosphere. Thus, new technologies will make the greatest impacts on in-situ missions, involving probes, landers and aerial platforms. While the Soviet VEGA balloons lasted for only two days in the upper atmosphere of Venus, future proposed small (Discovery) class missions could include entry probes as well as super pressure long-lived balloons, operating in the upper atmosphere above ~60km, potentially permitting balloon missions to circumnavigate Venus repeatedly, over many weeks. Deep probes and landers with current technology are limited to a few hours of operation due to the environment. For lifetimes on the surface and in the lower atmosphere of Venus of more than an Earth day, a specially designed dynamic Stirling Radioisotope Generator (SRG) power system could provide both electric power and active thermal control to the spacecraft. An air mobility platform, possibly employing metallic bellows, could allow for all axis control, long traversing and surface access at multiple desired locations, thus providing an advantage over static lander or rover based architectures. If this major technological hurdle can be overcome, long duration fixed and mobile floating platforms, such as the NASA's proposed Venus Mobile Explorer mission, will be enabled. This will be the key to intensive in-situ geological and geophysical investigation of the planet.

This section details technologies to enable future Venus exploration missions.

5.1. Orbiter Technologies

For orbital missions, much of the electromagnetic spectrum is blocked by the dense atmosphere, preventing the use of imagers in the visual range. Radar imaging deployed on Magellan has provided a global map. Advances in radar can provide improved topographic maps and potentially detection of surface changes using INSAR (Interferometric Synthetic Aperture Radar). Advances in passive infrared and millimeter spectroscopic techniques enable more effective probing of this part of the planet. However, much of the technologies associated with orbiters and flyby spacecraft can be handled with existing technologies, therefore, these are not discussed further in this chapter.

5.2. Protection Systems

In general, protection systems refer to those systems providing isolation from the extreme environment. Hypervelocity entry protection is a form of thermal control at extremely high peak heat fluxes. Pressure and thermal controls are also protection systems, although they are likely to be integrated into a joint pressure vessel for missions to Venus (see Plate 3).

5.2.1. Hypervelocity Entry. Hypervelocity atmospheric entry produces extreme heating (measured as heat flux in kW/cm^2) though both convective and radiative processes. Thermal Protection Systems (TPS) are composed of insulation layers that allow only a small fraction of the heat to penetrate the spacecraft surface conductively, and are designed to reject the majority of the heat through re-radiation and ablation. The success of hypervelocity entry is measured by two quantities: (1) the peak heat flux tolerated by the entry vehicle, and (2) the mass fraction dedicated to a thermal protection system. Current heritage carbon-phenolic family of materials can tolerate ~1 kW/cm^2, thus requiring mass fractions ranging from 12% for Venus missions to as high as 50% to 70% for missions to Jupiter. It is anticipated that technology development can improve the tolerated heat flux by an order of magnitude, thus allowing for reductions in the thermal protection mass fraction of anywhere from 25% to 50%. The rotational period of Venus is -243 days (retrograde), and at a 70 km altitude the super-rotating atmosphere is ~60 times faster than the solid surface. This results in a negligible ±390 km/h rotational difference at the equator between prograde and retrograde atmospheric entry experienced by an entry probe. Therefore, the planetary entry is not limited by the trajectory option.

5.2.2. Pressure Control. New advances in materials technology will enable advanced, lightweight pressure vessels that can be layered with insulating materials. The Soviet Venera and Vega missions, described above, used titanium pressure vessels surrounded by a rigid, porous, silicon-containing material that served as the outer thermal insulation. In order to compare emerging pressure vessel materials, three basic mechanical parameters may be used to estimate pressure vessel mass for a given shell diameter. The pressure vessel shell must satisfy these criteria at a temperature of 500ºC:

(1) Buckling should not occur at the ultimate load of 150 atm pressure. Buckling is a catastrophic failure mode, caused by lateral instability in a structural element that is subjected to high compressive stresses.
(2) Yielding should not occur at the proof load of 125 atm pressure. Material yielding occurs if the stress on the material results in a permanent deformation.
(3) The total allowable creep in 10 hours and under 100 atm external load must be less than 0.5%. Material creep describes the tendency of a material to deform over an extended period of time in order to relieve stresses.

These criteria are evaluated based on compressive yield strength, compressive modulus, and creep strain rates. In addition, pressure vessel material must be impermeable to gases, while retaining compatibility with the Venus chemical environment. Low thermal conductivity would be also desirable; however, this requirement could be mitigated against through better insulation. Other factors to be considered in selecting shell materials include: fracture toughness, heat capacity, and 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. This manufacturing technique could be used, for example, for aluminum/silicon. Honeycomb sandwich shells are often formed into curved geometries (e.g., for aircraft engine cowlings). This could be an appropriate fabrication technique for Inconel pressure vessels. [Pauken et al., 2006]

Additional mission architectures may exist, where mission duration is extended by equilibrating to the ambient pressure, while protecting against the temperature increase. Like many of the systems analyses facing technologies for extreme environments, the understanding of such an approach is also incomplete.

5.2.3. Thermal Management and Control. Advanced thermal protection provides the highest benefit to the missions in terms of survivability, regardless of configuration or mission duration. Advanced thermal protection technologies may extend in situ mission lifetimes significantly and would considerably enhance the scientific yield of the proposed medium class (New Frontiers) VISE mission.

Passive Thermal Control:

Aerogel. With a thermal conductivity approximately that of a gas at 0.1 W/mK, aerogel provides good insulation without convection. The current state of the art, has a density of approximately 20 kg/m^3.

Multi-layer insulation. 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 coarse-netting material, to keep the layers properly separated. Possible next generation 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-phenylenebenzo-bisoxazole) 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. While Kapton (polyimide) is not suitable because it will not tolerate Venus surface temperatures, aramid or other polymers could in principle be combined with silica fabrics.

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 with Pioneer-Venus. The current state of the art is the lithium salts with specific heat 296 kJ/kg used in the Soviet Venera and Vega landers. Materials are available with high transformation temperatures, high latent heat, and low density. However, the need for low volumetric change limits the transformations to solid-liquid and solid-solid transitions. A higher density

PCM may be more appropriate if it could require a smaller volume and consequently requires less container or filler mass. The state-of-art PCM is a paraffin (C16H34) or paraffin-like polymeric material that dissipates about 250 kJ/kg during its solid-to-liquid phase transition.

Active Refrigeration:

For any high temperature surface mission lasting more than several days, a proactive approach to thermal control is required. Active thermal control or refrigeration systems would be described generally by the efficiency, defined as the ratio of the output heat to the removed energy. Limited theoretically by the Carnot limit of 72%, it is likely that such a system would operate at about 30% efficiency relative to a Carnot engine, or at about 20% total efficiency. No such system currently exists. One potential architecture for a Venus surface mission is a three-stage refrigeration system, isolating the internal electronics enclosure with a series of cylindrical vessels. To minimize conductive heat transfer, electronic components would be housed in an evacuated inner vessel and maintained at a cooler temperature with a refrigeration system.

5.3. Component Hardening

"Component hardening" refers to technologies expected to be exposed to the ambient environment, with general categories of electronics, electro-mechanical systems, and energy storage. Component hardening is the process of developing technologies capable of tolerating the external environment. This section describes the individual elements considered key to mission operation and survival.

5.3.1. High Temperature Electronics. Active components. Terrestrial industries currently employ high temperature electronics in the fields or oil and gas exploration, automotive and aviation industries, geothermal wells and defense related fields. The temperature limits of today's commercial and military application needs are below 300°C. These temperatures are well below the temperatures encountered at the surface of Venus, indicating that the need for electronics, which can tolerate the extreme high temperature and pressure environments are unique to space agencies, planning to explore these target locations [Kolawa et al., 2006]. The most promising high-temperature semiconductor technology, capable of operating in the Venus environment, is silicon carbide. Silicon carbide devices have been demonstrated to operate as high as 500°C for limited periods of time (tens of hours), but the availability of silicon carbide-based integrated circuits is extremely limited. In missions with passive thermal control, such as VISE, high power electronic and telecom systems act as internal heat sources. Placing these systems outside the thermally protected vessel may reduce internal heating and extend the life of the mission. Small scale integrated SiC high temperature technologies and heterogeneous high temperature packaging can support this need and produce components for power conversion, electronic drives for actuators and sensors amplifiers.

Another approach to high temperature electronics is related to further development of the original solid state vacuum devices. Vacuum electron devices are well suited for extreme temperatures, especially in the application to the high temperature telecom system where they can provide a noise-performance advantage over SiC. This is because it is possible to design high temperature micro vacuum based power amplifiers that can directly operate in the Venus surface environment without any penalty in noise and linear performance. It should be noted, however, that careful design and improvement of the device packaging (vacuum enclosure) and materials are required in order to allow operation within the 500 ºC ambient environment. Furthermore, these vacuum devices are inherently unlikely to achieve the high levels of integration and functionality that is possible with semiconductor transistors. While both wide-bandgap semiconductor and vacuum tube approaches to high-temperature electronics have been demonstrated to operate at temperatures in excess of ~500°C, there are no strong commercial drivers for this technology.

In missions with active thermal control, medium-temperature large-scale integrated electronics can be used for fabricating all essential functions of the spacecraft. Electronics operating at medium temperatures (300°C) can reduce the temperature difference between the outside environment and inside of the thermally protected system. The smaller temperature difference will significantly reduce the corresponding power needed for cooling. Also, this type of electronics can enable Venus balloon missions to operate for prolonged duration down to 20 km altitudes where temperature does not exceeds 300°C. For intermediate (300°C) temperatures, it is more feasible to extend traditional silicon based electronics. Historical investments by the US Department of Energy, the oil industry, and the automotive industry have resulted in some silicon electronic components operational at 250–300°C. They are fabricated using silicon-on-insulator (SOI) technology to reduce device leakage current at higher temperatures. It is feasible that low-power medium-temperature Si-based electronics could be developed for hybrid systems for in situ Venus missions. [Del Castillo et al., 2006] [Spry et al., 2004]

Passive components. Passive elements for high temperature applications depend not only on the survivability of resistive elements, dielectrics or magnetic core materials, but also on the component packaging and interconnection technology. This is the most common source of failure for devices that have not been designed for high temperature operation. With respect to resistors, thin film and thick film resistors deposited on ceramic substrates provide the best performance and miniaturization of currently available resistor technologies. Potential problems include oxidation of thin film resistive elements with time at temperature and resistance value drift in thick film resistors. Degradation of potential candidate resistors must be characterized in detail, in order to make use of them in 500 ºC circuits.

Capacitors are particularly challenging for high temperature operation, since they tend to vary in capacitance with greater temperature, particularly as the dielectric constant and dielectric dissipation are increased. At elevated temperatures, the leakage currents of these capacitors become very high, making it difficult for the capacitor to hold charge. The most promising candidates for high temperature (500 ºC) capacitors are NP0 ceramic capacitors and piezoelectric based capacitors. NP0 capacitors have minimal variation in capacitance with temperature, but unfortunately they exhibit a significant increase in dissipation above 300 ºC. Piezoelectric capacitors are designed for operation at a specific temperature, and therefore exhibit optimum properties at the desired temperature. Unfortunately, the temperature window for this peak performance is very narrow, and these capacitors change significantly with increasing temperature. Various capacitor technologies, such as diamond capacitors and other alternative dielectric materials, are currently under development and may eventually offer superior properties throughout the entire temperature range from 23 to 500 ºC.

5.3.2. Electronic Packaging . Critical to the implementation of any high temperature electronics system will be the packaging approach and materials selected. Development of materials for interconnects, metallizations, conductive (solders) and non-conductive (ceramics) bonding materials, wire bonding systems, mechanical protection, and thermal management) must be integrated with the development of proper packaging systems for each application.

5.4. Electro-Mechanical Systems for High Temperatures

High temperature motors and actuators are the key components of the sample acquisition and transfer system. The acquisition of un-weathered samples from at least 20 cm below the surface layer of Venus is required for VISE mission. In addition, motors and actuators are required for a variety of functions during space system operations like opening and closing valves, deployment of landing gear, operation of robotic arms, antenna gimbals and many others. For VSE mission motors and actuators may be crucial for mobility systems if rover is selected as a mission baseline. In such a case the motors will be required to operate reliably for hundreds of hours.

The required technologies to be developed include motors and gearboxes, position sensors, high temperature electrical cabling, mechanical devices related to drilling and containing a sample, and mechanical sample transfer devices. A first step in the process is a selection of materials. For example, magnetic materials with high Curie temperature need to be identified and tested for the motor itself as well as suitable materials have to be identified for gearboxes and lubricants. Based on the results from materials testing at high temperatures, the motor assembly needs to be built and tested at high temperatures.

There are several approaches to reliably implement controlled motion and actuation in a high temperature environment, including electromagnetic systems, spring-based systems, thermally actuated switches, and piezoelectric devices.

5.5. Testing for Extreme Environments

The electrical anomalies experienced by all four Pioneer Venus Probes, starting around ~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 carbon dioxide 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. [Seiff et al., 1993]

The anomalies 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.

5.6. Power Storage and Power Generation

Power systems, either in the form or power storage or power generation are key enabling technologies in any space mission. For orbiter and high altitude Venus missions power can be generated with solar panels. Since in this section power technologies are considered for the extreme environments of Venus, solar power generation for orbiters and high altitude mission elements are not discussed further. Instead, we discuss relevant technologies for short and long lived in situ Venus missions, namely batteries and radioisotope power system.

5.6.1. Energy Storage for High Temperature Environments. In the US, over the past five decades, several high-temperature energy storage technologies have been developed by and for NASA, the Department of Energy (DoE), and the Department of Defense (DoD). Development efforts, led by researchers at Argonne National Laboratory, resulted in thermally regenerative galvanic cells for the direct conversion of heat to electricity. Although not fully developed, several battery chemistries were created and qualified, which operated at or above 400°C. Without the need for high temperature batteries at the time, development was virtually stopped in 1995, due to the overwhelming interest in Li-ion batteries, offering high performance at 25°C. In ESA studies, the use of high temperature batteries operating at 425°C aboard a balloon is an important consideration to solve the thermal control requirement by reducing the mass and volume allocation of the cold compartment. 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/FeS2 batteries. The sodium-sulfur (Na/S2) batteries have a similar operating temperature range and practical energy density of ~100 Wh/kg. (In technology trade studies a mean energy density of 100 Wh/kg, compatible with the Venus environmental constraints, can be used for the power subsystem mass and performance estimation.) Rechargeable batteries could be beneficial for atmospheric cyclers, however, there are a few rechargeable battery systems capable of operating at high temperatures. These systems are typically based on molten salts based on alkali halides and/or solid electrolytes, especially sodium beta-alumina ceramic. The most promising, Na-NiCl2 battery with molten salt electrolyte, is functional at ~460°C and can deliver up to 130 Wh/kg. This battery chemistry is still under development in Europe, and could likely be transitioned into an environment specific package in less than 3 years. High specific energy batteries could positively impact the proposed in situ missions to Venus and to the Giant Planets identified in roadmaps, such as Jupiter, Saturn and Neptune, by reducing mass and volume requirements for the power subsystem. Further details on energy storage can be found in [Mondt et al., 2004].

5.6.2. Radioisotope Power System for Long Lived In Situ Venus Missions. As discussed earlier, the roadmaps identified in situ missions with various mission durations and technology difficulties. Driven by science requirements, longer missions provide greater science return. While short lived missions could be designed with power storage systems (batteries), long lived in situ mission require external or internal power sources, such as solar panels or radioisotope power systems (RPS). For high-altitude balloon missions solar power is readily available, but for long lived surface or low altitude aerial missions a specially designed RPS is required. RPS enabled missions could operate continuously near or at the surface for many months, as long as other issues related to the extreme environments, such as pressure and temperature, are addressed. The RPS, and the rest of the spacecraft, would also need to tolerate the highly corrosive supercritical carbon dioxide environment. For Venus conditions dynamic power conversion (e.g., Stirling converters) may provide an advantage over static conversion systems, because for the latter power conversion efficiency is strongly coupled with the temperature difference between the hot and cold sides of the thermocouples. This would result in a very low conversion efficiency, higher mass and volume for the static conversion based power system and higher plutonium requirement for the heat source. Dynamic conversion systems, have significantly higher conversion efficiencies, and due to the lower plutonium requirement less excess heat to reject. In addition to power generation, an RPS for Venus would also require to power an active cooling system, in order to maintain a quasi steady state thermal environment for the payload. Current Stirling Radioisotope Generator (SRG) development work does not include a requirement to operate in the 480°C Venus environment. Therefore, future development work should include work on special dynamic conversion systems including a power generator and an active cooler to address the need for sustained power at or near the surface of Venus. The power system should also utilize a suitable coating to minimize the impact of the corrosive environment while maintaining or if possible improving heat rejection performance. Furthermore, an aerial platform would impose mass and volume constraints to the RPS design, which should be balanced with the power requirement of the mission. [Balint, 2006]

RPSs must be designed for all mission phases, namely earth storage, launch, cruise, entry, descent and landing (EDL), and operations. Conditions between these mission phases may vary and so as the heat transfer mechanisms to reject the excess heat generated by the radioisotopic decay of the plutonium fuel. . For example, operating in planetary environments with atmospheres heat is rejected through convection, conduction and radiation. For Venus in situ missions, during approximately 6 months cruise phase the RPS would be encapsulated inside an aeroshell, during which time heat would be removed by a fluid loop and rejected to space through external radiators. Sizing of the fluid loop and the radiators for Venus missions would be different than similar in situ missions to Titan, because of the extreme environmental conditions at the destinations (480°C at Venus versus -178°C at Titan). RPS sizing should also account for the atmospheric entry phase, when the probe or lander would be se still inside the aeroshell, but forced circulation would be no longer available. [Balint, 2006]

RPS technology is considered enabling for the proposed long lived in situ roadmap missions. [NASA, 2006]

5.7. Mobility Technologies

Roadmap missions call for aerial mobility at low, medium and high latitudes. Each of these altitudes represent different technology challenges and approaches to mitigate the environmental effects, including mobility related technologies and material selection options.

5.7.1. Aerial and Surface Mobility Technologies. NASA's proposed Venus Mobile Explorer mission is currently baselined with aerial mobility, but surface mobility options were also considered. An aerial platform may not require deployment from a landed platform, and the mobility is not limited by planetary surface roughness or bearing strength. The surface access could be over a range up to 1000 km, utilizing the super rotating atmosphere of Venus. Vertical control of a long lived low altitude metallic bellows configuration would allow for repeated aerial imaging of the surface, although the horizontal control of the platform would be limited. Sample collection would be limited to grab-sampling only, due to the short contact period with the surface. Anchoring or longer stay at the surface is not recommended, due to the high risk of snagging, which could result in mission failure. In comparison, a surface rover on Venus would have significant constraints regarding landing sites. Rough terrains at scientifically interesting regions, such as at Tessera, could significantly impact traversing. Mobility would also be impacted by the low bearing strength. Rovers require significant power for mobility, which is also a function of surface roughness. Since power availability for long lived in situ missions is expected to be limited, the actual traversing capability of such a mission would be below 10 km over the lifetime of the mission, which makes this type of in situ exploration architecture less desirable. However, a rover platform would allow for precise sampling, and even drilling, thus, as discussed before, subsurface access could answer important questions related to the age and composition of Venus. Based on the significant technology challenges, long lived in situ missions would falls under the large mission class. Furthermore, benefits provided by the various in situ platforms, aerial mobility could provide the largest operational flexibility and highest science return. To tolerate the extreme environments close to the surface, the platform is envisioned as a metallic bellows shown in Plate 2.

5.7.2. Materials for Balloons and Parachutes. High altitude balloons experience Earth-like conditions, and stay above the cloud layer. Therefore, the balloon material selection is not affected by extreme environments. A prototype high altitude balloon has been built at JPL in 2006 in support of a Discovery proposal. 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. At mid to low altitudes, the dense atmosphere of Venus may provide higher buoyancy for aerial platforms, and controlled descent for 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 Teflon coating for protection from the atmospheric sulfuric acid. While Teflon is acid resistant, it may not survive the near surface portion of the mission, since it becomes brittle at high temperatures. Zylon 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, at medium altitudes, below the cloud layer, Zylon could be corroded by sulfuric acid. For an ESA design, the high altitude balloon would use PET (polyester) as the baseline material, because it offers a good compromise on properties. For additional options, research should be carried out into the potential use of PPTA aramid. A potential solution for accessing both low and mid altitudes was proposed as a two-balloon system. The first balloon would operate near the planet's surface and would look like a cylindrical metallic bellows made of extremely thin sheets of stainless

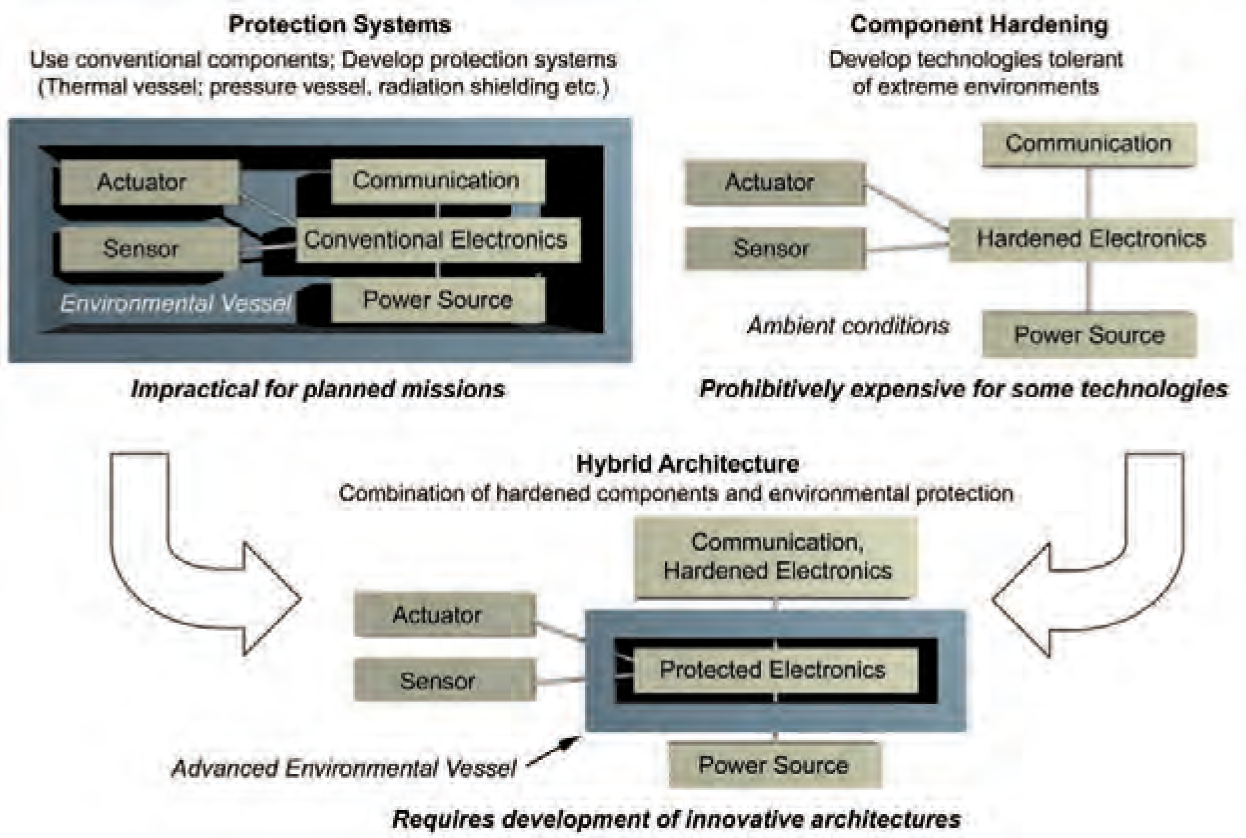

Plate 1. Hybrid Systems Architectures for Extreme Environments

Plate 2. Venus Mobile Explorer concept

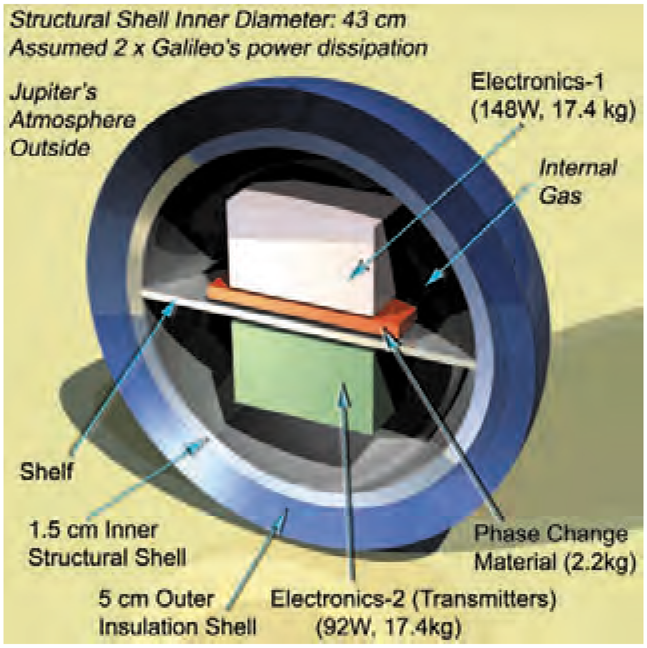

Plate 3. Illustration of the pressure vessel and thermal management for a Venus in situ mission

steel or another suitable alloy [Kerzhanovich et al., 2005]. The bellows would be flexible enough that it could be compressed like an accordion for storage on the way to Venus, and sturdy enough that it could survive the acidic clouds. The helium filled thin metal balloon would rise from the surface of Venus, carrying a suitable science payload. After reaching an altitude of about 10 to 15 kilometers, it would release a second balloon, which would climb to higher altitudes. Areal densities of 1 kg/m^2 are available with current technology; this will suffice for missions up to approximately 10 km altitude at Venus because of the very high atmospheric densities. The systems engineering of metal bellows balloons remain incomplete, including the key issue of deployment and inflation. Thus, the metallic bellows system is currently considered at a low TRL level, and would require technology investement to further develop it.

5.7.3. Atmospheric Cycler Concept. A reversible-fluid balloon filled with ammonia or water could cycle between near surface and 55 km altitudes. Near the surface, the payload lifetime could be extended to several hours through the use of thermal insulation and Phase Change Materials (PCM). At high altitudes, following the ascent phase, the PCM would be regenerated and the secondary battery onboard could recharge using solar energy. The total surface operation time would be limited to less than 100 hours, as a result of a limited number of altitude cycling. The cycling of ascent and descent phases would predominantly affect the thermal cycling of the electronics. The most critical technology issues are related to electronics, operating in environments of thermal cycling, and the performance of the electronic packaging to survive the repeated passes between low and high temperature regions. An advanced chip-on-board packaging technology is currently under development in a Mars Focused Technology Program, with the goal to survive 1500 cycles in the –120 to +80°C temperature range. At Venus, this temperature range would be wider towards the hot side, which would require further technology development.

5.8. Telecommunication Technologies and Strategies

Telecommunication technologies and data transfer strategies are necessary to guarantee the scientific data return from in situ Venus mission. The issues involved with implementing a high temperature interplanetary telecommunication system are intimately related to both the electronics and actuation technologies.

5.8.1. Telecommunications for high temperatures. In situ telecommunication systems on Venus would be likely limited to a fixed antenna, operating at S-band or X-band frequencies, since a precision gimbal system is not likely to be developed with high-gain pointing functionality. This is the result of the extreme temperature environment, where many of the sensors, electronic, and precision actuator elements would have to function reliably at 480°C. Each of the operating frequencies would pose its own challenge. Not only does a 10 W S-band communication link limit data transfer to 500 bps, the number of Earth-based S-band receivers is very limited (the Deep Space Network offers this functionality only at Goldstone), and they may be phased out by 2020. The X-band communications would provide even lower data transfer rates of 100 bps, and this design would result in a strong dependence on the X-band signal intensity on the elevation angle and proximity to Earth.

5.8.2. Telecommunication Strategies. Telecommunication system sizing is dependent on power and antenna sizing on the sending and receiving ends, their separation distance, the chosen frequency, environmental effect, and mission architectures. Communications between an in situ asset and a flyby spacecraft is time limited to about 1 to 2 hours. An orbiter would have similar constraints, but would allow re-visits for subsequent communications. This, however, would require a long lived mission, which would increase technology requirements on the in situ element. Direct to Earth (DTE) communication would be also limited by terrestrial constraints, for example DSN antenna size, weather, and line of sight. A multi probe mission to Venus could have a mixed communication architecture, where a probe could use DTE, while the others would communicate through an orbiter of flyby spacecraft. Due to antenna and power limitations on the probe the DTE data rate would be low. Even with the largest planned array, the radio-astronomy Square Kilometer Array (SKA), the data rate would be lower then using proximity links and relay data through a flyby or orbiter spacecraft. Furthermore, the SKA in currently not designed for lower frequencies and for planetary program support. Therefore, it is suggested that if the planetary community is planning to utilize the SKA, this request should be communicated to the radio-astronomy community in order to include lower frequency capabilities into the SKA design. Frequencies also play an important role in communication strategies. For proximity communication, lower frequencies could be beneficial and less affected by atmospheric attenuation, while higher frequencies could provide higher data rates over larger distances, if not affected by environmental conditions. Since the telecommunication system is responsible to relay all of the collected science data to Earth, its performance is essential to achieve mission success and the communication strategies should be assessed carefully.

5.9. Cross Cutting Technologies for In Situ Exploration of the Giant Planets

Understanding Solar System formation requires in situ measurements of Giant Planets atmospheric composition. Deep entry probes to Jupiter are proposed to measure atmospheric constituents and dynamics down to about 100 bars. At this pressure elevation on Jupiter the pressure and temperature conditions are similar to those at the surface of Venus. Therefore, many of the technologies are directly relevant between Jupiter and Venus entry probe technologies. Influenced by trajectories and telecommunication constraints, a Jupiter probe would descent into the atmosphere for about 70 minutes before reaching 100 bars. This again is comparable to the 1 to 2 hours Venus probe descent. Such short lived missions would employ phase change materials for thermal management inside the pressure vessel, and primary batteries for the power subsystem. From the probe's side the data rate would be limited by the power system, antenna size and environmental condition, such as atmospheric attenuation. This would make direct to Earth communication from a Jupiter not feasible, and from Venus it would severely limit the data rate.

6. SUMMARY

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. Current states of practice technologies do not support long lived in situ Venus missions. Therefore, an aggressive early program of systems analysis is important to define the best approach and to determine realistic technology performance goals.

Table 2 summarizes technology development impacts on Venus surface missions. This table suggests that 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 temperatures and pressure; this group includes items such as most scientific sensors and microprocessors.

7. CONCLUSIONS AND RECOMMENDATIONS

Venus exploration plans over the next three decades—as identified in the NASA 2006 SSE Roadmap—are anticipated to greatly enhance our understanding of Venus. Subsequently, it will also advance our overall knowledge about Solar System history and habitability. Parallel exploration plans by ESA' Cosmic Vision for 2015–2025 and JAXA are expected to significantly contribute to this effort.

The proposed in situ exploration mission architectures range from smaller high altitude balloons and descent probes to large long-lived mobile near-surface missions. The success of the Mars Exploration Rovers has demonstrated that long-lived mobile in-situ vehicles can provide substantially improved science returns. A similar strategy, based on long-lived mobile platforms, could highly benefit the Venus Exploration Program as well, but the mission elements must be tailored for environmental and surface conditions. This

Table 2. Technology development impacts on Venus surface missions

Design Reference Mission	Venus In-Situ Explorer (VISE)	Venus Mobile Explorer (VME)	Venus Surface Sample Return (VSSR)
Earliest Launch Date	2015	2025	2035
Architecture	Short-lived (hours) surface	Extended (days)Surface	Sample return
HT electronics and communications	Medium	Very High	Low
HT sample acquisition	Very High	Very High	Very High
HT energy storage	Low	Medium	Medium
Passive thermal control	Very High	Very High	Very High
Active thermal control	Low	Very High	Low
High pressure control	Very High	Very High	Very High
Aerial mobility	N/A	High	High

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.

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 will 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. Development of these new capabilities may require substantial technology investments. Thus, a credible long range technology investment strategy could animate a set of prior missions, some of which would permit validation of technologies needed for future missions. Since planetary extreme environments and related technologies are unique to space agency driven missions, agencies are expected to take the lead in the development of these critical technologies, with support from industry and academia.

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