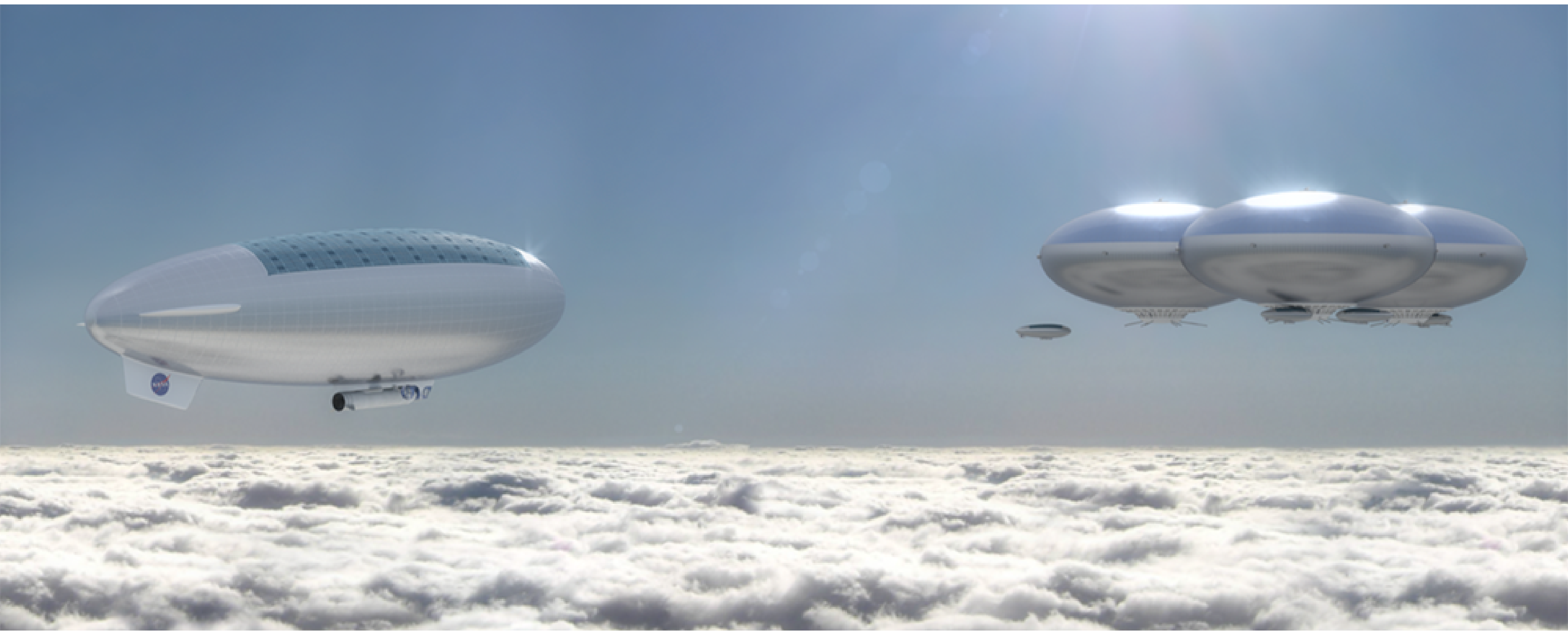
Venus Atmosphere Practical Outpost with Resource-Extraction (VAPOR)

Mission Brief



Word Count: 2777

NASA Mission Briefing

National Aeronautics and Space Administration
Washington D.C.
Venus Atmosphere Practical Outpost with Resource-Extraction (VAPOR) Mission Brief

Mission Overview

Following your successful path through astronaut selection and training, the Johnson Space Center is delighted to inform you of your selection as initial crew for the Venus Atmosphere Practical Outpost with Resource-Extraction (VAPOR) mission, a newly-proposed long-term mission to establish a permanent human presence on Venus. At 55km above the surface, Venus is the most Earth-like region in the solar system with temperatures around 25°C and normal pressure. Hence, NASA's interest in a habitat in this region. You will be living in a large floating balloon-like structure, experiencing Earth-normal gravity and pressure. The following mission briefing will describe in detail your transfer, the environment you should expect upon arrival, the habitat currently being designed for you, and the resource extraction procedures you will begin to develop, to ensure a sustainable Venusian settlement. In addition, as you may have been expecting a mission to Mars, where most NASA activity is currently focused, this briefing will highlight differences and advantages. Please familiarize yourself with this briefing before mission-specific training starts.

Venus Transfer

Trajectory and Aerocapture

Transfers to Venus are significantly differently than the Mars trip you may have been expecting from your training. The lowest energy transfer available is a Hohmann transfer to Venus – the simplest possible transfer, using a single burn to place you in an orbit with highest point at the Earth and lowest point intersecting with Venus – transfers take exactly half an orbit, 145 days. Cargo will be sent this way to maximize payload.

For both cargo and your crew vessel, arrival into Venusian orbit will be through aerocapture - braking using atmospheric drag. Venus' atmosphere is significantly denser than Earth's, having 93 times the total mass of Earth's atmosphere. The extra braking available upon arrival allows for a fast transfer of 110 days for the crew vessel (Lugo and Ozoroski 2015); since no fuel is

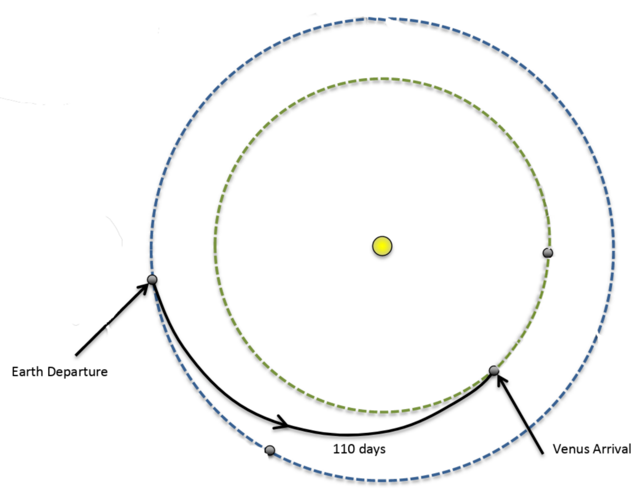


Figure 1: (Arney and Jones, Christopher 2015)Your transfer to Venus - this is a higher-energy transfer than the Hohmann transfer, but allows for short travel times. Cargo will be sent over a longer route to allow for heavier payloads.

needed for arrival, payload can be increased and the journey shortened relative to a Mars mission. This faster, non-Hohmann transfer is shown in Figure 1 above.

Payload is also increased by the reduced speeds needed for a transfer to and from Venus – departure speeds are 0.25 km/s slower to Venus than to Mars, further increasing the payload that can be carried. Despite this, transfer times are significantly lower; three months in each direction, rather than the 9 months required for a Martian transfer. Again, reduced food and water requirements en route allow for a significantly larger habitat, a key advantage over what you may have anticipated for a Mars mission.

Frequency of Transfer Windows

Transfer windows between Earth and Venus are also more common than for Mars. For any given transfer window, there is the same angle between the two planets. Venus' synodic period, the time for this angle to recur and hence the time between transfers, is 1 year 8 months, significantly shorter than Mars' synodic period of 2 years 2 months (David 2018). Together with the shorter transfer time, these properties will make the habitat you and your crewmates will establish significantly more useful than virtually any other location in the solar system, as resupply is much more common. Benefiting you specifically, shorter travel times increase the fraction of the trip spent on Venus, drastically reduce radiation exposure while in interplanetary space, and allow for more options to return once the habitat is established.

In addition, Venus has very frequent transfers to asteroid belt locations; while moving from one asteroid to another is always slow and energy-intensive, transfers from Venus require little more energy than returns to Earth (Landis 2003). Your mission may therefore later integrate with parallel asteroid explorations,.

Environment at Venus

Atmosphere and weather

At the surface, Venus is not survivable, much less habitable. Temperatures exceed 400°C, the melting point of lead – damaging almost all standard electronics as solder melts. The atmosphere is mostly carbon dioxide, with trace nitrogen, pressurized to 93 atmospheres - requiring a pressure vessel stronger and therefore heavier than could be transported. However, ascending to the upper atmosphere, pressures fall to an Earth-normal one atmosphere at 50km above the surface. This altitude still experiences uncomfortably high temperatures of 50°C at noon (Williams 2019). However, temperatures fall relatively slowly relative to altitude in this region, at a gradient of only 10.2 °C/km. Ascending so that noon-day pressure is 25°C, you would experience 0.8

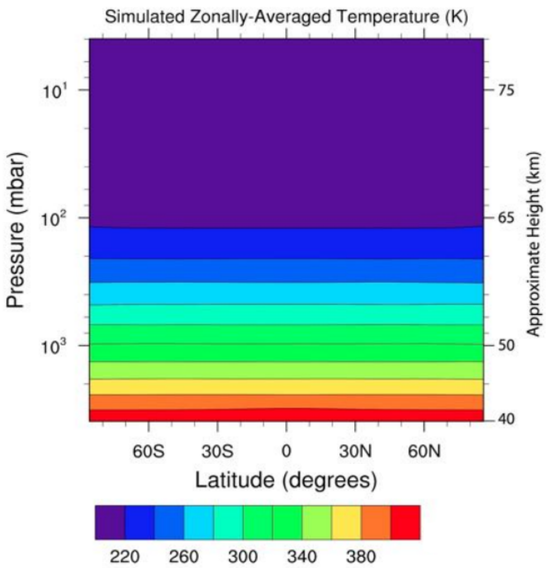


Figure 2: (Parish and Mitchell 2018) Model of the average temperature and pressure across Venus. At your altitude of 53km pressure is a Denver-normal 0.8 atmospheres with temperature around 25 °C.

atmospheres, as you can see in Figure 2; this is the pressure felt in high-altitude cities on Earth such as Denver. In practice, depending on exact habitat mass and weather conditions your altitude will fluctuate. However, you will never enter a lethally hot or low-pressure region; this habitat design is resilient to mass and altitude excursions.

A major weather difficulty that drives design is the presence of concentrated sulfuric acid droplets in the air. Sulfuric acid clouds begin at 30km atltitude and extend through your altitude to 60km above the surface, consisting of small acid droplets lofted in the atmosphere. Though there appear to be gaps between the lower and upper cloud layers, you are not guaranteed to always be in these gaps. Therefore these diffuse acid droplets are the major environmental hazard, governing habitat construction and your ability to survive outside the habitat.

Travel & the Day-Night Cycle

Venus rotates extraordinarily slowly, revolving on its axis less than once every Venusian year. However, upper atmosphere winds move significantly faster than the surface – 100 m/s at your altitude independent of latitude – carrying you around the planet once every 4 days, depending on latitude, creating days and nights lasting two Earth days each. This not close enough to the Earth's cycle to use, and so an artificial day will be kept. Usefully, however, these fast winds mean the atmosphere is well-mixed and you should not expect large temperature fluctuations between day and night, due to the limited time to gain or lose heat. In addition, the constant travel allows you to survey the surface.

Vertical travel within the atmosphere will be possible by adjusting the density of the habitat. Trips downwards, for science or resource-gathering, will be required. However the heat capacity of the habitat is enough that short trips down will not heat the station dangerously. Direct solar heating is not excessive due to the cloud layer, so most of the heating is slow conduction from the atmosphere.

Extra-Vehicular Activity (EVA)

The high wind speeds do not pose a threat to activity outside your habitat – as you will be living in effectively a blimp, it travels at exactly wind speed and you would not feel any wind whatsoever. Since the pressure matches Earth's, you will not need a pressure suit to work externally either, merely a respirator to provide oxygen. Major risks are falling – the tethers you are used to from working at the International Space Station should be sufficient – and the sulfuric acid droplets in the air, which will require a resistant suit, similar to a wetsuit. This will be significantly less restrictive than a full pressure suit as needed for Mars EVAs, allowing for much more delicate motion with fingers, and much less time spent suiting up. In addition, risks are much lower; a tear in the suit will not lead to asphyxiation and death, but a very slowly-developing burn since the acid droplets are widely dispersed. Time to either patch the suit or return inside will be less than the time until damage is done.

Health concerns – Gravity & Cosmic Ray Protection

A major benefit of habitats in-atmosphere, rather than surveying from orbit, is the radiation protection provided by Venus' atmosphere. At the 50km level, the atmosphere above you provides 1.290 kg/cm^2 of mass; this exceeds the protection on Earth's surface, whose atmosphere only provides 1.030 kg/cm^2 of mass, and is vastly superior the Martian surface where you would feel only 0.016 kg/cm^2 of shielding. Atmospheric mass shields by acting as a physical obstacle to solar and cosmic radiation; this will be sufficient to bring radiation down to acceptable levels.

Your overall dose will be significantly less than a Mars mission; the significantly reduced transit time will reduce exposure in deep space where protection is harder, and you will receive negligible dose on the surface even during activity outside of the habitat. Mars' lack of an atmosphere or magnetic field means that habitats will likely have to be small and radiation shielded, likely by being underground, while surface activity would have to be time-restricted to limit radiation exposure (Marc 1997).

Venus unfortunately does not have its own magnetic field; it does have a molten metal core like Earth, however there does not appear to be sufficient movement to create a magnetic field. Instead, a small field comes from the interaction of the upper atmosphere with solar wind. Positively charged ions are created by solar radiation; in turn, solar wind drags those ions away from the sun. Although the solar wind is normally net uncharged, the positive ions added create a net current away from Venus which in turns creates a very weak magnetic field, roughly 1.5×10^{-5} times the strength of Earth's (Odenwald 2005). This will not be sufficient to protect you, nor does it protect the upper atmosphere from being stripped away as Earth's field does. However, out-gassing from the surface appears to be enough to maintain the Venusian atmosphere at its incredibly high density.

Gravity on Venus is also close enough to Earth normal to protect you from the health risks of micro-gravity, and to allow you to recover from bone loss experienced during the transfer. You will experience 8.9 m/s^2 of acceleration, or 0.91*g,* which should not feel appreciably different. Again, this is in contrast to Mars, where the surface gravity of only 0.38*g* would feel noticeably different, and would have as yet health effects, as it is not guaranteed to be strong enough to maintain bone density and muscle strength.

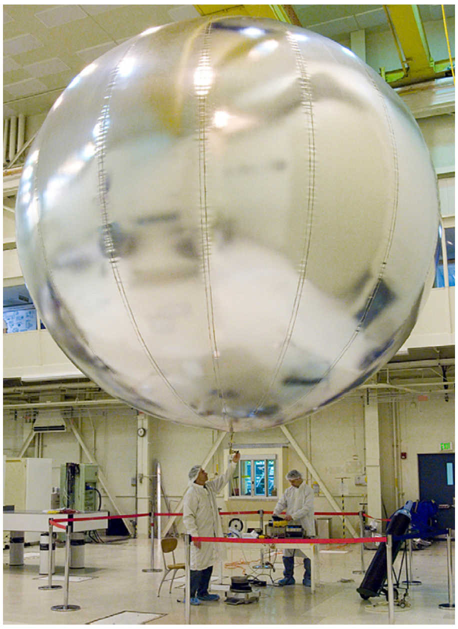


Figure 3: (Hall, Fairbrother, and Frederickson 2008)Prototype balloons showing the laminate fabric used - a clear layer of Teflon, bonded to metal foil and urethane undercoat for strength.

Habitat Description

Design and Materials

Aeroplanes are feasible on Venus – the slightly lower gravity and thick atmosphere means that terrestrial designs, given an electric power supply and proofed against sulfuric acid, would fly perfectly well. However, powered flight is power-intensive and is prone to catastrophe if power is lost or the structure fails.

Using lighter-than-air habitats reduces your exposure to these risks. A nitrogen and oxygen mixture is a lifting gas in the dense Venusian air, allowing the entire volume of the habitat to serve as lifting volume as well as useful habitable space. There is no need for a large gas bag as terrestrial zeppelins use – a large habitat will float itself. The lifting capability of an Earth-normal oxygen/nitrogen mix is sufficient to loft cities – an 800 meter diameter habitat could have a mass of 350,000 tonnes, which is the scale of the masses of skyscrapers, meaning city-scale habitats are plausible.

Lighter-than-air habitats have other benefits. Firstly, they require high volumes of livable space – the density of the habitat must remain low, so interior spaces will be large. Since the outside pressure will match the inside pressure, plus a small over-pressure to keep the habitat inflated, the habitat requires little structural strength, and so can be made of a lightweight fabric. Any rip in the habitat would not be catastrophic, as the low pressure differential means that leak rates are slow even with large rips, giving you time to repair them before descending too far.

Your habitat will be a large spherical structure, with a rigid metal skeleton bearing the weight of the internal floors, and a thin skin. Given there is little pressure difference to withstand, the main design limitation of the skin is its sulfuric acid resistance. Sulfuric acid is a common industrial chemical, produced in the millions of tonnes yearly, so strategies for dealing with it are well-known. However, these rely on nickel and stainless steel alloys, which are too heavy for your habitat, and are best-suited for resisting turbulent scouring flows of sulfuric acid from industrial processes (Davies 2013). Given there will be no apparent wind experienced by your lighter-than-air ship, slightly more delicate fluoropolymer-coated fabrics will be used; the strong carbon-fluorine bonds resist any attack from sulfuric acid. PTFE-coated urethane has already been developed for use in the skin itself, as have its techniques for joining from the interior only, meaning the join cannot be attacked by the acid droplets outside.

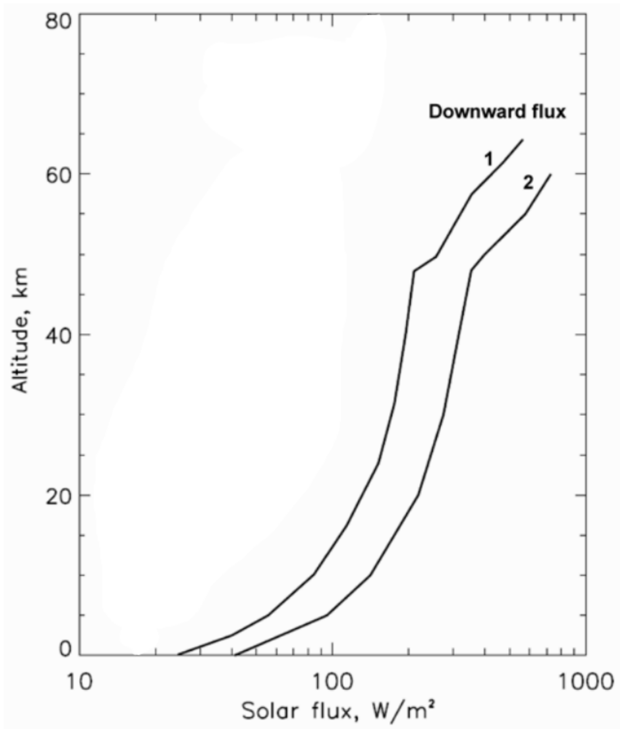


Figure 4: (Titov et al. 2007) Downward solar irradiance experienced by 1- the American Pioneer probes and 2- the Soviet Venera probes. These both descended at relatively northerly latitudes, explaining the slightly lower power generated than your estimated 150W/m² power budget. The step in both curves at 55km shows the probe entering the clouds.

Pressure balance

Lifting power for a gas is defined by its molecular weight and pressure – N_2 and O_2 are both lighter molecules than CO_2, and so either is a lifting gas. There will be some amount of room to experiment to find the correct gas balance. A mixed gas environment is likely desirable to reduce fire risk. However, existing at 800mBar with the standard 21% oxygen mixture will provide slightly less oxygen than you are used to.

Boosting the fraction of oxygen will increase the partial pressure back to normal, but will cause your altitude to fall slightly as oxygen is denser, which will increase ambient temperature - you will have leeway to experiment to find the optimum altitude and gas mixture.

Power

Above the clouds, Venus receives significantly higher solar irradiance than the Earth. Its proximity to the sun means it experiences a mean flux of 625 W/m^2 – the energy input averaged over latitude and the day/night cycle. However, the cloudtops reflect almost almost all energy, radiating 475 W/m^2 back into space – before it would become accessible to your habitat in the middle of the cloud layer. Roughly 150 W/m^2 of downward flux, as shown in the US and Soviet lander data in Figure 4 above, remains available to power your habitat, similar to the average flux in European cities. Venus' saving grace, however, is the reflectivity of the atmosphere and surface below you; since Venus has the highest albedo, 0.8, of any planet in our solar system, there is nearly 150 W/m^2 of upwards flux available to solar cells on the underside of your habitat (Landis 2001). 300 W/m^2 of available energy is akin to Northern Africa's levels of solar capacity. Furthermore, since the atmosphere is well-mixed and homogeneous, this is reliable power with little weather variation to disturb it. Most variation will come from the day/night cycle created by the winds carrying you around the planet, but the predictability of these means your schedules can be designed to conserve power overnight, and batteries can be sized to last the 48-hour night without needing to have an extremely large, heavy power reserves in case of extended bad weather.

Solar cells will be mounted on the outside of the habitat's skin – therefore they need protection from the acidic environment. They will be coated with FEP-Teflon or polypropylene, both of which are transparent polymers which can be coated onto the solar cells and provide 90% transparency, while being resistant to sulfuric acid erosion. These coatings are known to work despite this application being a non-standard use, as seen in Figure 5.

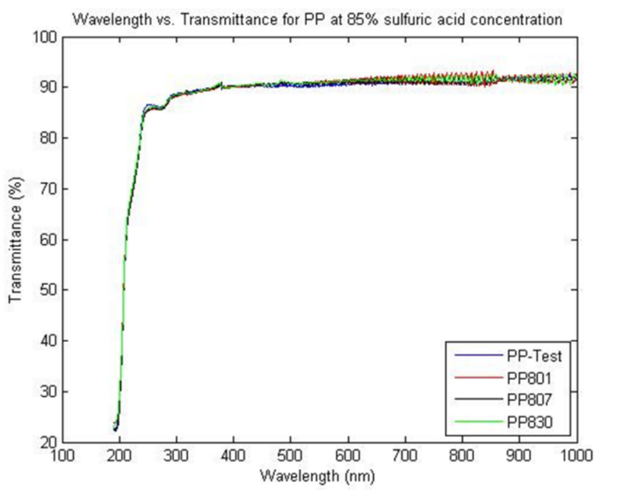


Figure 5: (Jones and Arney 2015) The curves show the transmittance of polypropylene after spending up to 30 days submerged in 85% concentration sulfuric acid, a significantly harsher environment than the aerosol environment on Venus. No degradation is found supporting the durability of your habitat's exterior.

Resource extraction

Maintaining a permanent habitat on Venus will not be possible without eventually beginning to use the resources available on Venus rather than relying on resupply from Earth. The inherent disadvantage in your floating habitat is that it floats – you will have no direct access to the surface to gather materials. Two options remain – remote control of surface devices, and resource extraction from the atmosphere.

The atmosphere, mostly carbon dioxide, is also 3% nitrogen. Since the Venusian atmosphere is so much denser than Earth's, however, Venus holds more nitrogen in total than Earth, despite Earth's atmosphere being 78% nitrogen. You will be able to extract and concentrate nitrogen, and your current mission design involves a robotic craft to gather nitrogen to inflate your habitat, reducing the mass of gases to be carried en route. Nitrogen is also vital as fertilizer, which will be required for farming to start – the top layers of your habitat will experience Earth-like light levels allowing you to grow crops.

Robotic operation on the surface is difficult, with no lander having yet survived longer than 2 hours due to the extreme pressure. Robots which spend brief amounts of time on the surface, inflate balloons to ascend and cool, then return have been proposed by NASA (Adams 2009) although not yet implemented. By your launch time these may have been developed, at which point your habitat will be useful for teleoperation.

Summary

VAPOR will establish a base in the most Earth-like region of the solar system – Venus' upper atmosphere. Living in a floating habitat 55km above the surface, you will uncover the history of Venus, which is currently not understood below the cloud layer, and will do so in significantly more hospitable conditions, in a larger habitat, than possible on any other planet or moon.

Johnson Space Center
January 2020

Acknowledgments

The format of this article is inspired by a NASA Space Shuttle mission briefing (NASA 2011), while the cover page image and NASA logo (Ferebee 2014) are from an artist's impression of a Venus habitat along a design which made it through initial NASA planning 6 years ago. I'd also like to thank my personal tutor Helen Brindley for encouragement that this slightly non-standard format was actually a good idea.

References

Adams, Michael. 2009. 'Venus Mobile Explorer'. NASA: Goddard Space Flight Center. https://www.lpi.usra.edu/vexag/reports/VME_FINAL_ITAR_Compliant.pdf.

Arney, Dale, and Jones, Christopher. 2015. 'HAVOC - An Exploration Strategy for Venus'. In . Pasadena: NASA Langley Research Center. https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20160006329.pdf.

David, Hollister. 2018. 'Cosmic Train Schedule'. http://clowder.net/hop/railroad/sched.html.

Davies, Michael. 2013. 'Alloy Selectionfor Service Insulphuric Acid'. Edited by Geir Moe. Nickel Institute. https://www.nickelinstitute.org/media/4122/alloy-selection-for-service-in-sulphuric-acid-10057.pdf.

Ferebee, Melvin. 2014. 'HAVOC'. NASA Systems Analysis and Concepts Directorate. https://sacd.larc.nasa.gov/files/2016/06/havoc_slider.png.

Hall, J, D Fairbrother, and T Frederickson. 2008. 'Prototype Design and Testing of a Venus Long Duration, High Altitude Balloon'. *Advances in Space Research* 42 (10): 1648–55. https://doi.org/10.1016/j.asr.2007.03.017.

Jones, Christopher, and Dale Arney. 2015. 'High Altitude Venus Operational Concept: Proofs of Concept'. *American Institute of Aeronautics and Astronautics*, August. https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20160006580.pdf.

Landis, Geoffrey. 2001. 'Exploring Venus by Solar Airplane'. In . Albuquerque: NTRS. https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20020022923.pdf.

———. 2003. 'Colonization of Venus'. In . Abuquerque: Glenn Research Center. https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20030022668.pdf.

Lugo, Rafael, and Thomas Ozoroski. 2015. 'High Altitude Venus Operations Concept Trajectory Design, Modeling, and Simulation'. In . Pasadena: American Institute of Aeronautics and Astronautics. https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20150006858.pdf.

Marc, Cohen. 1997. 'Design Research Issues for an Interplanetary Habitat'. *SAE Transactions Journal of Aerospace* 106: 967–94. www.jstor.org/stable/44650478.

NASA. 2011. 'STS-135 Mission Summary'. https://www.nasa.gov/pdf/558175main_STS135%20Mission%20Summary-4.pdf.

Odenwald, Sten. 2005. 'Venus' Magnetic Field'. Imager for Magnetopause-to-Aurora Global Exploration Education Center. https://image.gsfc.nasa.gov/poetry/venus/V3.html.

Parish, Helen, and Jonathan Mitchell. 2018. 'Simulating Venus' Cloud Level Dynamics Using a Middle Atmosphere General Circulation Model'. Pre-print. Los Angeles. https://arxiv.org/abs/1811.07669.

Titov, Dmitry, Mark Bullock, David Crisp, Nilton Renno, Fredric Taylor, and Ljudmilla Zasova. 2007. 'Radiation in the Atmosphere of Venus'. In *Exploring Venus as a Terrestrial Planet*, 121–38. Geophysical Monograph Series 176. Washington DC: American Geophysical Union. https://doi.org/10.1029/176GM08.

Williams, David. 2019. 'Planetary Fact Sheet'. NASA. https://nssdc.gsfc.nasa.gov/planetary/factsheet/.