Venus Interior Probe Using In-situ Power and Propulsion (VIP-INSPR)

NIAC Phase-I Final Report, January 2016

1.0 Background

Venus, despite being our closest neighboring planet, is under-explored due to its hostile and extreme environment, with a 92 bar pressure and 467 °C temperature at the surface. The temperature decreases at higher altitudes, almost at the rate of 7.9 $^oC/km$, reaching the Earth surface conditions at 65 km (Fig. 1). Due to the less extreme conditions, balloon missions could survive as long as 46 h at an altitude of 54 km.[1] However, because of the opacity of the Venus atmosphere filled with clouds of sulfuric acid and CO_2, orbiter or balloon missions are not as revealing and informative in characterizing the surface, as similar missions on Moon and Mars. To understand the evolutionary paths of Venus in relation to Earth, it is imperative to gather basic information on the crust, mantle, core, atmosphere/exosphere and bulk composition of Venus, through *in-situ* investigations using landers, probes and variable-altitude areal platforms.

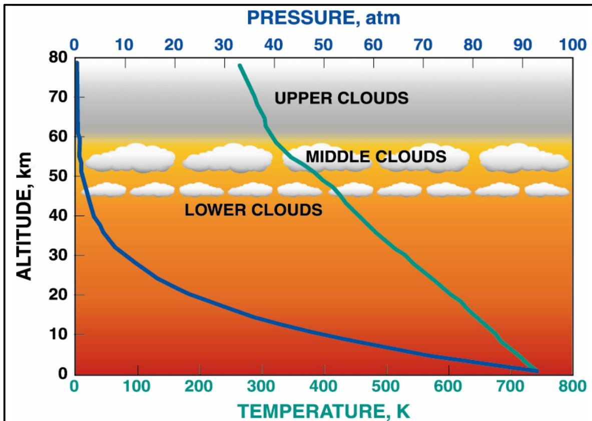

Fig. 1 Venus temperature/pressure vs. altitude.

2.0 Power Technologies

All missions require power, which is needed to operate the command and control system, make observations with the scientific instruments, and power the radio communications system that sends the data back to the scientists on Earth. Most conventional power system technologies are not capable of operation at Venus temperatures, although it is plausible for very-short duration missions to accept a power system that they will only be able to operate for a short period, until it reach equilibrium temperature with the environment (possibly with the benefit of thermal mass or phase-change materials designed to slow down rate of heat rise). For an extended mission, however, it is necessary to use a power system capable of operating at higher temperature.

The exo-atmospheric solar flux at Venus is ~2600 W/m^2, roughly twice that of Earth's solar flux. At lower latitudes, however, it is considerably reduced to make solar arrays insufficient for inner-atmospheric probes. The thick cloud layers result in relatively low light intensity below the clouds. The performance at the surface is relatively low, with an estimated area of about 1.2 square meters required to produce one watt of power.[2] At an altitude of 10 km above the surface, the required area for a watt of power reduces to about 0.4 square meters. An alternative for long-duration missions is to use an isotope power supply, based on Advanced Sterling Radioisotope Generator, proposed for Venus surface missions[3-5] or a Radioisotope Thermoelectric Generator

RTG . The use of a nuclear power source, is however, challenging a high temperature heat sink at low altitudes (10-15 km) and a high CO_2 pressure.

Primary batteries were the only power technology option available for the low-altitude probes, Lander and probes on Venus. The previous Venus landers, the Russian Venera series and Vega 2 Landers,[6] used lithium primary batteries and survived for less than 2 hours, despite the use of *considerable insulation, phase-change materials and similar heat sinks to isolate the payload and avionics from high surface temperatures*. Venus *in-situ* atmospheric and imaging exploration missions have therefore been of short duration (<2 h) due to the limited lifetime of the primary batteries at temperatures at low altitudes and at the surface of Venus. While some rechargeable battery technologies are capable of operating over long periods at the temperatures prevalent at low altitudes (10-15 km), there is no power source for recharging these the batteries. A new power generation and energy storage approach is required *to enable an extended exploration of the Venus atmosphere and near-surface environment, which is being developed here.*

2.1 New Power Technology for Venus Probe

Under the NASA-NIAC (Phase-I) program, we have been developing a new mission concept for long-duration robotic exploration of the Venus Interior. Specifically, we have been developing a novel architecture for a Venus Interior Probe that utilizes *in-situ* resources for power generation and propulsion (VIP-INSPR). Both hydrogen and oxygen are generated at high altitudes (55-65km) from *in-situ* resources, i.e., solar flux and sulfuric acid, and utilized to generate long-term power at low altitudes using high-temperature fuel cells. Additionally, a portion of hydrogen generated via electrolysis will be used control the buoyancy of the probe, as shown in Fig. 2. The architecture involves: i) an electrolysis cell to generate H_2 (and O_2) from sulfuric acid using solar arrays in the upper atmosphere where H_2 is adsorbed in a metal hydride (MH), ii) an altitude-control system using an electric pump or an electric winch to compress the balloon to guide the probe to lower altitudes (10 km), iii) a high temperature solid oxide fuel cell generating power from *in situ* generated H_2 desorbed from the MH and O_2 and iv) a H_2 buoyancy-based altitude control system, for subsequent navigation of the probe across the Venusian atmospheric layer. This report summarizes the progress made in Phase-I of this innovative concept development.

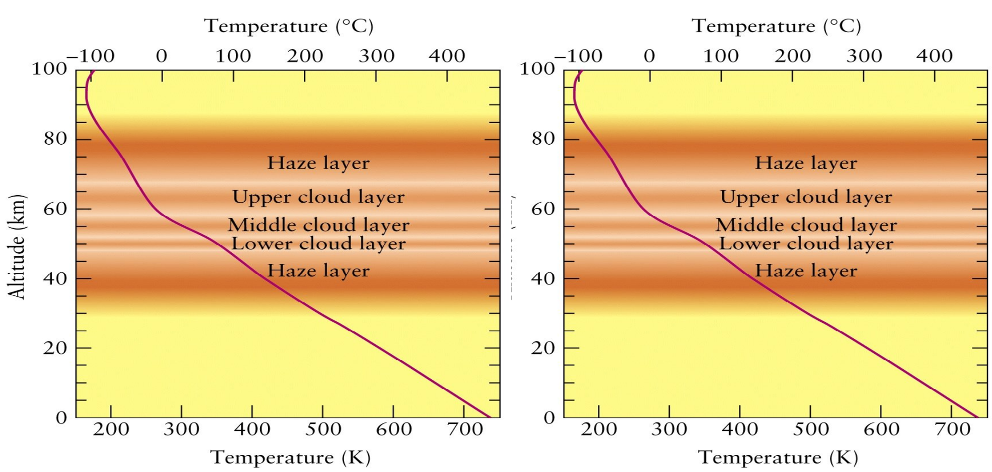

Fig. 2: Schematic of VIP-INSPR probe

3.0 Benefits and Science Value

The Venus Interior Probe proposed here will overcome the problem of limited mission lifetime attributed to the poor survivability of the power technologies in the Venus environments. This architecture, if successful will pave the way for new Venus atmospheric exploration missions. Specific benefits associated with the proposed architecture are: i) *In-situ* resource utilization to enable sustained exploration by generating H_2 and O_2, ii) Development of a unique low altitude power generation system for Venus missions, where both solar cells and RTGs are not efficient. iii) Development of new 'Venus Balloons' using *in-situ* generated hydrogen. Thus far Venus balloons have used helium launched from Earth, iv) Sustained atmospheric exploration of Venus, at much lower costs than nuclear alternatives, v) Extension of the architectural concept to other planetary bodies for power and navigation and vi) Development of intermediate temperature fuel cell technology developed here has significant terrestrial value, as evident from recent DOE interest.

The Venus interior atmosphere cannot be imaged accurately with orbiters due to the opaque atmosphere, nor can it be explored with probes or landers due to the extreme atmospheric conditions of high temperature and pressure. Prior Venus probes and landers barely survived for a few hours, though some balloons have survived in the upper atmosphere for longer. The limitations result from a lack of suitable power generation technologies and poor survivability of primary batteries, which have been the main option. The proposed VIP-INSPR has the potential to support long-term exploration of Venus, which will enable Venus probe missions for understanding its atmosphere and surface.

4.0 Technical Progress

Some of the challenges addressed in Phase I for the proposed Venus probe are: (1) What are the process limitations of extracting sulfuric acid in the upper atmosphere? (2) What are the suitable types of solar arrays and components required for the electrolysis cell based on thermal stabilities? (3) What type of H_2-O_2 fuel cell is appropriate at intermediate temperatures? (4) What design of a hydrogen-based inflatable system is appropriate to navigate the probe between high and low altitudes and (5) What are the anticipated lifetimes from the individual components and for the probe in the upper/lower Venus environments.

We have devised a plausible scheme for the operations of the probe, identified key subsystems, defined their requirement, selected appropriate technologies for these subsystems and developed strategies for adapting them to the Venus environment. The major subsystems of the probe include the following, in addition to the payload and avionics:

i) In-situ Fuel Generation from Venus upper atmosphere
ii) High-temperature tolerant Solar array
iii) Fuel (H_2) and oxygen storage
iv) High temperature reversible fuel cell for power generation at low altitudes (and electrolysis at high altitudes) and
v) Hydrogen balloon to navigate the probe across the Venus atmospheric layers

Fig. 3 shows the architectural design of the Venus probe. Salient aspects of the probe are:

i) Hydrogen required for the balloon may be carried from Earth and the hydrogen fill tanks may be discarded after the hydrogen is transferred into the balloon.
ii) Hydrogen released from the balloon during descent is stored in a tank and transferred back into the balloon during ascent.
iii) We can start with an excess of hydrogen, which will allow us to go to lower altitudes directly, without having to spend much time for harvesting
iv) H_2 in the MH is fed into the SOFC (and also O_2) during power generation. Water vapor produced is collected, condensed and electrolyzed at high altitudes for H_2 regeneration.
v) Additional fuel and oxygen may be generated at the high altitudes from the sulfuric acid/water harvested from the Venus clouds. These may compensate for the leakage of either H_2, O_2 or water.

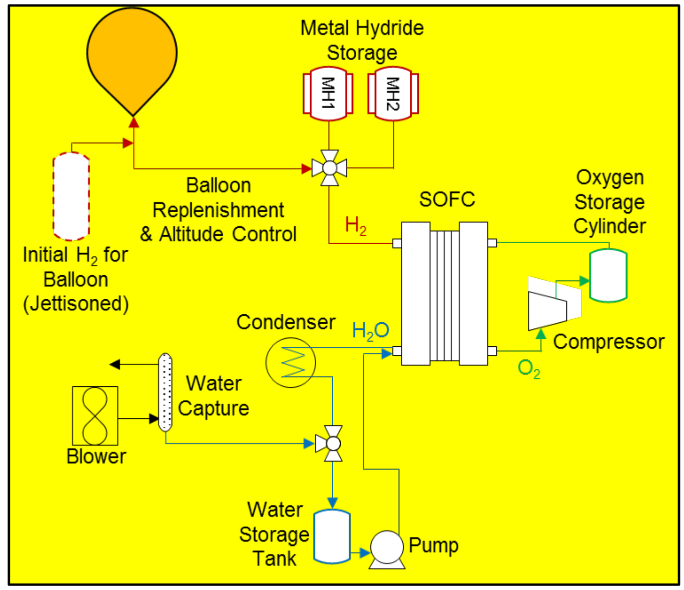

Fig. 3. Block diagram of VIP-INSPR

Details on the progress made on each of these subsystems are provided below

4.1 Operational Scheme:

Initial hydrogen to fill the balloon will be carried in a high pressure cylinder which can be used to quickly fill the balloon and then jettisoned to reduce the payload mass. Balloon altitude control would be achieved by storing hydrogen from the balloon in a metal hydride. This metal hydride storage material could be used both for altitude control and to provide hydrogen to the fuel cell during time spent beneath the clouds. Solid oxide fuel cells (SOFC) and electrolysis cells typically operate above 800 °C, far above the surface temperature of Venus. These electrochemical cells are capable of efficiently (>60%) converting H_2 and O_2 to electricity and can be used in reverse to generate H_2 and O_2 from water if electricity is supplied. SOFCs must be kept warm to function properly, however they are quite robust with commercial installations up to the hundreds of kW becoming available.[7]

By using an arrangement as depicted in Fig. 3, a reversible SOFC (RSOFC) could be used to power a spacecraft on Venus below the cloud layer where there is not enough sunlight for solar panels. Such a craft would arrive at Venus with a metal hydride material and an oxygen cylinder which it could use to power itself during dark periods of operation. During exposure to the sun, the RSOFC can operate in electrolysis mode, whereby it converts the water created (and captured) during fuel cell operation. During electrolysis, the cell would replenish the metal hydride storage material and the oxygen cylinder for more operations in the dark. This would allow the spacecraft to cycle between light and dark operations indefinitely. The fuel cell can be based on the peak power requirement and the storage would be sized based on the duration. Additional fuel and oxygen could potentially be produced from the moisture present in the atmosphere of Venus. Water retrieved from the atmosphere can be electrolyzed by the RSOFC to produce H_2 and O_2. This would allow the system to compensate for leaks in the balloon or in gas and liquid losses from the power system.

4.2 In-situ Fuel Generation

4.2.1 Harvesting Sulfuric Acid

Clouds on Venus are primarily composed of sulfuric acid (H_2SO_4) with droplets ranging in size from 0.4 µm up to 8 µm with concentrations ranging from 10 droplets per mL to 1500 droplets per mL.[8] The clouds are between 47 and 70 km where the temperature ranges from -48 °C to 94 °C. These droplets could be captured using a high surface area mesh or film since H_2SO_4 is a liquid under these conditions. A pump or blower would be required to move the cloud and the atmosphere around it over the capture device. In order to provide 2 kWh of energy for the probe, for example, the amount of hydrogen required is 84.7 g (or 42.3 mol) assuming a fuel cell efficiency of 60%. The total volume of atmosphere required to collect 42.3 moles of H_2SO_4, assuming cloud droplets are pure H_2SO_4, was estimated based on the data presented in Knollenberg's 1980 paper[8] for upper, middle, and lower cloud bands is presented in Table 1.

Based on the values in Table-1, the amount of time required to pump that volume vs. the rate of the pump (or blower) is estimated as shown in Fig. 3. Due to the extremely low concentration of H_2SO_4 droplets in the clouds, either a very large pump or a very long dwell time would be required to process the required volume of atmosphere. Dwell times longer than ~5 days (120 hr) are probably impractical since many day/night cycles would limit the amount of time available for actual electrolysis. This practical requirement would limit operation to a large blower in the range of >10,000 liters per minute and the spacecraft would have to stay in the lower clouds where solar flux may be reduced. Assuming enough H_2SO_4 can be collected, it could be decomposed to H_2O and SO_3 (Eqn. 1). This process takes place above ~100 °C and does not require a catalyst.[9] Sulfur trioxide is unstable at high temperature and decomposes to SO_2 and O_2 (Eqn. 2). The nickel hydrogen electrode in a solid oxide electrolysis cell (SOEC) is susceptible to sulfur poisoning, even at operating temperatures of ~800 °C [9] and would require some kind of sulfur sequestration. Care would also need to be taken to maintain separation between H_2 formed on the cathode of the SOEC and O_2 formed as a decomposition product of SO_3.

Equation1: $$H_2SO_4 \xrightarrow[100\ °C]{} H_2O + SO_3$$

Equation 2: $$2\ SO_3 \xrightarrow[400\ °C]{} 2\ SO_2 + O_2$$

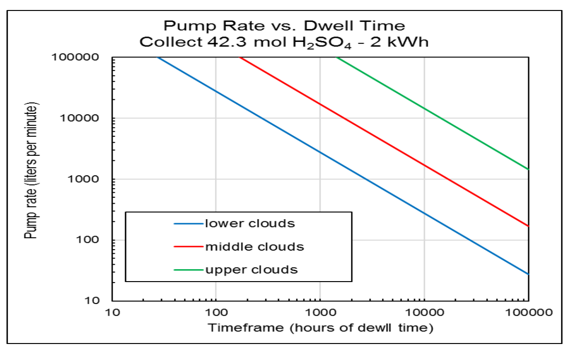

Fig. 4: Pump rate vs. dwell time for H_2SO_4 capture at various regions of the Venus atmosphere

Table 1: Concentration of H_2SO_4 in clouds and volume containing 42.3 mol H_2SO_4

	Lower clouds	middle clouds	upper clouds
H_2SO_4 Concentration (mol/L):	4.9×10^{-9}	4.1×10^{-8}	2.6×10^{-7}
Cloud volume (L):	1.7×10^{8}	1.0×10^{9}	8.7×10^{9}

Table 2: Concentration, volume containing 42.3 mol H_2O and change in entropy to purify water

	lower estimate	middle estimate	upper estimate
H_2O Concentration (ppm):	5	30	100
Volume required (L):	1.9×10^{6}	3.2×10^{5}	9.5×10^{4}
Entropy change (Wh):	357.7	305.2	269.9

4.2.2 Harvesting water

Although the clouds of Venus are primarily composed of H_2SO_4, there is a considerable amount of water vapor in the atmosphere below 65 km.[10] Estimates vary between 4 and 100 ppm depending on the measurement technique and there appear to be significant concentration gradients with differences of an order of magnitude or more.[11] Since there appears to be such a significant variation in the concentration of water in the atmosphere, low, mid and upper estimates were made to calculate the total volume needed for 42.3 mol H_2O in Table 2. Even at the lowest estimate of 5 ppm H_2O, the total volume required for 42.3 mol H_2O is significantly lower than the highest estimate for the amount of H_2SO_4 in the clouds (Table 1). Given these promising results compared to H_2SO_4 capture, a similar comparison between pump rate and dwell time was performed (Figure 4). Collection time is now significantly reduced to much more reasonable values, even at 5 ppm H_2O. A rate of 100 liters per minute would pump enough atmosphere to capture 42.3 mol H_2O in 53 hours if the H_2O concentration was 30 ppm. An efficient method to remove the trace water from the atmosphere would still be required, however, since the water exists as a gas and not droplets under these conditions (unlike sulfuric acid).

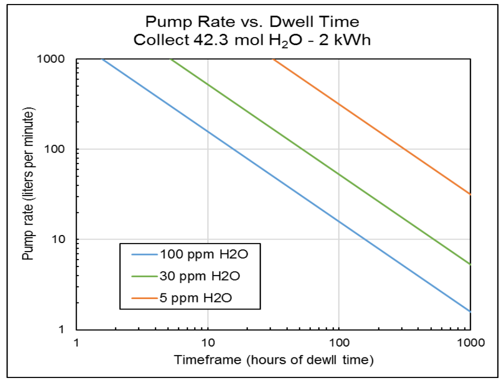

Fig. 5: Pump rate vs. dwell time for H_2O capture assuming various concentrations of H_2O.

Using water as the reactant to produce H_2 and O_2 is much simpler than using H_2SO_4 because there are no sulfur compounds present to poison the RSOFC and no decomposition reaction to facilitate. Retrieving the water vapor from the atmosphere will likely present significant challenges due to its low abundance. For example, the dew point of water at 5 ppm concentration is -65°C, so removal via heat pump would require significant investment in a cooling system. Alternatively, water adsorption materials, such as zeolites, could potentially be used. Table 2 lists the change in entropy (in Wh) required to increase the concentration of water from 5, 30 or 100 ppm to 1 atmosphere at 300 K. This additional energy input is significant compared to the 3.3 kWh that is estimated to electrolyze enough water to store 2 kWh of energy, up to 358 Wh, if the water concentration is only 5 ppm. This calculation does not take into account any inefficiencies present in the purification system.

4.3 High-temperature Solar Array

Conventional triple junction solar cells, $GaInP_2/GaAs/Ge$ with an efficiency of ~30% will be used. These solar cells need to have adequate survivability at the high temperatures (300-

350°C) prevalent at low altitudes (10-15 km) in non-operating mode. NASA-GRC has been developing solar arrays for high temperature near-sun operation with the goals of improved efficiency at high temperature and also improved lifetime at high temperature. For the VIP-INSPR, howver, it is the lifetime that is crucial, since power at low altitudes (high temepartures) is provided by the fuel cell.[12] Solar cells made from wide bandgap compound semiconductorsare an obvious choice for such an application, since the higher voltage of wide bandgap solar cells results in less degradation.[13,14] For example, silicon solar cells (1.1 eV) lose about 0.45% of their power per degree C increase in operating temperature. GaAs cells (1.4 eV) lose about 0.21% per degree C.[15]

4.4 Hydrogen and Oxygen Storage:

Metal hydrides are the most relevant of hydrogen storage media over the altitude and temperature conditions of interest for this effort. The thermodynamics of H_2 adsorption / desorption, specifically the enthalpy values govern their temperature and pressure range of applicability.[16] Fig. 3 shows the equilibrium pressure as a function of temperature over the range of relevance for the Venus Interior Probe and compares the equilibrium pressure of several calculated hydride enthalpies and superimposes these onto a plot of the atmospheric pressure of Venus.[17]

Plotted as a function of temperature that spans an altitude range above the planet surface of 0 to ~65 km from left to right, a range of 67 to 76 kJ/mole H_2[18] that *would correspond to Mg_2NiH_4 and MgH_2 hydride enthalpies respectively, would appear to be suitable for providing the required balloon pressure near the planet surface*.[20] However, the equilibrium hydride pressures for these hydrides drop substantially faster than the atmospheric pressure at higher altitudes suggesting that a *multi-stage hydride bed technology may be required in order to span the desired range of interest*.[21] Tuning balloon buoyancy may require the design of several hydride beds. Fortunately, commercial H_2 compressor systems developed for ambient temperatures will serve as models for this effort.

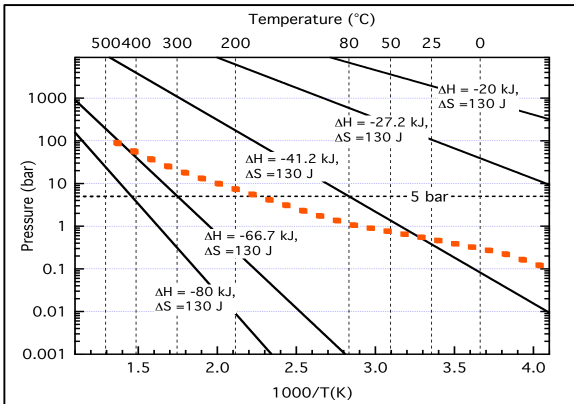

Fig. 6. Calculated van't Hoff for several enthalpy values for different metal hydride materials assuming a constant entropy value. The dotted trace in orange is the atmospheric pressure on Venus as a function of temperature and spans the range of 0 km at the surface at the left to ~65 km above the status on the right.

Based on the hydrogen absorption characteristics of the selected metal hydride materials (magnesium, magnesium nickel and magnesium iron alloys) the hydrogen storage subsystem has been sized for a 2 kWh power system. This would require 42.4 moles of H_2. Each kg of H_2 requires 12.1 kg (and 8.5 liters) of Mg on theoretical basis with 6% efficiency, or 17.3 kg (and 6.3 liters) of Mg_2Fe. The amounts of Mg and Mg_2Fe for the 2 kWh system are 1.34 kg (1.67 liters) and 1.9 kg (2.37 liters) of Mg or Mg_2Fe, respectively. Two different hydrogen storage materials will be utilized to cover the range of pressures at different altitudes. This hydrogen storage subsystem will interface with the electrolyzer/fuel cell as well as with the balloon for its ascent and descent operation. Finally, a suitable method for the storage of oxygen will be identified, possibly in a tank, using electrochemical compression.

4.5 SOFC Fuel Cell for Low Altitude Power Generation

The extreme temperature of Venus' lower atmosphere makes SOFCs a logical choice for a power system since they are designed to be stable to temperatures of up to 1000 °C and routinely operate above 700 °C, well above even the surface temperature of Venus (462 °C). SOFCs are constructed from a solid oxide conducting membrane, such as yttria stabilized zirconia (YSZ) which exhibits oxide ion conductivity at elevated temperatures (>700 °C). A perovskite such as lanthanum strontium manganese oxide (LSM) is often used for the oxygen electrode while nickel is typically used for the hydrogen electrode. These materials can be used in both fuel cell and electrolysis mode, creating a unitized reversible fuel cell design (Fig. 7).[8] SOFCs using typical components have been demonstrated to develop close to 1 W/cm^2 of power in fuel cell mode,[8] however this may include operating on large excesses of reactants or unreasonable flow conditions for our intended use, so a conservative estimate of 300 mW/cm^2 was used to perform rough scaling calculations. If we then assume that the spacecraft will require no more than 100 W during descent, we estimate the required size of the SOFC as being ~350 cm^2. An SOFC this size could either be made up of a single tubular cell or a stack of planar cells depending on packaging and efficiency considerations. Single cells tend to be more durable than stacks due to the reduced number of interconnects (a major source of failure and performance degradation in SOFCs), therefore a single cell may be preferable for a long term mission. Sulfur poisoning is a large concern for the nickel electrode in an SOFC,[8] therefore any sulfur present in the system would need to be sequestered effectively or risk irreversibly poisoning the cell. This is not a concern if the mission was to use pure H_2 and O_2 taken from earth, however it could be a significant issue if the atmosphere is harvested to produce H_2 from H_2SO_4 in particular. Harvesting water from the atmosphere would likely pose less of a risk, but there may be trace H_2SO_4 in the atmosphere during water collection.

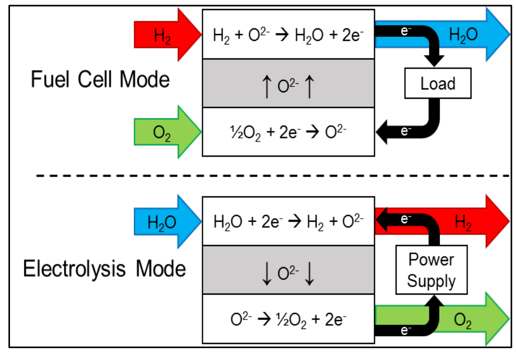

Fig. 7 Operation of reversible SOFC in fuel cell and electrolysis modes

Commercial SOFCs are available (Ceramatec, for example) and would be the best starting point to prove the concept of using an SOFC under Venus-like conditions. Although these devices have been commercialized, they are typically used under different flow and gas composition conditions than would be required for operation on a Venus balloon. A significant challenge would be to optimize the design of the supporting equipment necessary for SOFC in regenerative operation and verify the performance under mission relevant conditions.

Oxygen compression is also of significant concern for the proposed mission because, unlike H_2 storage where metal hydrides can be used, O_2 storage must be done at high pressure. Mechanical oxygen compression is of course and option, however it is also possible to use the reversible SOFC as an electrochemical oxygen compressor.[22] Oxygen compression could be accomplished either by the same RSOFC used for power generation, or it could be done using a separate (smaller) SOEC stack that would function independently during oxygen generation. This stack would also need to operate at high temperature, so it would likely be thermally coupled to the main RSOFC. Electrochemical compression offers the potential for improved compression efficiency as well as fewer moving parts.

4.6 Design of Balloons for Navigation of Probe Across High and Low Altitudes

Figure 8 provides a schematic overview of atmospheric conditions as a function of altitude. Large altitude excursions, between 65 km and near surface (10 km), require a single balloon material that can withstand the extreme conditions. The challenge of ballooning at higher altitudes (> ~65km) is that the low atmospheric density requires prohibitively large balloon volumes to buoy the payload and the additional mass of the balloon material. As buoyancy scales with volume×density, the balloon must offer exceptional buoyancy control capability to accommodate the 10 to 65 km altitude range. Balloon size is furthermore limited due to launch vehicle payload and volume limits.

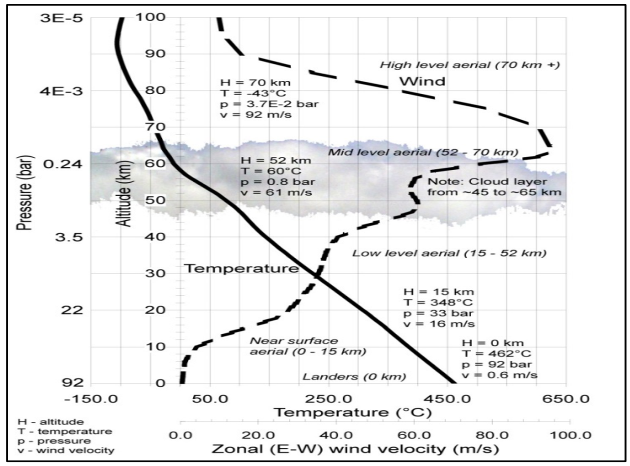

Fig. 8 Pressure, temperature and wind conditions at Venus.

4.6.1 Current Baseline Venus Balloon

Superpressure balloons (SPBs) are generally required for operation of a sustained aerial lighter-than-air platform. SPBs offer float altitude stability assuming no unforeseen need to vent helium and provided no descent below the zero-super-pressure altitude. While zero pressure capability is the most common scientific balloon used on Earth, active control requirements are typically achieved through gas venting and ballast drops which eliminates this approach for longer term *in situ* observation missions. The Soviet VEGA mission employed two super-pressure balloons (11.6 ft diameter) in 1985; these are the only balloons to have ever flown on another planet. The VEGA success proves that Venus balloon aerial deployment and inflation is feasible.

Super-pressure balloons capable of lifetimes in excess of 30 days on Venus at a constant altitude of 55 km are at a TRL of 5 to 6.[23] Small balloons in the 3.5 m class with 8 kg payload flew in the 1980s and ballons in the 5.5 m class with a 45 kg payload have been built and tested in relevant environments. Most recently, (2013) NASA-JPL's baseline studies of super-pressure balloon performance[24] include: i) 7 meter diameter super-pressure balloon, ii) 55 km float altitude, iii) Helium buoyancy gas and iv) Super-pressure (inside-to-outside pressure difference) of 5,000 Pa. Efforts are currently underway[25] to: i) Increase the payload capability to 100kg by increasing the balloon diameter to 7 m and ii) Extend flight lifetime by improving the leakage performance of the balloon envelope material. The 7-meter class NASA-JPL VALOR Venus balloon (2005) was designed with a 5× safety factor over the maximum stress that would be experienced under the most adverse combination of atmospheric environment during updrafts on the day side of Venus.[26] The on-going NASA-JPL efforts on the Venus balloon technology provide guidance and a comparative basis for the current study. A significant advantage on Venus is that the high density of CO_2 allows for a very wide range of lifting gasses to be considered for balloon flight beyond the generally presupposed H_2 or He. Helium was used in the previous balloons, but hydrogen is used here as the lifting gas.

4.6.2 Modeling of the VIP-INSPR Ballon

The balloon system modeled will cycle between 10 to 65 km and carries a 150 kg suspended payload mass. The initial VIP-INSPR balloon system concept employs a single, near-spherical zero-pressure balloon (ZPB) to keep balloon design simple and lightweight. This means that the envelope does not need to sustain high circumferential, internal pressure-induced loads. A ZPB will be inherently lighter than a SPB system however, it needs to be robust to deployment loads. Post-entry deployment of the VIP-INSPR balloon will use internal load lines to reduce loads of the suspended payload on the envelope. Initial inflation with hydrogen from fill tanks is assumed with *in-situ* generated hydrogen used to provide leakage make-up gas.

The selection of hydrogen avoids mixing lifting gases, simplifying analysis and control and also ensures longetvity based on the hydrogen egenrated from the Venus *in-situ* resources. Altitude cycling and control is by means of buoyant gas pumping, pressurization and temporary storage. Taking as little as 200 g of hydrogen gas from the envelope and storing it at much higher density than ambient (at the lower altitude range), results in negative balloon buoyancy that causes the balloon to descend to 10 km in just over 7 hours. Withdrawing smaller amounts from the balloon will result in longer descent times. Re-filling the balloon with stored gas allows the balloon to return to positive buoyancy and ascend. Making slight adjustments near the bottom and top of the altitude range can enable quasi-altitude stability operation. A simple control system to descend, ascend and maintain desired altitudes is suggested here.

4.6.2.1 Altitude Cycling Mode

A vertical altitude cycling and control model was developed to simulate the profiling flight of the balloon system through the Venus atmosphere. The model makes several assumptions on balloon system parameters. First, the balloon is spherical at all altitudes, with constant drag coefficient $C_d = 0.2$ (high Reynolds regime). Payload drag is neglected in the model. 1-mil coated Kapton with areal density 36 g/m^2 + 5% seam allowance = 37.8 g/m^2 is assumed. Balloon hydrogen temperature and pressure are taken to be homogeneous and equal to ambient values at all times. Wind, gusts, and horizontal motion are neglected. A payload (non-balloon) mass of 150 kg is assumed, along with an initial stored hydrogen mass of 200 g (in addition to the initial fill tank mass).

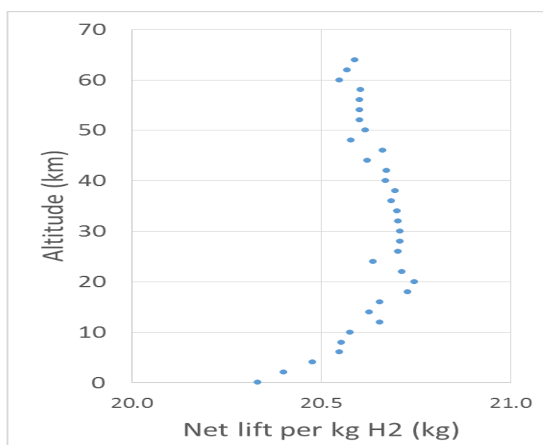

Figure 8: Net lift capacity of each kilogram of hydrogen lifting gas in balloon

The atmosphere data used in the model follows from (Seiff, 1983).[27] Using these atmospheric data, the resultant net lift per kg of hydrogen lifting gas (total buoyancy minus weight of lifting gas) is shown below. These data show a peak in hydrogen buoyancy at about 20 km altitude.

Initial VIP-INSPR Balloon Model Parameters

Based on a state of stable float at 65 km, the model produces a balloon design with a maximum diameter of 11.8 meters and maximum volume of 865 cubic meters. The resulting envelope mass is 16.6 kg. The roughly 8.1 kg of hydrogen lifting gas is supplied from initial fill tanks which are discarded after balloon inflation. The total amount of hydrogen onboard (balloon + storage) remains constant in the assumed closed system. Any leakage losses are replaced through in-situ generated hydrogen.

Table 3. Initial VIP-INSPR Balloon Model Parameters

	VIP-INSPR	Vega aerostats
Type	ZPB	Spherical SPB
Gas	8.1 kg Hydrogen	2.1 kg Helium
Volume	865 m^3	20.6 m^3
Diameter	11.8 m (65 km) 2.1 m (10 km)	3.4 m
Envelope Material	1 mil coated Kapton	Teflon laminate
Envelope Density	37.8 g/m^2	~300 g/m^2
Envelope Mass	16.6 kg	12.5 kg (includes 13 m tether)
Payload Mass	150 kg	6.9 kg
Design Altitude	10 – 65 km	54 km

Results from the preliminary model are presented below (Fig. 9). The circles represent the relative sizes of the balloon at 65 km and at 10 km in relation to a familiar Goodyear airship. This scenario begins with the system at neutral float at 65 km. 300 g of hydrogen gas is then withdrawn from the balloon into storage, starting the 6 hour descent. Near 10 km, 250 g of hydrogen is added back to slow the descent before reaching the target altitude. The system drifts at 10 km for 3 hours, with small adjustments made using PID (Proprtional Integral Derivative) control loop (in the model, this is implemented without any noise, perturbations, or sensor error) to maintain altitude. after 3 hours, hydrogen is added to the balloon to begin an ascent to the clouds at 55 km, and is again withdrawn into storage upon reaching the target altitude. After 6 hours maintaining altitude in the clouds, the system adds hydrogen to the balloon and begins a final ascent leg back to 65 km. The amounts of hydrogen gas transferred into and out of the balloon for ascent and descent depend on the desired rate of ascent/descent. Slower rates of ascent/descent will require smaller amounts of gas transfer. A preliminary parametric study was conducted to show this variation, shown in Fig. 10.

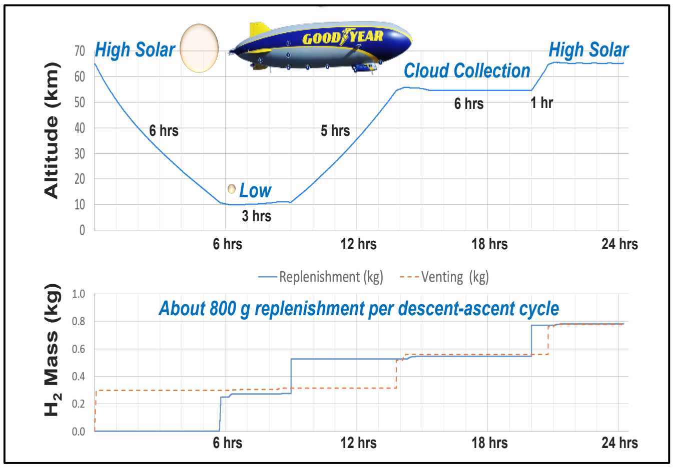

Fig. 9: Lifting gas (hydrogen) changes during ascent and descent of the balloon

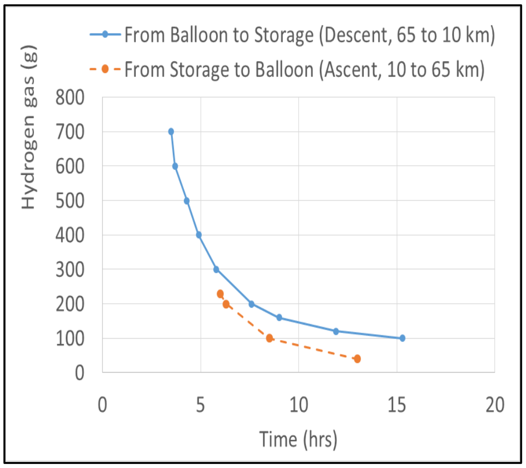

Fig. 10: Required lifting gas transfers for various descent and ascent times

Some of the questions being addressed are: i) What are desired times at various altitudes? Vertical wind shear affects zonal trajectory and speed around planet, ii) How will operations differ between day and night sides? iii) What ConOps is possible with various level of replenishment gas?, and iv) How is hydrogen released from hydride storage? At what pressures and temperatures? Is the chemical hydride a better method vs storing in a tank for the balloon navigation

Balloon System Design Considerations

VIP-INSPR balloon design considerations include harsh environment, packaging, material and seaming approach, envelope fittings, and altitude change and control approach. Any VIP-INSPR balloon design must meet packaging requirements dictated by the storage volume available and deployment scheme. Typical balloon packed volume can be 4-5 times the envelope film volume. As packing factors are reduced, film creasing and the potential for hole formation can increase. This problem can be exacerbated when the film thickness is high. For example, folding endurance (1000 cycles) can be fifty time greater for 1 mil vs. 5 mil thick Kapton® HN film. The balloon envelope must also meet the environmental conditions without damage and leakage. The temperature at 10 km altitude is about 385°C while the temperature at 65 km altitude is about -30°C. It is the high temperature that is the primary concern. Not only does the base material need to withstand the high temperatures, but the seam adhesives must also. Another major environmental consideration is the sulfuric acid in Venus cloud droplets. Unprotected film can degrade causing leakage and failure. The level of sulfuric acid solution could be as low as 85% growing to 98% at lower cloud levels where condensates are evaporated. Sulfuric acid protection near seams is important, but also challenging if significant amounts of base film is exposed. Seam design is a significant design consideration especially if the base material has little to no inherent resistant to sulfuric acid.

Another design consideration is the shape of the balloon and the amount of material at the base and apex fittings. Axial (along seam direction) loads on the envelope near the base fitting will be proportional to the payload weight and inversely proportional to film thickness and run-length. A near spherical balloon will have a run-length that is on the order of the circumference of the base fitting, which can be quite short. As the balloon descends and temperatures increase tensile strength is reduced so the combination of run-length and thickness must be sufficient to support the payload at the highest temperature seen. If tensile strength is significantly reduce, alternate balloon patterns could be employed to increase run-length near the fittings, e.g. cylindrical segments of the required run-length. When the balloon is at its lowest altitude, the gas bubble shrinks in size placing increase loads on the envelope near the balloon apex. These loads can result in designs similar to the balloon near-base design to increase run-length and/or increase envelope thickness. Small spherical segments known as apex caps could be employed in a similar fashion to the balloon caps on NASA's high-altitude scientific balloon to reduce chance of envelope damage at launch where the bubble is smallest.

Finally, if a balloon is required to descend to 10-20 km altitude, an approach to changing net buoyancy and controlling altitude must be considered. Several altitude control schemes have been proposed in the past, and some tested, including the use of various phase change fluids, simple buoyant gas venting and replenishment from on-board storage, pumping buoyant or ambient atmosphere into pressure vessels to increase the average density of the system, and storing hydrogen gas in hydrate-containing pressure vessels at high altitude. One concept, to be initially assumed here, is buoyant gas pumping and storage because it can operate indefinitely without consumables, it seems to require less mass than some other options, and it allows the capability to return the buoyant gas back to the envelope in a rapid manner for altitude change and control.

Envelope Design Options

Key categories for envelope design are film material, sulfuric acid protection scheme, and seam fabrication approach. Current envelope film material options include two polyimide films (i.e. Kapton® HN and Upilex-S) and Polybenzimidazole (PBI). These films are noted for their high-temperature properties, especially for dielectrics. In addition, they all have some inherent resistance to sulfuric acid exposure. Table 4 describes some properties of these films.

Table 4 Candidate Venus Balloon Film Properties

Film Material	Film Type	Density (g/cc)	Melting Point Temperature (°C)	Glass Transition Temperature (°C)	Tensile Strength (MPa)	Tensile Modulus (GPa)	1 mil Folding Endurance (cycles)	Thermal Degradation at 400°C (%)	Time for 50% Tensile Strength at 400°C (hours)	Resistance to Strong Acids
Polyimide	Kapton® HN	1.42	None	360-400	231	2.5	285,000	<3	TBD	Excellent
	Upilex-S	1.47	None	510	520	9.1	>100,000	<1	80	Good
Polybenzimidazole (PBI)	Celazole®	1.30	None	427	160	5.9	TBD	<1	TBD	Fair - Poor

Options for sulfuric acid protection include vacuum deposition (VD) of Gold or SiO_2 directly to the film or VD of another metal or alloy that would allow electroplating gold to the VD metal layer. The latter approach may be important if the VD layer is found to be porous allowing water (and acid) through to the film layer. VD SiO_2 coatings are particularly promising since they are already used to protect solid materials in highly corrosive environments.

Many physical seam options exist, e.g. lap, butt, pinch, however the temperature found at 10 km rules out most adhesives. An alternative is to use the base polymer resin as the adhesive so that the adhesive has the same properties of the base film. In this case fabrication could be a challenge. Sulfuric acid protection of seam edges could be achieved by VD coatings.

4.6.3 Balloon Design Summary

Descent to 10 km and altitude cycling present unique challenges for this Venus balloon design. The model supports the basic feasibility of hydrogen replenishment-based altitude control. Desired ascent and descent rates will determine hydrogen gas transfer requirements. Envelope material challenges are diminished with a zero pressure balloon design owing to reduced film stresses. High-temperature film and sulfuric acid protection options and mass assumptions continue to be investigated. Further work will investigate gas handling components and performance as well as simulate traverse trajectories using global winds.

5.0 Summary of Phase 1 Effort:

To summarize, we have made good progress on all the individual tasks outlined in the Phase-I schedule.

Task1: Level 1 Requirements of the Venus Probe: We have formulated requirements for the Venus probe, which include: Power of 2 kWh, payload of 150 kg, hydrogen as the lifting gas, altitude cycling between 55-65 and 10-15 km from the surface and longevity for the balloon and probe.

Task 2: Select suitable component Technologies: Selected suitable components technologies for the fuel cells (SOFC) in the regeneration mode to function as fuel cell and electrolyzer.

Task 3: Design Electrolyzer cell and select PVs: Estimated the durations for harvesting hydrogen from the in-situ resources. SOA solar arrays with good thermal stability will be utilized.

Task 4: Identify suitable metal hydrides for 25-350°C: Based on the analyses, magnesium based metal hydrides (Mg_2Ni and Mg_2Fe) as well as Fe-Ti seem to be suitable or these environments. A dual hydrogen storage system will be used to cater to the wide range of temperatures and pressures.

Task 5: Design the Intermediate Temp Fuel Cell (350°C): Instead of a low-TRL Intermediate Temperature Fuel Cell (at 350°C), it appears that a solid oxide fuel cell would be a better option due to its high TRL and proven stability at high temperatures.

Task 6: Identify compatible materials for balloon: Suitable materials have been identified for the Zero-pressure balloon with hydrogen as the lifting gas.

Task 7: Generate performance data on electrolyzer, hydrides, fuel cell and balloon by test or analysis: Detailed analysis have been performed on the electrolyzer, hydrogen storage materials, fuel cells and balloon ascent and descent modes.

Task 8*: Integrate the components and assess system-level compatibility, analyze test data and assess the tech maturity of the probe and submit Final Report*: A detailed model has been performed to determine the viability of the overall system. Quantitative estimates were made on the hydrogen transfer in and out of the balloon for its ascent and descent. Also, the probe is being designed for payload of 150 kg and a low-altitude power of 2 kWh. This report will be updated after a completion of the Phase-I.

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