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A Conceptual Architecture for Venus Surface Sample Return

Geoffrey A. Landis[1], Steven R. Oleson[2]
NASA John Glenn Research Center, Cleveland, OH 44135, USA

Anthony Colozza[3]
HX5, LLC, Fort Walton Beach, FL 32548, USA

A conceptual architecture for retrieval of a sample of the surface of Venus is proposed. The mission concept incorporates a high-temperature aircraft to retrieve the sample from the surface and raise it into the upper atmosphere, a balloon-borne platform to produce fuel from the carbon dioxide atmosphere of Venus, and a launch vehicle to bring the sample into Venus orbit, where it is retrieved by an Earth-return vehicle.

Introduction

Venus is a fascinating planet: nearly the same mass and diameter as Earth, and the only one of the solar system's rocky inner planets (other than Earth) with more than a tenuous atmosphere, but in many ways very different. With the arrival of the DaVinci+ mission at Venus in 2031 and the Veritas mission estimated as arriving in 2032, Venus may at last take its place rivaling Mars in the public's attention. What do we do next?

Our knowledge of our sister planet Venus is primarily based on views from above the cloudy atmosphere, with only a handful of missions even reaching the surface. At 450°C and 92 bar pressure, the surface of Venus is the most hostile environment to explore in the solar system. Because of this, our knowledge of the geology and mineralogy of surface of Venus is mostly hypotheses, with little "ground truth" supporting the hypotheses. Only one NASA mission has even entered the atmosphere, the Pioneer Venus atmospheric probes. One of the Pioneer probes continued to transmit for an hour after reaching the surface, but made measurements only of the atmosphere, not of the surface. The Soviet Venera and VeGa missions did slightly better, with the longest-lived Venera lander transmitting for two hours from the surface, but made only relatively crude measurements of mineralogy, since sophisticated instruments were not yet available that could operate at Venus conditions.

A. Previous Sample Return Studies

Returning a sample of the Venus surface to Earth is a tremendously difficult problem. Not only must the systems operate on the surface to collect the sample, experiencing the high temperature, high pressure, and corrosive environment, but the mission must then launch through the thick Venus atmosphere to take the sample to orbit and thence from orbit return to Earth. Nevertheless, mission concepts for Venus sample return were analyzed by workers at JPL in the late 1990s.

A conceptual architecture for returning a Venus surface sample was outlined by Cutts and co-workers in a 1999 study [1], in which they analyzed the difficulties encountered in adapting the Mars Sample Return architecture to Venus. They point out that launching a rocket to Venus orbit from the surface is almost impossibly difficult due to the density of the atmosphere of Venus. The solution they proposed was to launch from the thinner upper atmosphere. Citing unpublished work by Jones, Nock and Blamont [2], they proposed doing this by lifting the ascent rocket up from the surface in a balloon. Sweetser *et al.* give further details on architecture [3], and Kerzhanovich and co-workers discuss a proposed that could survive the surface temperature balloon using a novel metal-bellows structure [4]. Later work considers more details of the system architecture [5,6] and the proposed high-temperature balloon [7].

While these early design concepts made a case that return of a sample from the surface was not impossibly difficult, ended up requiring a huge mission campaign: larger than a typical Flagship mission, at a likely cost well outside the

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[1] Researcher, Power Division, NASA Glenn Research Center. AIAA Associate Fellow.
[2] System Engineering and Architecture Division, NASA Glenn Research Center.
[3] Senior Research Engineer, Cleveland Program Office, HX5.

scope of a NASA mission. The concept required an orbital launch vehicle capable of surviving the 450°C corrosive surface conditions, a difficult problem. An alternative possibility, rendezvous with the launch vehicle suspended from an aerostat in the upper atmosphere, brought up difficulties in performing a rendezvous in the Venus middle or upper atmosphere. The proposed missions were difficult enough that further work on the concept was discontinued in favor of analysis of the somewhat easier possibility of returning an atmospheric, rather than a surface, sample. More recently a NIAC study also evaluated the possibility of returning an atmospheric sample [8].

This project will evaluate a new proposal for launching a sample from Venus, leveraging new technologies that were yet unknown or unproven when earlier studies were done.

I. Mission Concept

A. Baseline Mission Overview

We propose to apply two new technologies: producing the rocket propellant with in-situ resource utilization (ISRU) from materials available at Venus, and utilizing newly-developed high-temperature batteries and electronics to operate systems on the surface. Making propellant in situ removes the requirement to ship three tons of rocket propellant to Venus and brake it into the atmosphere, while the high temperature systems will allow us to avoid the requirement for developing the metal-bellows balloon, an extremely difficult technology element of the original system.

Figure 1 shows in schematic the structure of the atmosphere of Venus. The problem of sample return can be considered in two parts: first collecting the sample from the hot (~450°C), high pressure (90 bar) and corrosive surface and raising it to the middle atmosphere (~55-60 km, 0-20°C), and then launching the sample from the middle atmosphere into orbit. As with NASA's proposed Mars sample return mission, once in orbit the samples are retrieved by a separate Earth return vehicle to carry them back to Earth.

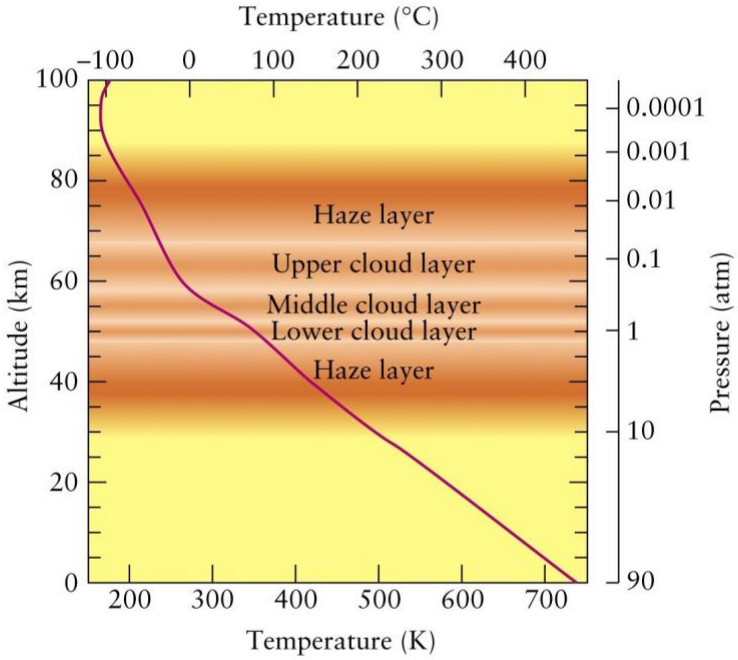

Figure 1: Variation of temperature and pressure with altitude above the Venus surface

B. Raising the sample from the Venus surface

For the surface systems, our concept will adapt electronics, power system, and mechanical technologies now being developed at NASA for high temperature and high-pressure operation [9].

Starting with the sample collected from the surface, the sample return sequence starts by lifting the sample cannister off from the surface with an aircraft designed for flight in the hostile environment of the Venus surface, powered by high-temperature batteries and using components designed for high-temperature operation. Due to the high atmospheric density at the surface, about 64.8 kg/m^3, the flight speed to sustain powered flight is much lower on Venus than on Earth. The power P required for flight is proportional to

$$P \propto (mg)^{3/2}\rho^{1/2} \tag{1}$$

where m is the aircraft mass, g the gravitational constant, and ρ the atmospheric density. At the surface of Venus, the power required to fly is 7.6 times less than that to fly an aircraft of the same mass and wing area at Earth sea level.

As it climbs above the lower atmosphere and through the thick middle cloud layer, sunlight becomes available [10], and the aircraft transitions from the high-temperature batteries used at low altitudes to solar power, dropping the now-expended high-temperature batteries. The aircraft then carries the sample up to rendezvous with the propellant manufacturing plant and return vehicle, floating on a balloon at about the 60-kilometer level.

Figure 2 shows the concept, with the solar-powered aircraft with the Venus surface sample approaching the balloon-borne orbital launch vehicle.

Figure 2: artist's conception of the airplane, now operating in solar-powered mode, approaching the balloon platform carrying the Venus launch vehicle.

The sample is transferred from the solar airplane using the mid-air "skyhook" technique pioneered by the Air Force in the Corona program in the 60s (or, more accurately, a reversal of the sky-hook technique, with the aircraft moving and the balloon platform stationary with respect to the wind.)

Once the sample is transferred to the return vehicle, the propellant manufacturing plant, no longer needed, is jettisoned, and the subsequent reduction in weight allows the balloon and return vehicle to rise another few kilometers, to roughly the 65 km level.

C. ISRU propellant production for launch to Venus orbit

Even launching from the upper atmosphere, reaching orbit from the surface of Venus is not easy. The escape velocity of Venus, 10.46 km/s, is only slightly less than the 11.18 km/s required to launch to escape from Earth; and for a launch from a nominal altitude of 65 km above the surface, the atmospheric density is only slightly less that of Earth. The net result is that it is nearly as difficult to launch into orbit from Venus as it is to launch from the surface of the Earth. The launch from Venus requires a fully-fueled vehicle nearly as capable as the launch vehicles needed to reach orbit from Earth:

Unlike Mars and Lunar ISRU propellant production concepts, we propose to produce not just the oxidizer, but both oxidizer and fuel for the rocket from the available resource, the carbon dioxide atmosphere. To do this we will adapt a novel rocket propellant developed by Diane Linne of NASA Glenn over thirty years ago [11,12]: the carbon monoxide-oxygen rocket engine.

Processing of carbon dioxide to produce oxygen has now been demonstrated on Mars by the MOXIE experiment [13,14]. What is less well appreciated is that a byproduct of oxygen production by the solid-oxide electrolysis method is carbon monoxide. Although considered a pollutant on Earth, carbon monoxide is in fact combustible, and a mixture of liquid carbon monoxide and liquid oxygen can be used as rocket propellant with specific impulse of 250 seconds. This is somewhat lower than the highest energy rocket propellants in use, but comparable to that of solid-fuel rocket engines used for Earth launch, for example, the engines on the Scout launch vehicle, with specific impulse of 236 (sea level) to 255 (vacuum) seconds, or the Space Shuttle SRB engines, with specific impulse of 242 seconds.

At a command from Earth, the three-stage liquid-fueled rocket is fired, taking the sample into Venus orbit, where it is collected by the Earth Return Vehicle.

(The final mission conops will include the full mission operations including Earth to Venus transfer, entry, descent, and deployment in the Venus atmosphere and sample collection on the surface of Venus, and rendezvous with the Earth return, but since the Earth return will use conventional technology, it is not discussed in detail here).

II. Technology Choice

A. Aircraft

A key innovation of the airplane is the use of an aircraft to retrieve the samples from the surface and bring them to an altitude where they can be transferred to the balloon-borne launch vehicle. Solar aircraft for flight on Venus had been analyzed by Landis and co-workers [15-17]. Figure 3 shows one example from an earlier design study, in which an aircraft designed for Venus operation has been folded to fit inside an aeroshell for entry, descent, and deployment in the Venus atmosphere. Testing of the Ares Mars airplane concept has shown that it is possible to deploy such a folded aircraft from the encapsulating aeroshell, unfold it into flight configuration during parachute descent, and transition to flight.

However, these earlier concepts had been analyzed for operation on atmospheric missions flying at altitudes above the thick middle cloud belt, where temperatures are moderate. Aircraft have not, in previously studied missions, been proposed to descend to the surface.

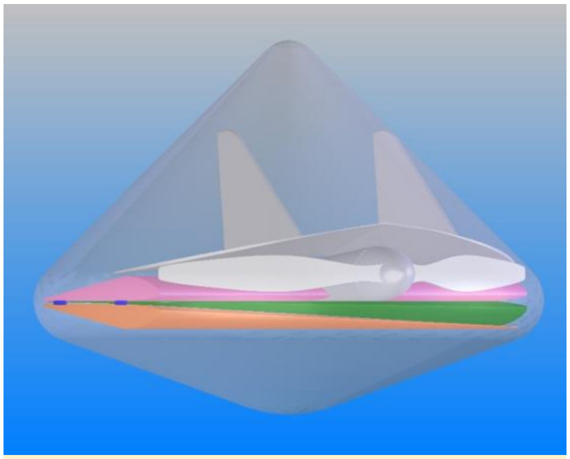

Figure 3: Design of Venus aircraft, showing how the vehicle folds to fit inside an aeroshell for entry into the Venus atmosphere.

What is different now from when the previous Venus aircraft studies were done is that we now have developed a much more extensive range of technologies developed that can operate at Venus surface conditions.

Above the middle cloud layer, previous studies have shown that solar energy is abundant, and flight on solar power is not difficult. Below the cloud layer, solar intensity drops rapidly, and high temperatures decrease the power output of solar cells [10]. Grandidier and co-workers [18], as well as others [19] have shown that solar cells can be made to withstand the temperature conditions (with appropriate glass encapsulation to protect against the corrosive environment), but the power output is not enough to sustain level flight (much less climb). For the descent to the surface, the aircraft will be gliding, and require power only for control and instruments, but not propulsion. In this descent, we can convert the aircraft's potential energy into power using the propeller as a generator.

Once on the surface and for the subsequent climb, the vehicle must operate on high-temperature batteries. Potential solutions to the problem of battery operation on Venus were outlined by Landis and Harrison [20], with sodium-sulfur batteries having been demonstrated to operate up to Venus temperature and pressure. High temperature batteries are now being developed in the NASA HOTTech program [21] and elsewhere [22,23]. Such batteries have been proposed for a long-lived Venus demonstration mission [24], with prototypes now having been demonstrated for 118 days of operation at 450°C and Venus atmospheric pressure.

Once the aircraft has climbed to an altitude above roughly 30 km, solar energy will start to be available to augment the battery power, and at about 50-55 km the aircraft can jettison the now-depleted high-temperature batteries and continue in solar-powered flight.

A key to the aircraft to fly at low altitudes is the use of materials which can not only withstand the ~450° temperature, but are also robust to the corrosive atmosphere. Until recently, the effect of the combined temperature and atmosphere on materials had been unknown, but in the last few years, materials test in the NASA Glenn GEER ("Glenn Extreme Environment Rig") has compiled lists of materials which withstand the environmental conditions, as well as a list of those which do not survive [25,26], which can be used in the design.

B. High temperature electronics and mechanisms.

Silicon Carbide (SiC) electronics capable of high-temperature operation has made extensive improvements in recent years [27-30], with the first high-temperature SiC microcontrollers now being tested at NASA Glenn [31]. In addition, Gallium Nitride microelectronic components are also being developed for high temperature electronics [31,32], with prototype integrated circuits made and tested. Diamond electronics, which are in principle capable of even better performance at high operating temperature [33,34], are in a less advanced state of development as an electronic material, but will be investigated. Using these technologies, prototype high-temperature radio systems have been demonstrated and tested working at Venus conditions [35]. Mechanical systems will use high-temperature components which have been demonstrated for Venus conditions [9], such as high-temperature motors developed and tested by Honeybee Robotics [36].

In addition, cameras suitable for operation at Venus surface conditions, previously unknown, are being developed in several development programs.

C. In-situ fuel generation from carbon dioxide.

The technology of generating oxygen by the electrolysis of carbon dioxide in a solid-state fuel cell has now been demonstrated on Mars by the MOXIE ("Mars Oxygen") experiment on the Perseverance rover, which has now successfully produced over 122 grams of oxygen [13] and nearly twice that amount of carbon monoxide. Thus, the proposed fuel production can be considered a flight-proven technology.

Since Venus also has a carbon dioxide atmosphere, adapting the system for Venus would be straightforward. The atmospheric pressure at the levels of interest on Venus is much higher than that on Mars, and so a MOXIE-based oxygen generation system would be somewhat simpler, not requiring the compressor used on the MOXIE demonstration unit.

Although MOXIE requires scale-up to produce the propellant volume needed, scaling the system to larger production rates has been analyzed in engineering studies of Mars sample return [13] and human [37] missions, with a scale-up of a MOXIE-like system to production rate of 2-3 kg/hr proposed [13]. This rate would produce the amount of carbon monoxide and oxygen propellant needed to launch from Venus in 16 to 25 days.

While temperatures and atmospheric pressure will not be a problem for operation (at high altitudes on) Venus, the system will require a filter on the input, to avoid contamination of the input carbon dioxide stream with Venus aerosols (most particularly, sulfuric acid droplets).

D. Balloon platform and launch vehicle

Compared to the challenging technology development of Venus atmospheric airplanes and high-temperature electronic and surface systems, the balloon platform and associated rocket are at a relatively high state of technology development. Two balloons were successfully flown at 54 km altitude above the Venus surface by the Soviets as part of the 1986 "VeGa" mission, demonstrating that balloon platforms are feasible. The balloons are at high enough altitude that the temperature is not a difficulty. The key materials problem is that the balloon envelope must be resistant to attack by sulfuric acid. The approach used by the Soviet mission was that the outermost layer of the multi-layer envelope was a thin coating of PTFE ("Teflon"), which, unlike other common polymers used for balloons, is impervious to sulfuric acid attack. This approach will be used here.

For the baseline approach, the balloon lifting gas will be helium, but alternate lift gasses including helium, methane, carbon monoxide, and ammonia will be considered.

Since Venus' escape velocity is similar (but slightly less than) to that of Earth, and atmospheric density at launch altitude similar to Earth's, the launch vehicle for the ascent to orbit can be modeled as like that of a vehicle launching from Earth to orbit. The smallest vehicle to ever launch a payload successfully from the Earth into orbit is the Japanese SS-520 vehicle with an added solid-fuel third stage. This vehicle has a length of 9.5 meters, a mass of 2.6 (metric) tons, and launched a payload of 4 kg to a 180 x 1800 km orbit [38]. Since our CO/LOX propellant will have a specific impulse nearly the same as the HTPB-based solid propellant of the SS-520, our vehicle is conservatively expected to be very similar in size, weight, and fuel mass. Based on this comparison, the amount of fuel to be produced will be 2.35 tons. Use of ISRU fuel production means the mission needs to transport to Venus only the empty weight of the launch vehicle, 250 kg, rather than the fully fueled weight of the rocket. This enables a much more reasonable system architecture.

III. Conclusions

A mission conceptual architecture for retrieval of a sample of the surface of Venus is outlined, building on previous mission concepts analyzed by JPL and others [1-6]. The mission concept incorporates a high-temperature aircraft to retrieve the sample from the surface and raise it into the upper atmosphere, a balloon-borne platform to produce fuel from the carbon dioxide atmosphere of Venus, and a launch vehicle to bring the sample into Venus orbit, where it is retrieved by an Earth-return vehicle.

A detailed design study [39,40] is now in progress as a NASA Innovative Advanced Concepts (NIAC) phase-I project.

IV. Acknowledgement

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