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MITIGATING EXTREME ENVIRONMENTS FOR IN–SITU JUPITER AND VENUS MISSIONS

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ABSTRACT

In response to the recommendations by the National Research Council (NRC), NASA's Solar System Exploration (SSE) Roadmap identified the in–situ exploration of Venus and Jupiter as high priority science objectives. For Jupiter, deep entry probes are recommended, which would descend to $\sim$250 km — measured from the 1 bar pressure depth. At this level the pressure would correspond to $\sim$100 bar and the temperature would reach $\sim$500°C. Similarly, at the surface of Venus the temperature and pressure conditions are $\sim$460°C and $\sim$90 bar. Lifetime of the Jupiter probes during descent can be measured in hours, while in–situ operations at and near the surface of Venus are envisioned over weeks or months. In this paper we discuss technologies, which share commonalities in mitigating these extreme conditions over proposed mission lifetimes, specifically focusing on pressure and temperature environments. Pressure vessel designs are evaluated from the current State of Practice (SoP) to advanced concepts proposed for next decade missions and beyond. Thermal designs, both active and passive, are also addressed for the two target destinations. In addition, we briefly discuss other enabling technologies, such as high temperature electronics and power storage. It is expected that the findings from these assessments would help NASA with identifying future technology investment areas, and in turn enable or enhance planned SSE missions, while reducing mission cost and risk.

INTRODUCTION

The Solar System Exploration Decadal Survey [1] by the National Research Council (NRC) of the National Academies summarized our current state of knowledge of the Universe and identified key science goals, objectives and priorities for future explorations. In response to the NRC recommendations, Solar System Exploration (SSE) pathways were identified in the Vision for Space Exploration [2], including the Moon, Mars, the Solar System and beyond. These recommendations were further refined in NASA's 2006 Solar System Exploration Roadmap [3]. Further science input to NASA is provided by the NASA Advisory Council (NAC), and by science advisory groups, such as the Outer Planets Assessment Group (OPAG) [4], the Venus Exploration Analysis Group (VEXAG) [5] and the Lunar Exploration Analysis Group (LEAG) [6]. NASA's Science Mission Directorate (SMD) supports an ongoing effort to review technologies currently under development at NASA, academia, and industry. In the SSE Roadmap [3] a number of missions are proposed, which would reach and operate in extreme environments. Environments are defined as "extreme," if they present extremes in pressure, temperature, radiation, and chemical or physical corrosion. In addition, certain planned missions would experience extremes in heat flux and deceleration, leading to their inclusion as missions in need of technologies for extreme environments.

This paper addresses proposed in–situ missions to the extreme environments of Venus and Jupiter.

IN SITU MISSIONS TO VENUS AND JUPITER

Venus is one of the first planets visited by spacecraft. Over the past 40 years, more than 20 missions succeeded to explore it, through flybys, orbiters, probes or landers. 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.

Future exploration of Venus is addressed in NASA's SSE Roadmap [3], in the upcoming ESA Cosmic Vision Program [7] (for which the Announcement of Opportunity (AO) is expected by the end of 2006), and in JAXA's plans, for which the Venus Climate Orbiter, also known as Planet–C, is planned for launch in 2010 [8].

In this paper, however, we only focus on technologies relevant to in–situ exploration of Venus, specifically in the vicinity of the surface. The relevant mission concepts include the Venus In–Situ Explorer (VISE), and the Venus Mobile Explorer (VME). [3]

Similar extreme environments are encountered by deep entry probes to Giant Planets. The Galileo probe, the only probe mission to date into the atmosphere of a Giant Planet, entered Jupiter in 1995. While extensive research and technology development work has been done within NASA, many of the capabilities and core competence has been deteriorated over the years. Therefore, it is expected that a future Jupiter probe mission may require significant technology development. Probes are necessary to provide in–situ measurements, to complement and validate remote sensing observations. For example, the Jupiter Deep Entry Probes (JDEP) mission [9], discussed in this paper, is planned for a launch opportunity that would follow successful data return from Juno around 2017. (Juno, the 2^{nd} New Frontiers missions, is planned for a 2011 launch.)

In summary, the success of Venus missions depends on the capability of the spacecraft to survive in the Venus environment. In case of Jupiter, the main challenge is related to the thermal protection during descent and the ability of the probe to communicate with orbiter.

EXTREME ENVIRONMENTS

NASA's Solar System Exploration program is formulated to answer questions about solar system formation and habitability. At some of these destinations, however, we have to deal with extreme conditions, including extremely high and low temperatures, high pressures, high radiation, and thermal cycling. Proposed in–situ missions to Venus and Jupiter encounter some of the most hostile environments in our Solar System.

At Venus, the 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 between the altitudes of ~45 and 70 km. The zonal winds near the surface are ~1 m/s, increasing up to 120 m/s at an altitude of ~65 km. 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 these conditions near the surface, the CO_2 becomes supercritical, which could further complicate missions planned to explore these regions.

In comparison, Jupiter has a primarily hydrogen (~85%) and helium (~14%) atmosphere, with a small fraction of additional constituents, including ammonia, water vapor, and other organics and noble gases. The cloud layer is stratified; between 0.25–1 bars it contains NH_3; around 2–3 bars it consists of NH_4SH, (NH_3 + H_2S); and in the region of 5 to 10 bars it has H_2O and potentially other clouds and silicates. The wind speed, as experienced by the Galileo Probe, is fairly steady below 5 bars pressure elevation, with a maximum velocity just under 200 m/s. The temperature increases with pressure depth. In the tropopause at ~0.1 bar it is ~110K; while at 100 bars it reaches over 670K (400°C); and at 1000 bars it is expected to be over 1000K. [9]

From a technology point of view it is important to point out that Jupiter Deep Entry Probes at a 100 bars pressure elevation would experience similar coupled high pressure and temperature conditions, as those for Venus in–situ missions near the surface. Therefore, mission architectures and related technologies must address ways to mitigate these environmental conditions.

SYSTEMS ARCHITECTURES

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

Environmental Isolation

One potential solution for extreme environment system architectures is to maintain all electronics and sensitive components in an environmentally controlled vessel (see Figure 1). While this could be feasible option, its implementation could have a significant impact on cost and even on the overall mission architecture. Consequently, environmental isolation architectures typically require additional resources, thus, they may not provide ideal solutions for all missions to extreme environments. In addition, some of the in–situ components — e.g., sensors and sample acquisition systems — would be directly exposed to the environment, making the implementation of this approach even more challenging.

Environmental Tolerance

An alternative extreme to isolation is the development of hardware components that could reliably operate and survive in extreme temperature/pressure conditions (see Figure 1). This would eliminate the need for environmental control, however, this approach is considered ideal only on the purely theoretical level, since some of the key technologies would require a large investment to achieve the desired performance (e.g., components, which could operate at $\sim$500°C). While the concept of environmentally tolerant technologies is appealing (e.g., removing the need for a pressure vessel and thermal management), actual technology developments may not be able to answer these challenges due to fundamental physical limitations or impractical investment strategies.

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, inside a controlled enclosure, either passive or active cooling could be applied, but only for components that cannot be hardened to tolerate the extreme environments of Venus or Jupiter. Simultaneously, high temperature tolerant components would be employed where practical, including in–situ sensors, drills, and sample acquisition mechanisms, which would be fully exposed to the extreme environment.
Consequently, some temperature–sensitive components would be maintained inside an insulated thermal enclosure, while other more tolerant components would remain outside. This approach would result in a simpler and lighter thermal control, and would be more cost–effective. The integration of isolation and tolerance to form a hybrid system is illustrated in Figure 1.

TECHNOLOGIES

Technologies can be categorized as heritage, enhancing, or enabling. Heritage technologies are flight qualified and do not need significant technology investments. Enhancing technologies would benefit the mission, but without them the mission could still be successful, although with a less optimum configuration or reduced utility. Without enabling technologies the mission could not be executed at its conceived way. Technology needs are highly influenced by mission goals and architectures. Enabling technologies are specifically required for accessing the surface of Venus and for exploring the deep atmosphere of Jupiter. Consequently, new technologies would greatly impact these in–situ missions, including entry probes, landers and aerial platforms. This section provides a brief overview of technologies that could enable these proposed missions to Venus and Jupiter.
The pertinent technology needs could be categorized into three general areas:

- Environmental protection technologies providing isolation from extreme environments;

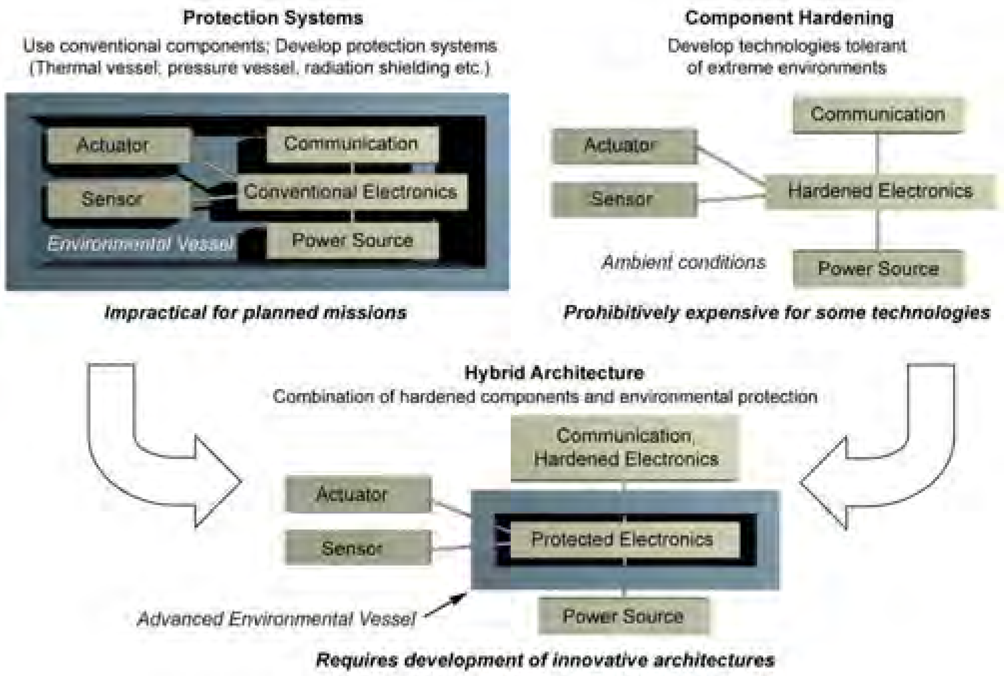

Figure 1: Illustration of the pressure vessel and thermal management for a Venus in–situ mission

- Environmental tolerance for exposed components or systems;
- Operations in extreme environments.

The first area describes technologies designed to protect spacecraft subsystems from the environment, including thermal protection systems (TPS) for hypervelocity entry, and pressure & temperature control for the vessels. The second group includes technologies for which it is practical to develop tolerance to relatively harsh conditions through "component hardening," such as electronics, electro–mechanical systems, and energy storage, where temperature tolerance can be included by design. Component hardening is the process of developing technologies capable of tolerating the external environment. The third area covers technologies like mobility or sample acquisition, which provide capabilities to operate in extreme environments in order to achieve mission science objectives. Finally, the environment could have a effect on telecommunication strategies during the operational phase, and pre–launch testing. These areas are also addressed.

Protection Systems

In general, protection systems refer to systems which provide isolation from the extreme environment. These include hypervelocity entry protection to mitigate the extremely high peak heat fluxes; and pressure and thermal controls for the payload.

Hypervelocity Entry

The Thermal Protection System (TPS) protects (insulates) a body from the extreme heating encountered during hypersonic flight through a planetary atmosphere. (It is defined as heat flux in kW/cm^2.) Since TPS is a single point–of–failure subsystem, it is critical and it's performance needs to be validated through both ground test and analysis. During entry, the aeroshell encounters multiple environmental factors, such as atmospheric pressure, convective heating, and radiative heating. The heating during hypersonic entry is a complex phenomenon. In addition to the atmospheric composition, the size and shape of the entry body, the ballistic coefficient and the TPS material interaction with

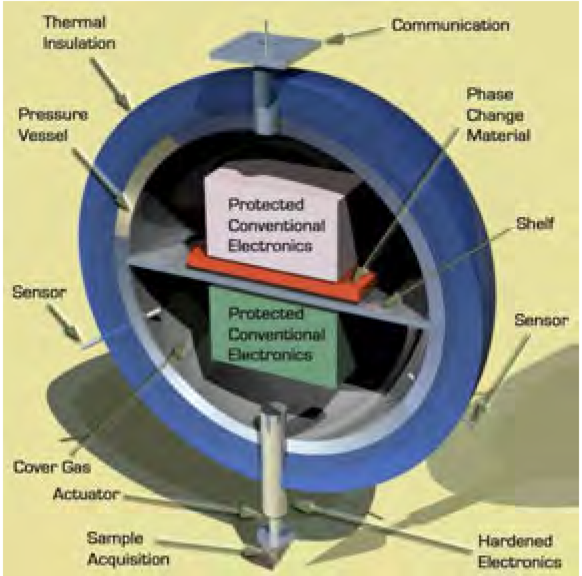

Figure 2: Illustration of the pressure vessel and thermal management for a Venus in–situ mission

the flow field all contribute to determining the resultant heating. The heating at the surface is a balance between the incoming shock layer radiation emanating from the excited /dissociated gas behind the shock wave; the frictional heating of the boundary layer with the wall; the energy radiated from the wall; and the energy taken away due to pyrolysis and ablation. This simple description is compounded by the fact that the ablation products absorb radiation, and massive blowing — as a result of ablation — changes the boundary layer characteristics. TPSs 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. In general, there are two classes of TPS. For *reusable TPS* there are no changes in the mass or properties of the material after exposure to the entry environment. Reusable TPS applications are mostly limited to relatively mild entry environments (e.g., Shuttle), and not applicable for Venus and Jupiter missions. In contrast, *ablative TPS* materials accommodate high heating rates and heat loads through phase change and mass loss. *Ablative* TPS materials are categorized by density (i.e., low, medium, and high density). Material strength increases with density, but so does the thermal conductivity. Consequently, material selection for a given mission entry environment requires a balance between ablative and insulation efficiency, while recognizing the optimal performance regime for each class of materials. When a material is used outside of its optimal zone, its performance is inefficient which leads to a non–minimal TPS mass fraction. Notionally, as density increases, the threshold for char spallation moves to higher pressures and heat fluxes. Char spallation is an undesirable phenomenon as it consumes mass (periodically) with minimal loss of thermal energy and, importantly, is difficult to characterize and predict. Ablative materials have been the classical approach to TPS used for over 40 years. For example, all NASA planetary entry probes (to date) have used ablative TPS, including the Pioneer Venus and Galileo probe missions, which employed fully dense carbon phenolic (C–P). C–P was developed by the United States Air Force for ballistic missile applications. Current heritage carbon–phenolic family of materials can tolerate $\sim$1 kW/cm^2, thus requiring mass fractions ranging from 12% for Venus missions to as high as 50% to 70% for probe 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. Currently, NASA is planning future in–situ Venus missions. If these missions would retains the same aeroshell shape as Pioneer–Venus, it would be logical to employ the same forebody TPS. However, the heritage material employed for Pioneer–Venus may no longer be available since it used a carbon cloth derived from a specific rayon fabric produced in the 1970s. Similar, C–P composites are currently being evaluated using carbon cloth derived from alternate rayon fabrics or other precursors. Characterization and qualification of such composites is straightforward, but will require time and resources.

In comparison, Jupiter's rotational velocity is about 12.6 km/s, which would reduce the ∼59.8 km/s probe approach velocity to ∼47.3 km/s. Under these conditions the Galileo probe experienced a heat flux of ∼30 kW/cm^2. Polar or retrograde probe entries to Jupiter would not benefit from the planet's rotation, resulting in entry velocities of ∼62.9 km/s and ∼72.4 km/s, respectively.

Testing TPS materials for the Pioneer–Venus entry mission was a challenge, and it remains so today. Peak heating rates and pressures projected for Venus entry are attainable in existing arc jet facilities, albeit in air and on small samples. However, no existing arc jet facilities operate on CO_2. Radiative heating rates can be simulated with existing high–energy laser facilities, although the radiative spectrum would not be representative. Fortunately, that is not a major issue for high–density carbonaceous materials as such materials are surface absorbers over a broad range of wavelengths.

TPS can be instrumented to measure pressure, temperature heat flux, and recession. These measurements could be used for atmospheric and entry reconstruction and TPS performance evaluation, therefore, their use is highly recommended.

Pressure & Temperature Mitigation

There are several potential mission scenarios for the exploration of Venus and the outer Gas Giants. For in–situ exploration of the Gas Giants, the mission architectures usually assume atmospheric probes. While the Galileo probe descended to ∼23 bars using a vented pressure vessel, the proposed Jupiter Deep Entry Probes would have to mitigate extreme pressure and temperature environments, down to 100 bars. A Venus in–situ mission would experience similar conditions, and the mission configurations could include balloon platforms, atmospheric probes, landers, rovers or seismic probes, among others. Lifetimes for various mission architectures are expected to vary from hours to months. The diversity of possible mission architectures dictates that the technology development and design of a pressure vessel for extreme high pressures and temperatures should address both structural and thermal issues. An example of this concept is shown in Figure 2.

Future missions to the surface of Venus or deep within Jupiter's atmosphere will require capabilities far exceeding those of the Pioneer–Venus probes or the Galileo probe. Extending mission lifetime beyond one or two hours will call for pressure vessels that are significantly lighter and thermal control systems that can keep all components operational significantly. The mass saved in the pressure vessel could be put to better use in the thermal control system or into additional science instrumentation. Furthermore, the mission architectures themselves will need to permit communication back to Earth for more than just a couple hours.

Most pressure vessels consist of a monolithic metal shell such as steel, titanium or aluminum. Steel and aluminum do not have the specific strength of titanium and therefore are not competitive alternatives for a Venus probe. Carbon fiber reinforced composite overwrapped pressure vessels for space applications are well developed and offer significant mass reductions, compared to metallic shells. However, composite vessels are unable to survive the extreme temperatures encountered in the Venus environment because of the matrix resins used in fabrication.

The extremely high (up to 200–400g) deceleration loads experienced by spacecraft entering the atmosphere of Venus or Jupiter amplify the benefits of reducing the mass of the pressure vessel. For example, new advances in materials technology will enable advanced, lightweight pressure vessels that can be layered with insulating materials. The Venera and Vega missions, by the USSR, used titanium pressure vessels, surrounded by a rigid, porous, silicon–containing material, that served as the outer thermal insulation. The mass of a titanium pressure vessel can be reduced by approximately 50 to 65% using new materials and manufacturing methods. At least three new technologies have been identified with pressure vessel mass saving potential. These technologies include forming: (1) a Beryllium shell using powder metallurgy (PM) and Hot Isostatic Process (HIP) to create a light weight monolithic shell with a high heat capacity, (2) a Silicon Carbide/Titanium Matrix composite shell, which also uses HIP and (3) a honeycomb sandwich shell structure using Inconel or possibly titanium. The development of manufacturing methods to produce spherical shapes is one of the biggest challenges of this technology. (Future missions could also benefit from miniaturization of the instruments and the use of advanced materials, consequently allowing for reductions in probe volume and mass.) [10]

In the design process, structural analysis should cover (a) entry and landing loads; (b) buckling loads; (c) creep of the structural material; (d) manufacturability using standard or advanced materials; and (e) strength, brittleness and adhesion of external insulation at high temperatures. (f) The pressure vessel should also incorporate windows, penetrations and feed–throughs. Beside structural analysis, the thermal analysis of the pressure vessel should address: (g) heat flow through the structural shell and penetrations; (h) gas leakage through seals and penetrations; and (i) power dissipation and temperature limits of electronics and science instruments.

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.

The pressure vessel material technology development program should focus on developing manufacturing engineering plans, followed by fabricating and testing doubly curved material samples. The best material candidates could then be selected to fabricate a subscale prototype pressure vessel that would be tested in a Venus–like temperature and pressure environment.

Spacecraft electronic systems will require varying degrees of thermal protection from the Venus and Jupiter thermal and pressure environments. Advanced thermal protection provides the highest benefit to missions in terms of survivability, regardless of configuration or mission duration. These technologies may significantly extend in–situ mission lifetimes and would considerably enhance the scientific yield of the proposed future missions.

Development of high temperature electronics would allow many components to operate at either Venus ambient temperatures of 460°C or at some other intermediate elevated temperature, such as 200°C or 300°C. Systems that can operate at these temperature regimes can simplify the spacecraft thermal control system and potentially reduce the overall system mass. However, it is likely that some electronic components would not be able to survive in high–temperature and high–pressure environments. Specific science instruments, may fall into this category, since these are typically one–of–a–kind components, and requiring them to operate at high temperatures may be impractical. Thermal systems for these kinds of electronic devices could use several techniques to keep them operational for the duration of the mission.

Thermal control methods rely on isolation from external heat sources, removal of self generated heat by local thermal energy storage, or by active cooling. Isolation and thermal storage would work well for short duration missions, but long–term operation would require active cooling techniques. *Passive thermal control* includes aerogel, multi–layer insulation, and phase change materials. *Aerogel* has a thermal conductivity approximately that of a gas at 0.1 W/mK, and provides good insulation without convection. The current state of the art has a density of approximately 20 kg/m^3. (Other insulation materials include metal foams and ceramic foams that are suitable for high temperature, high–heat flux applications.) *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 layers 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 could 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. *Phase change materials* (PCMs), with high thermal inertia, may be used to absorb the additional heat dissipated when the components. These were used on the Pioneer–Venus probes. The Venera and Vega landers used lithium salts with a specific heat of 296 kJ/kg. The best PCMs would have 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 achieve a smaller volume and consequently would require less container or filler mass. The state–of–art PCM is a paraffin ($C_{16}H_{34}$) or paraffin–like polymeric material that dissipates about 250 kJ/kg during its solid–to–liquid phase transition.

It is unlikely that significant breakthroughs in thermal energy storage or insulation technology will be made in the near future. Both of these areas are relatively mature. However, innovative uses of thermal energy storage could have significant benefits in extending the surface lifetime in the Venus environment.

Long–lived missions on Venus would require a form of *active refrigeration* to keep sensitive electronics operating for periods longer than a day. 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 ∼30% efficiency relative to a Carnot engine, or at ∼20% total efficiency. This type of system currently does not exist. 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. Active refrigeration technology has been focused on cryocooler development, and has become a mature technology. However, none of this "high–heat lift" capability has been directed toward systems that could operate in a Venus environment.

The most viable source of power for a cooling system would be a radioisotope power system (RPS). Basic thermodynamic calculations show that driving a cooling system with a radioisotope thermoelectric generator (RTG), while utilizing a standard thermoelectric converter, is impractical since the conversion efficiency from thermal energy to electric power would be below 4% in the Venus environment. Therefore, a significantly higher energy conversion cycle would be necessary to convert the available thermal energy of the radioisotope power source into a more useful form. The most practical energy forms to drive a cooling system are either electrical or mechanical. At first order, a mechanical power source derived from a Stirling cycle is considered the most attractive option, since it eliminates the inherited inefficiencies that come with producing electricity from a mechanical system. Mechanical power for this cycle would need to come from the Stirling Radioisotope Generator (SRG) Additional cooling systems may use either Stirling, Malone (a variation of the Stirling cycle using a liquid instead of a gas as the working fluid) or Pulse–Tube cycles. However, none of these techniques has been demonstrated for the heat lifts required in a Venus environment.

High–T Electronics

Most commercially available electronic devices have a rated operating temperature limit of 125°C, far below the requirement for the Venus environment (480°C). Conventional silicon (Si) devices cannot be used above 200°C, due to increase in leakage current and latch–up at reverse bias junctions. For functionality, up to 300°C, these problems may be managed by the use of Si–On–Insulator (SOI) technology, where the integrated circuits are dielectrically isolated from the base substrate. Beyond this temperature, however, SOI becomes unusable, due to leakage. Therefore, at temperatures above 300°C, alternatives, such as wide bandgap semiconductors, are needed. The most highly developed of these are SiC and GaN. Another alternative set of non solid–state devices capable of operating at 500°C are thermionic vacuum devices [11] [12]. In addition to the aforementioned active devices, the development of passive components has had mixed success. Currently, thick film ruthenium oxide resistors are capable of operating for long periods of time at 500°C; however, general–purpose ceramic capacitors, the best candidate technology for high temperature operation, often tend to exhibit wide variations in capacitance with increases in temperature, particularly as the dielectric constant is increased. Finally, the packaging of high temperature devices requires the careful selection and evaluation of substrate, die attach, and interconnect materials, that are capable of withstanding high temperatures, without decomposing, forming excessive brittle intermetallics, Kirkendall voiding, or cracking, due to mismatched coefficients of thermal expansion.

For Venus surface missions and Jupiter deep probes, thermally controlled pressure vessels would be used to protect much of the remaining electronics and instruments from the high temperatures and pressures of the external environment. Maintaining all of the electronics within a thermally insulated, near Earth temperatures ambient requires significant energy, and under several circumstances limits the mission's science return. Certain subsystems for Venus surface missions, such as sensor and actuator systems, will be required to operate within the ambient surface environment (480°C), if they are to obtain the desired extraction and measurement of soil sample. Placing high temperature electronics in the immediate vicinity of these sensors will enable signal conditioning, signal amplification and increase the sensor signal to noise ratio. In addition, sample acquisition systems, such as drills, will require high temperature position sensors and drive electronics.

Since thermal control is mainly achieved through insulation (Venus In–Situ Explorer or Jupiter Probes) or a combination of insulation and active cooling (Venus Mibile Explorer), having subsystems that generate a significant amount of heat within the vessel is counter productive and greatly increases the amount of power required to maintain the desired internal environment. Therefore, the development of 500°C electronics would allow the removal of high heat dissipating subsystems, such as signal transmitters for telecom, power converters, and actuator drive electronics, from the pressure vessel. This would greatly improve the efficiency of the cooling system and increase the overall lifetime, reliability, and science capability of the mission.

Small scale of integration available with 500°C electronics will limit their use to applications such as those listed above. At the same time, other critical and essential functions of spacecraft, such as a solid state data recorder, digitizer, and avionic computer, will require technologies capable of large scale integration. Nevertheless, lifetimes of the electronic components within the environmentally protective pressure vessel and efficiency of the cooling used to maintain this environment could be significantly improved by increasing the operating temperature of the electronics within the vessel. Increasing the operating temperature of the electronics within the pressure vessel impacts the system in two ways: (a) for systems with active cooling, increasing the operating temperature of the electronics from 125°C to 300°C reduces the differential temperature between the external environment and that which the cooling system must maintain. This results in an increased efficiency of the system and reducing the amount of power required for such cooling; (b) for systems with passive cooling, increasing the operating temperature of the electronics increases survival time. It will take longer for the system to reach a temperature at which the electronics will no longer operate.

In addition, electronics capable of operating at 300°C could be used without additional cooling for Venus balloons at altitudes of 25 km (300°C) or higher. Fortunately, at 300°C (intermediate high temperature), it becomes feasible to exploit the use of Very Large Scale Integrated (VLSI) electronics based on SOI technology.

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°C) 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°C. 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°C.

Critical to the implementation of any high temperature electronics system will be the electronic 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.

Careful design and improvement of the device packaging (vacuum enclosure) and materials are required in order to allow operation within the 500°C ambient environment. 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.

Power Storage and Generation

Power systems, either in the form of 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. This technology is not considered for the extreme environments of Venus, and therefore, not discussed further. Instead, we discuss relevant technologies for short and long lived in–situ Venus missions, namely batteries and radioisotope power system.

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, 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 [13].

Radioisotope Power System for Long Lived In Situ Venus Missions

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. [14]

PRSs 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 the 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. [14] RPS technology is considered enabling for the proposed long lived in–situ roadmap missions. [3]

Mobility Technologies

Proposed Venus missions considered 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.
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 fall under the large (Flagship) 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, as discussed in the subsection below.
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.

Balloon & Parachute Materials

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. 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 steel or another suitable alloy [15]. 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 investment to further develop it.

Sample Acquisition & Mechanism

The acquisition of un–weathered samples from at least 10–20 cm below the surface layer of Venus is required for the VISE and VME missions. Consequently, high temperature motors and actuators, gear boxes, position sensors, cabling, and mechanical devices related to drilling, sample acquisition and transfer systems are key components of in–situ Venus missions. In addition, motors and actuators are required for a variety of function during space system operations, such as opening and closing valves, deployment of landing gear, operation of robotic arms, antenna gimbals and many components. Furthermore, actuators are used on lander pedal motors, drive/steering motors, manipulator joint motors, latching and deployment motors, and robotic arm motors. For the VME mission, motors and actuators could be also relevant for the mobility system, with an operational lifetime measured in hundreds of hours. Atmospheric sampling is a requirement for Jupiter deep probes as well, where some of these technologies could be employed.

Operating motors and actuators at 480°C on the surface of Venus is an extreme challenge. Thermal cooling can improve the environment for drive electronics and batteries, however, actuators, bearings, cabling/insulation, solders, and control sensors may have to be located external to any environmentally controlled space, and have to operate in Venus environments. In addition to high temperature and pressure, chemical corrosion can significantly limit the useful life and performance of motors and actuators. Material compatibility, chemical reactions, alloying, annealing, diffusion can effect the chemical and physical nature of components that are being used. Also, thermal expansion mismatch can be catastrophic to a system that requires precision fits.

The intrinsic problem with high temperatures in standard actuators based on ferromagnetic or ferroelectric materials is the transition – or

Curie – temperature, where the materials switch from ferro to para and lose their actuation capability. Magnetic actuators, such as brush, brushless, and stepper motors, all require a magnetic material. Today's commercial units operate at a maximum temperature of approximately 200°C. In these actuators the primary breakdown mechanism is shorting in the windings insulation, rather than operation above or near the Curie temperature. While some motors designed to operate up to 500°C, their lifetimes are measure only in a few hours. Currently no off–the–shelf motors, or known R&D prototype motors, exist that are capable of operating under Venus surface conditions for any appreciable or reliable amount of time. Nonetheless, Honeybee Robotics has developed and demonstrated a first–generation prototype motor operating under these conditions, and NASA developed a small switch–reluctance type motor, which operates without permanent magnets and tested up to 460°C. The motor continued to function as it was brought to this temperature several times over two hours during which time it was started and stopped repeatedly. An optimized version of this motor could be used to power drills, robotic arms, and other devices that may be landed on the surface of Venus.

Telecommunication issues

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

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 one 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.

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.

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.
These 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 very important.

CONCLUSIONS

In–situ missions to Venus and deep entry probes to Jupiter are anticipated to greatly enhance our understanding and overall knowledge about the Solar System. Proposed missions must address four key interrelated areas: they have to be scientifically interesting; programmatically affordable; and enabled by appropriate mission architectures; and technologies to achieve mission success.
These missions will encounter particular challenges, because they require to operate in extremely harsh environments (over 480°C and 90 bars). In addition, for Venus missions, prior to reaching the surface a lander would face the hurdle of passing through extremely corrosive sulfuric acid clouds at higher altitudes.
Systems architectures will play a key role in establishing which technologies will enable systems exposed to the environment, and which technologies will require consistent protection.
In general, in–situ missions to Venus and Jupiter would benefit from a number of technologies for high temperatures, including passive or active thermal cooling, pressure vessels, high–temperature electronics, energy storage, and high–temperature mechanisms.
Deep probes and landers with current technologies are limited to a few hours of operation, due to the environment. For short–duration in–situ and probe missions passive thermal control approaches may be adequate, but long–lived Venus missions near the surface would require active cooling to "refrigerate" the thermally controlled avionics and instruments. (Active cooling would be coupled with a specially designed Stirling Radioisotope Generator.) In addition, certain functions would remain impractical for implementation at high temperatures and pressure; this group includes items such as most scientific sensors and microprocessors. Improvements in pressure vessel materials could reduce mass, which then could be utilized for additional payload or other mission related areas. These will need to remain in a protected environment. High–temperature sample acquisition systems will clearly require environmental tolerance and appropriate systems engineering, since they openly interface with the environment.
Materials research will continue to play an important role in developing technologies for aerial mobility, and parachute descent. For example, a Venus air mobility platform, possibly employing metallic bellows, could allow for all axis control, long traversing and surface access at multiple desired locations. This would provide an advantage over static landers or rover based architectures.
These technologies would be important to enable missions for intensive in–situ geological and geophysical investigations of Venus, and to address key scientific questions about the composition and dynamics of Jupiter. Current states of practice technologies do not support long lived in–situ Venus missions, and heritage technologies might not be available for the proposed JDEP mission. Therefore, enabling these missions could require substantial technology investment.
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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