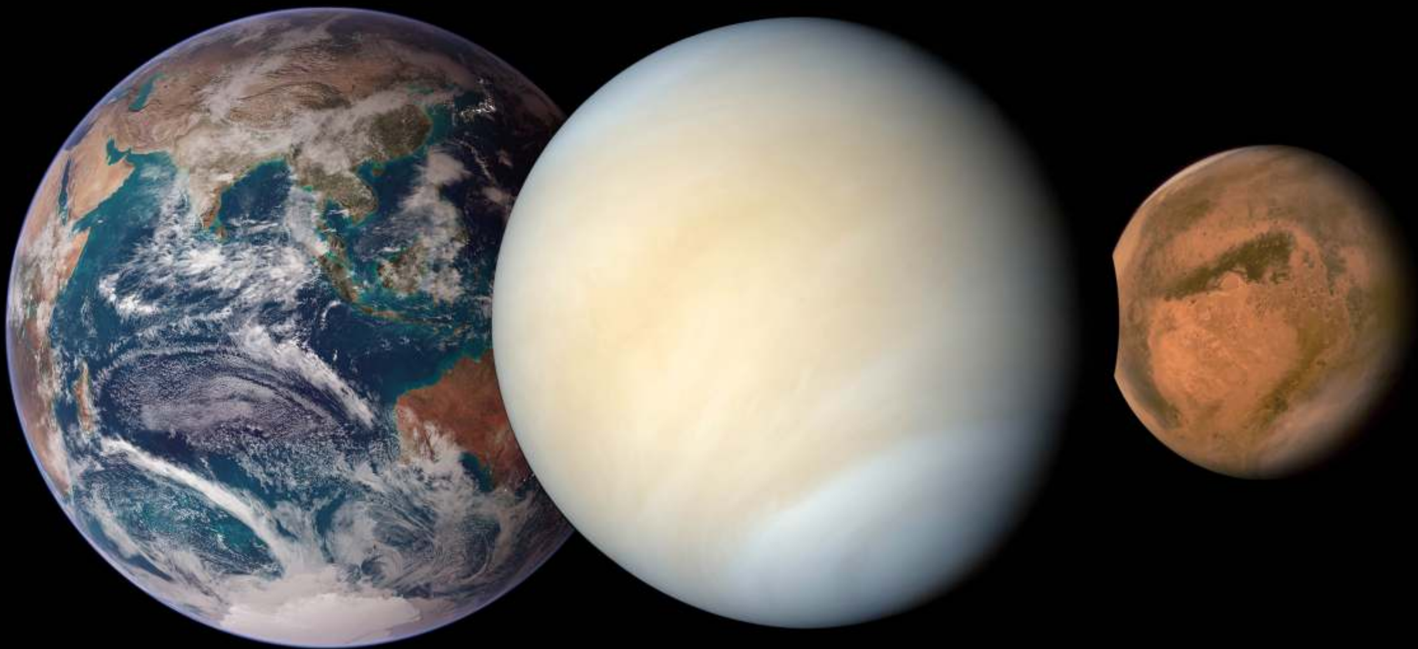
Rethinking Our

Sister Planet



A Handbook For The Development Of Venus

Rethinking Our Sister Planet:

A Handbook For The Development Of Venus

First Edition

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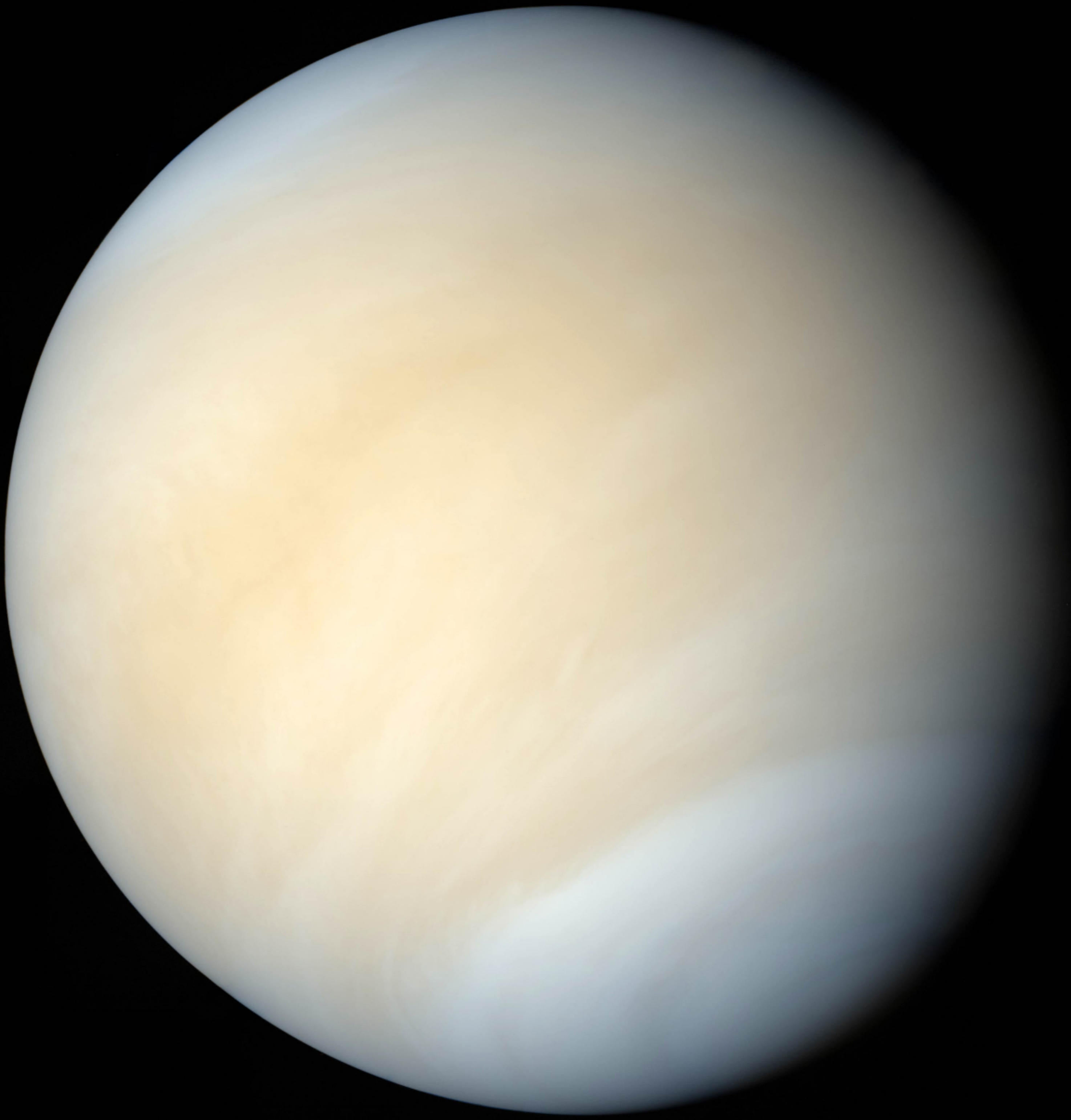

As a star goeth forth amid stars
In the darkness of night,
The star of evening,
That is set in heaven as the fairest of all

Homer
The Iliad (XXII, 318)

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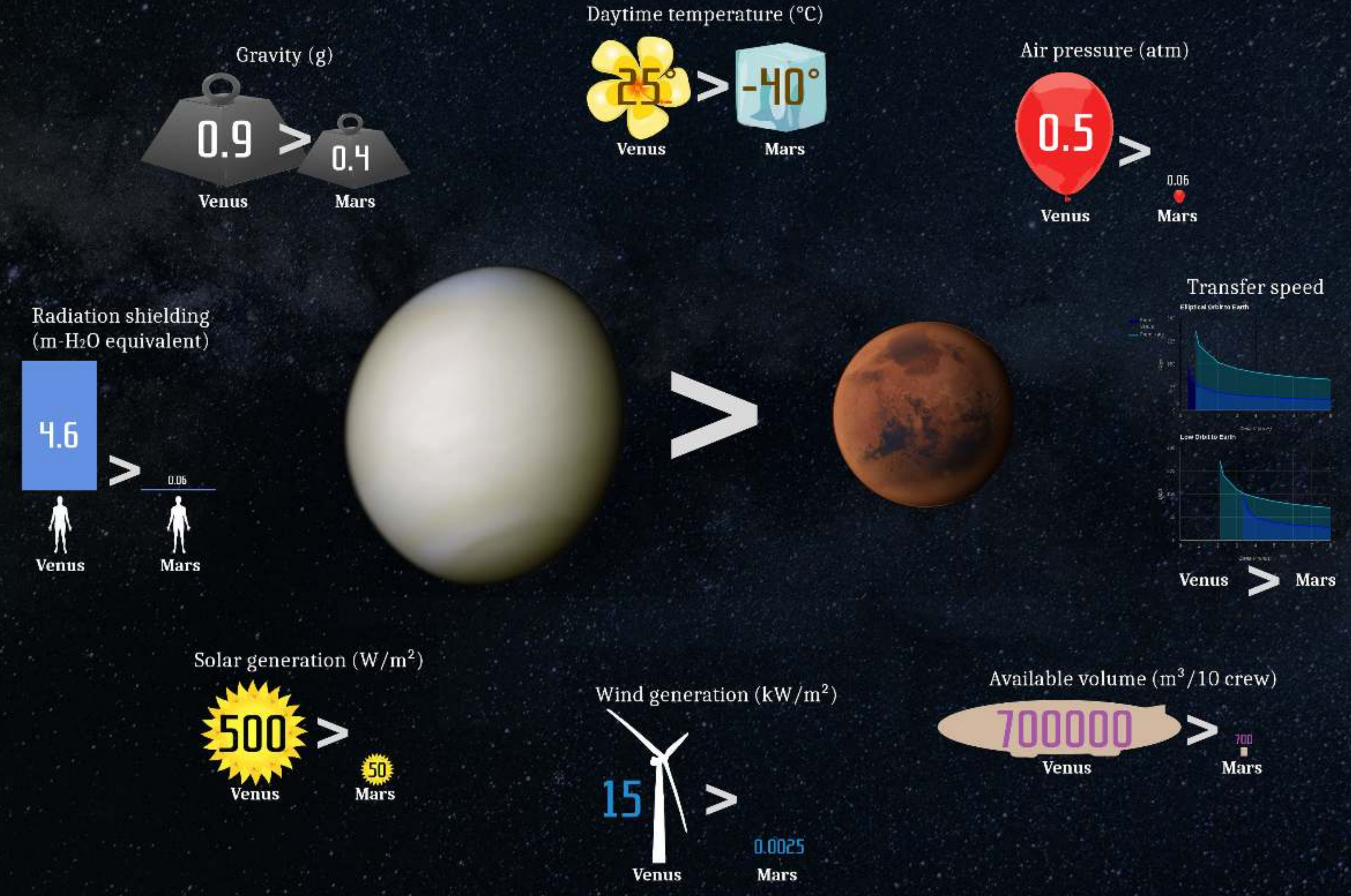

Since the realization that the *planētai* our ancestors had watched since time immemorial were, in fact, entire worlds, people have speculated about their nature. Venus, having already been subject to frequent allusions in prose and poetry as the morning star and goddess of beauty, was no exception. In 1761, watching the transit of Venus through a small refracting telescope, Mikhail Lomonsov first observed a distortion that he correctly attributed to an atmosphere.[1] Soon, "faint and changeable spots" quickly became attributed to cloud features.

Morning Star (ca. 1900) by Eugen Bracht.

While occasionally speculated to be a dry and arid expanse, the common consensus seemed to be that - being entirely shrouded in clouds - Venus must be a wet, lush world, akin to a primitive Earth. Early science fiction played upon these themes, such as Edgar Rice Burroughs' Venus Series and C.S. Lewis's Space Trilogy, with characters encountering vast oceans and swamps inhabited by dinosaurs and other great beasts. In his 1950 short story "The Long Rain", Ray Bradbury wrote of weather on Venus:

> *"It was a hard rain, a perpetual rain, a sweating and steaming rain; it was a Mizzle, a downpour, a fountain, a whipping in the eyes, an undertow at the ankles; it was a rain to drown all rains and the memory of rains."*[2]

By this time, however, science had begun to diverge from fiction. Repeated attempts to detect water in Venus's cloudtops had failed. Radio telescopes suggested an unexpectedly hot surface - so hot, given Venus's albedo, that there was reluctance to accept the data as a valid surface temperature reading.[3] With the landing of the Soviet probe Venera 7 on the surface, there could no longer be any question: with a surface mean pressure of 93 bar and a temperature of 467°C, this was a hellish planet.

There would, in short, be no dinosaurs.

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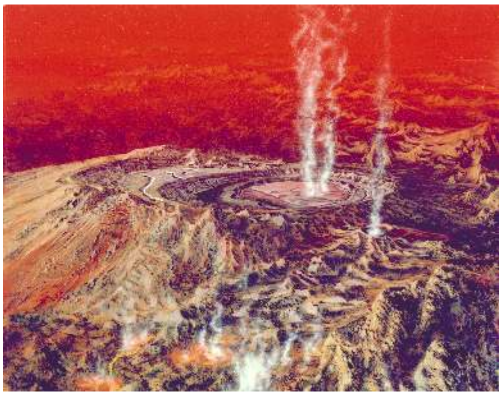
[1] Shiltsev, V. (2014). The 1761 discovery of Venus's atmosphere: Lomonosov and others. Journal of Astronomical History and Heritage, 17(1), pp. 85-112

[2] Bradbury, R. (1980). *The stories of Ray Bradbury*. New York: Knopf.

[3] Taylor, F. W. (2014). *The scientific exploration of Venus*. New York, NY: Cambridge University Press.



Artist's conception of Venus, 1977 (Rick Guidice, NASA / ARC).

With the surface conditions highly hostile to life, interest in the settlement of Venus waned in favor of Earth's much smaller, more distant neighbor Mars. But it can be argued that Venus is perhaps an unfortunate victim of happenstance. Had its atmosphere stopped in its middle cloud layer, few would be focusing on Mars today. In this layer, between 51 and 57 km above the surface, exists generally earthlike air pressures and temperatures, on a world with earthlike gravity.[4] The atmosphere overhead, massing around the same as half a dozen meters of water, provides sufficient shielding that a solar radiation event of historic scale would not deliver a life-threatening dose.[5] Launch windows to and from Venus are frequent. Wind and solar energy are almost unfairly abundant. The science benefit of reduced latency for surface probes on Venus is far greater than on Mars. The scientific unknowns are greater, and with great implications for the formation of Earthlike worlds, the fate of Earth's climate, and the search for habitable exoplanets. Even the sparse smoggy particulate matter is more of a benefit than a hindrance - compatible with a significant range of structural materials, and readily decomposed with heat to yield oxygen and water or hydrogen.[6] The diversity of in-atmospheric resources on Venus outshines that of any other planet in the solar system. While local life has been argued to be possible,[7] reduced risks of contaminating the environment[8] makes manned and unmanned missions cheaper and simpler.

A sparse fog on Earth, analogous to Venus's middle cloud layer. Sunlight is diffuse with no distinct sun disc, only variations in brightness relative to direction and cloud density.

In short, habitats based around airships in this earthlike layer of the atmosphere - lifted by the very air that people breathe - is a scenario that begs comparison:

[4] Pätzold, M., Häusler, B., Bird, M. K., Tellmann, S., Mattei, R., Asmar, S. W., . . . Tyler, G. L. (2007). The structure of Venus' middle atmosphere and ionosphere. *Nature*, 450(7170), 657-660. doi:10.1038/nature06239
[5] Dartnell, L. R., Nordheim, T. A., Patel, M. R., Mason, J. P., Coates, A. J., & Jones, G. H. (2015). Constraints on a potential aerial biosphere on Venus: I. Cosmic rays. *Icarus*, 257, 396-405. doi:10.1016/j.icarus.2015.05.006
[6] Barbarossa, V., Brutti, S., Diamanti, M., Sau, S., & Demaria, G. (2006). Catalytic thermal decomposition of sulphuric acid in sulphur–iodine cycle for hydrogen production. *International Journal of Hydrogen Energy*, 31(7), 883-890. doi:10.1016/j.ijhydene.2005.08.003
[7] Landis, G. A. (2003) *Astrobiology: The Case for Venus*. Journal of the British Interplanetary Society; Volume 56; No. 7/8; 250-254
[8] *Planetary Targets for All Mission Categories*. NASA Office of Planetary Protection. Venus is Category II (*"only a remote chance that contamination carried by a spacecraft could compromise future investigations"*), while Mars orbiters are Category III; Mars landers are Category IV.

	Earth (equatorial)	Mars (median / Curiosity)	Moon (equatorial)	Small solar system bodies	Venus (54.5km, 70° latitude)
Gravity (g)	1	0.38	0.17	Very low	0.9
Air pressure (atm)	1	0.006	0	0	0.5
Day temp. (avg., °C)	25[A]	-40[B]	-25[C]	Usually low	25[D]
Diurnal variation (°C)	8-15[E]	90[B]	300[C]	Very high	15[D]
Day length (h)	24	24.5	336	Widely varied	48[F]
Local mobility	Moderate	Low	Low	High	High
Radiation shielding, meters of water mass equivalent	10.3[G]	0.06[G]	0[G]	0[G]	5.3[G]
Magnetic field	25-65 μT, intrinsic[H]	Weak, induced; 20-40 nT MPR, 5-20nT magnetosheath[I]	None	None	Weak, induced; 40-80 nT MPR, 10-40nT magnetosheath[I]
Health hazards	Those which humans evolved to	Fine, abrasive dust / silicosis[J]; perchlorates[K]; chromium(VI)[L]	Highly abrasive dust / silicosis[J]	Highly abrasive dust / silicosis[M]	Corrosive acid mists; numerous known and theorized chemicals[N]
Other local hazards	Those which humans evolved to	Marsquakes[O]; landslides; dust storms; solar storms. Others?	Moonquakes[O]; landslides; solar storms. Others?	Solar storms. Outgassing? Landslides? Poorly quantified.	Lightning? Gusts / shear? Icing? Storms? Limited data.[P]
Planetary protection	Not applicable	Category IV[Q]	Category II[Q]	Category I to II[Q]	Category II[Q]
Delta-V to destination, from LEO (km/s)	0	4.5[R]	6.1[R]	As low as 3.8, but usually well more[S]	3.5[R]
Delta-V to LEO (km/s)	10.1[R]	5.9[R]	5.6[R]	Low to extremely low	11.8[R]
Transit time (mo)	0	9[R]	0.1[R]	Widely varied	5[R]
Launch window frequency (mo)	0	25[T]	Several days per month[U]	Widely varied	19[T]
Aerobraking	Available	Available	Absent	Absent	Available
Parachute decel.	Significant	Limited	Absent	Absent	Significant
Surface hazards	Present	Present	Present	Present	Not approached[V]
Peak solar energy (29% triple junction W/m²)	<290[W]	~50[X], up to 129; sometimes almost none	400[Y] (but two weeks w/o light)	Widely varied	500[Z]
Wind energy resources	Moderate	Effectively none	None	None	High[F]
Diversity of resources	Baseline	Probably moderate to low[AA]	Probably low[AB]	Low	Probably high, but arid[AC]
Valuable resources	Moderate	Probably moderate to low[AA]	Moderate to low[AB]	High[AD]	Probably high[AE]
Accessibility of resources	Moderate	Moderate	Moderate	High but hindered by microgravity	High atmospheric, low surface

Summary of advantages and disadvantages of different destinations. Transits assumed to be minimum energy and use aerocapture. Basic planetary statistics from Moore (2000)[9]

[9]*A*: CRU TS3.0
B: Spanovich, N., Smith, M., Smith, P., Wolff, M., Christensen, P., & Squyres, S. (2006). Surface and near-surface atmospheric temperatures for the Mars Exploration Rover landing sites. *Icarus*, 180(2), 314-320. doi:10.1016/j.icarus.2005.09.014
C: Vasavada, A. R., Bandfield, J. L., Greenhagen, B. T., Hayne, P. O., Siegler, M. A., Williams, J., & Paige, D. A. (2012). Lunar equatorial surface temperatures and regolith properties from the Diviner Lunar Radiometer Experiment. *Journal of Geophysical Research*: Planets, 117(E12). doi:10.1029/2011je003987
D: (2005) *Venus Global Reference Atmospheric Model (Venus-GRAM)*. NASA/MSFC; 8.6°C greenhouse effect assumed (ambient = 16.6°C)
E: CRU TS3.0, in Timothy C. Bonebrake and Curtis A. Deutsch. 2012. Climate heterogeneity modulates impact of warming on tropical insects. *Ecology* 93:449–455.
F: VeRA-derived zonal winds (~70m/s) from Piccialli, A. (2010). *Cyclostrophic wind in the mesosphere of Venus from Venus Express observations*. Berlin: Uni-Edition.; diameter = 6051.8 + 54km; circumference = 38364km; at 70° = 12444km;; day

It may be best to look upon Venus as akin to an ocean-world, with the middle cloud layer as its “surface”. Down below, the environment is inhospitable and crushing; we do not explore and settle the oceans by living on the seabed. We live on their shores, spend time sailing their surfaces, and send submersibles down into their inhospitable depths. The same can be said for Venus: its hostile depths are adjacent to balmy tropical "shores", a cloudy environment upon which a lighter-than-air vehicles can float.

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length = velocity / circumference. Note that VIRTIS suggests a slower, ~40m/s windspeed; however, the VeRA measurements are evaluated to be more reliable due to its higher resolution deep sounding.

G: Based on pressure from (2005) *Venus Global Reference Atmospheric Model (Venus-GRAM)*. NASA/MSFC.

H: Finlay CC, Maus S, Beggan CD, Bondar TN, Chambodut A, Chernova TA, et al. International Geomagnetic Reference Field: the eleventh generation. *Geophys J* Int. 2010;183:1216–30.

I: Bertucci, C., Mazelle, C., Slavin, J. A., Russell, C. T., & Acuña, M. H. (2003). Magnetic field draping enhancement at Venus: Evidence for a magnetic pileup boundary. *Geophysical Research Letters*, 30(17). doi:10.1029/2003gl017271

J: Lam, C., James, J. T., Mccluskey, R., Cowper, S., Balis, J., & Muro-Cacho, C. (2002). Pulmonary Toxicity Of Simulated Lunar And Martian Dusts In Mice: I. Histopathology 7 And 90 Days After Intratracheal Instillation. *Inhalation Toxicology*, 14(9), 901-916. doi:10.1080/08958370290084683

K: Davila, A. F., Willson, D., Coates, J. D., & Mckay, C. P. (2013). Perchlorate on Mars: a chemical hazard and a resource for humans. *International Journal of Astrobiology*, 12(04), 321-325. doi:10.1017/s1473550413000189

L: Wise, J. T., Xie, H., Wise, J. P., Jr., Mason, M., Jeevarajan, A., Wallace, W., & Wise, J. P., Sr. (2015). Comparative toxicity of lunar, martian dust simulants and urban dust in human skin fibroblast cells. *Gravitational and Space Research*, 3(1), 51-58.

M: Asteroidal regolith hazards treated as equivalent to lunar regolith

N: Barsukov, V. L., Khodakovskii, I. L., Volkov, V. P., Sidorov, I. I., Dorofeeva, V. A., & Andreeva, N. E. (1982). Metal chloride and elemental sulfur condensates in the Venusian troposphere - Are they possible. Lunar and Planetary Science Conference, 12th, Houston, TX, March 16-20, 1981, Proceedings. Section 2. (A82-31677 15-91) New York and Oxford, *Pergamon Press*, 1517-1532.

O: Knapmeyer, M., Oberst, J., & Spohn, T. (n.d.). Of Moonquakes and Marsquakes. Final Colloquium DFG Schwerpunkt 1115,
2008-02-28 - 2008-02-29, Münster (Germany).

P: V. Linkin, V. Kerzhanovich, A. Lipatov, K. Pichkadze, A. Shurupov, A. Terterashvili, A. Ingersoli, D. Crisp, A. Grossman, R. Young, A. Seiff, B. Ragent, J. Blamont, L. Elson, R. Preston (1986). VEGA Balloon Dynamics and Vertical Winds in the Venus Middle Cloud Region. *Science.*

Q: *Planetary Targets for All Mission Categories*. NASA Office of Planetary Protection.

R: Minimum energy Hohmann transfer between LEO / habitat with aerocapture; other transfers covered in *Transfer to and from Venus*.. Atmospheric and gravity losses assumed at 2 km/s for Earth, 0.2 km/s for Mars, 0.1 km/s for Luna, and 1km/s for Venus; 0.9 km/s assumed for Mars landing, 0.5 km/s for the moon.. No budget for transfer contingency is made.

S: Benner, L. A. (2017, January 20). Near-Earth Asteroid Delta-V for Spacecraft Rendezvous. Retrieved from http://echo.jpl.nasa.gov/~lance/delta_v/delta_v.rendezvous.html

T: Synodic period $P_{SYN} = 1 / (1 / P1 - 1 / P2)$; P_{VENUS} = 243.025d; P_{EARTH} = 365.256d; P_{MARS} = 686.971d.

U: Wheeler, R. (2009). *Apollo lunar landing launch window: The controlling factors and constraints*. Retrieved from https://history.nasa.gov/afj/launchwindow/lw1.html

V: Does not land on surface; precision in location targeting not required.

W: Nominal clear-sky Earth surface 1000W/m^2 * 0.29. Operating condition baseline. Clouds and dust reduce generation.

X: Opportunity surface flux ~145W/m^2 from Lemmon, M. T., Wolff, M. J., Bell, J. F., Smith, M. D., Cantor, B. A., & Smith, P. H. (2015). Dust aerosol, clouds, and the atmospheric optical depth record over 5 Mars years of the Mars Exploration Rover mission. *Icarus, 251*, 96-111. doi:10.1016/j.icarus.2014.03.029. Multiplying * 0.29, unadjusted for temperature, flux or spectrum. Contrarily, the base flux of 591W/m^2 minus ~25% non-storm atmospheric absorption and times 0.29 is 129W.

Y: Earth/moon solar constant (1336W/m^2) * 0.29. Not adjusted for temperature, flux or spectrum.

Z: Data from Landis, G. A., & Haag, E. (2013). Analysis of Solar Cell Efficiency for Venus Atmosphere and Surface Missions. *11th International Energy Conversion Engineering Conference*. doi:10.2514/6.2013-4028. Interpolating between 50 and 54.5km height data to represent latitude-related losses and increasing by 1.6x for bidirectional exposure.

AA: West, M. D., & Clarke, J. D. (2010). Potential martian mineral resources: Mechanisms and terrestrial analogues. *Planetary and Space Science*, 58(4), 574-582. doi:10.1016/j.pss.2009.06.007 - bolide-formed ore deposits being the most interesting.

AB: Crawford, I. A. (2015). Lunar resources: A review. *Progress in Physical Geography*, 39(2), 137-167. doi:10.1177/0309133314567585 - most interesting being lunar KREEP resources, but processes for further enrichment are limited.

AC: Covered under *Chemical Environment, Envelope and Crew Considerations*.

AD: James, W. W., Zacny, K., Craft, J., Chu, P., & Cohen, M. M. (2014). Robotic Asteroid Prospector (RAP) NIAC Phase 1 Results. 7th Symposium on Space Resource Utilization. doi:10.2514/6.2014-0500

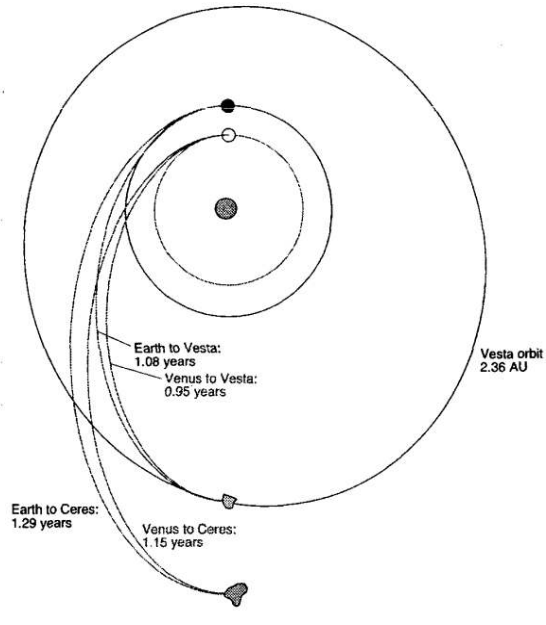
AE: Covered under “Mineral Resources and Economics”.

Other: Moore, P. (2000). The Data Book of Astronomy. CRC Press. ISBN 9781420033441 - CAT# IPE702

An analysis of such “cities in the clouds” was considered by Geoffrey Landis in 2003.[10] When considering how to loft aerial vehicles on Venus, it became apparent that two lifting gases are most readily available: nitrogen and oxygen, both of which are lighter than carbon dioxide and yield around half as much lift as an equivalent volume of helium on Earth. One immediately notes the consequence: in a Landis habitat, the air inside the envelope is thus breathable, rendering large amounts of space therein available for habitation, agriculture, etc. This stands in contrast to that of alternative proposals, such as the early phases of HAVOC, where housing is slung underneath the envelope,[11] and is thus subject to the same size constraints that dog habitats on the surface of Mars.

While it may be instinctive to assume that the choice of Venus as a destination stands in competition with the settlement of other locations in the solar system, in practice it proves far more complimentary. With delta-V requirements similar to Mars, shorter transit times, ample sunlight en-route and an easier descent, the same transfer vehicle developed to take cargo and crew to Mars can be readily designed to be suitable for Venus service as well. Misalignment of synodic periods between Venus and Mars provide an opportunity to use transfer stages that would otherwise be sitting idle. And while basic habitats and resources on Mars are quite different, production chains converge. The Haber process does not care whether its nitrogen came from the atmospheres of Venus or Mars, or whether its hydrogen came from Venusian sulfuric acid or Martian permafrost. Synthesis of polyethylene from syngas is independent of whether that syngas came from the Sabatier reaction on air from Venus or Mars. And so forth - while there can occasionally be differences due to gravity or impurities in feedstocks, much of the same hardware developed for Mars can be used on Venus, and vice versa - from 3d printers to pipe extrusion to the countless small items, from power sockets to kitchen appliances.

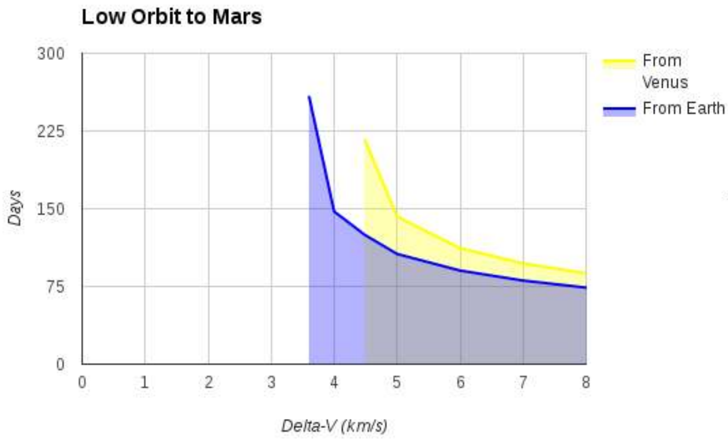
Counterintuitively, Mars and the asteroid belt are more accessible from Venus than from Earth. As the diagram to the right illustrates, minimum energy trajectories are advantaged by the high angular momentum of Venus, a phenomenon known as the Oberth effect.



Reproduced from Landis 2003[12]

Complicating the matter, the delta-V involved in minimum energy transfers from Venus and Earth to the asteroid belt do not involve the same minimum energies; the minimum energy from Venus is significantly higher. For an equivalent comparison, one needs to compare transfer times for equivalent amounts of delta-V. Let us do so for transits between Earth, Venus and Mars:

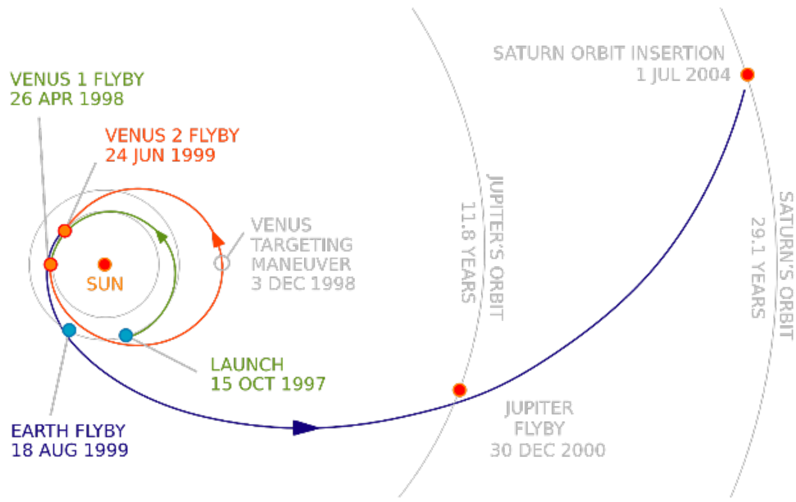
[10] Landis, G. A. (2003). Colonization of Venus. AIP Conference Proceedings. doi:10.1063/1.1541418
[11] Arney, D. C., & Jones, C. A. (2015). High Altitude Venus Operational Concept (HAVOC): An Exploration Strategy for Venus. AIAA SPACE 2015 Conference and Exposition. doi:10.2514/6.2015-4612
[12] Landis, G. A. (2003). Colonization of Venus. AIP Conference Proceedings. doi:10.1063/1.1541418



Transfers will be discussed in greater detail under *Transfer to and from Venus*

One can see that for the same amount of delta-V, transfers from Venus to Mars would appear to take slightly longer than from Earth. However, this can be deceptive. As Venus's synodic period is shorter, launch windows open up more frequently from Venus than from Earth; the above figures are only valid for closest approach, and are vastly increased when the bodies' orbital positions are mismatched.

Even when Earth is relatively lined up for a short conjunction transfer, this serves to open up an Earth gravitational assist for craft from Venus, decreasing their transit times significantly. Indeed, frequent gravitational assist opportunities are one of the great benefits of Venus's orbital environment; probes from Earth to the outer solar system frequently launch toward Venus to take advantage of one or more gravitational assists, often including Earth assists on the way back out.



The trajectory of NASA's Cassini probe, making use of two Venus flybys followed by an Earth flyby to boost it to Saturn[13]

While human habitation of other worlds is often seen as a way to provide a backup in case of a disaster on Earth, these far more fragile outposts are themselves much more likely to suffer a catastrophe. And in the event of a catastrophe on Mars or elsewhere in the solar system, Venus is more likely to be better positioned than Earth to send aid, should the type

[13] Cassini Mission to Saturn. (NASA / Jet Propulsion Laboratory -Caltech). Retrieved from https://saturn.jpl.nasa.gov/resources/1776/

of aid needed be on hand. Venus and Mars are not competitors in terms of expanding the human presence; they are allies.

Developing an environment for the safe, long-term sustainable habitation of Venus is not trivial. The favorable orbital environment of Venus is tempered by having to deal with the very factors that makes Venus such a good location for human health; being Earthlike means that it's hard to reach orbit, just as on Earth. Like Earth, Venus has storms, with turbulence reminiscent of Earth's troposphere.[14] Like Earth, lightning is present on Venus, although its nature and location is still uncertain.[15] Venus's atmospheric chemical environment, while a source of resources, also must be dealt with properly in habitat design. And Venus's surface, while likely holding a wealth of resources and great potential to advance our scientific knowledge, is a harsh environment for probes to operate in.

The purpose of this book is to address all of these issues, and many more, in order to observe how they influence the design and development of an initial Venus habitat, as well as the future habitation of Venus.

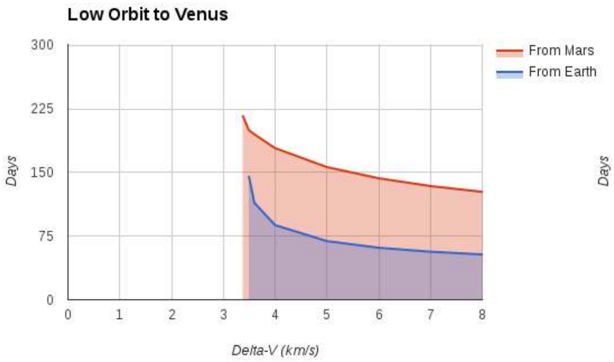
[14] V. Linkin-V. Kerzhanovich-A. Lipatov-K. Pichkadze-A. Shurupov-A. Terterashvili-A. Ingersoli-D. Crisp-A. Grossman-R. Young-A. Seiff-B. Ragent-J. Blamont-L. Elson-R. Preston (1986). VEGA Balloon Dynamics and Vertical Winds in the Venus Middle Cloud Region. *Science.*

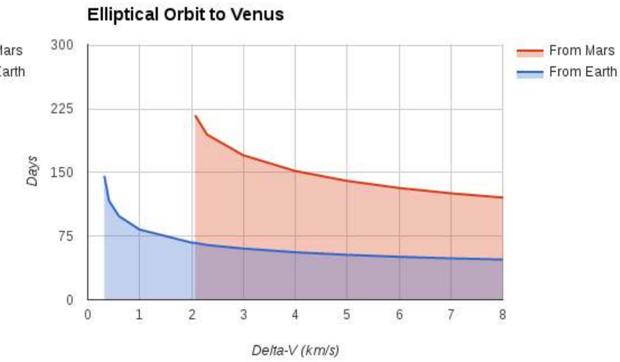
[15] Majid, W. (2015). A Low-Cost Approach to the Investigation of Venus Lightning. EGU General Assembly 2015, 12-17 April. Bibtex:.147002015EGUGA..1714700M

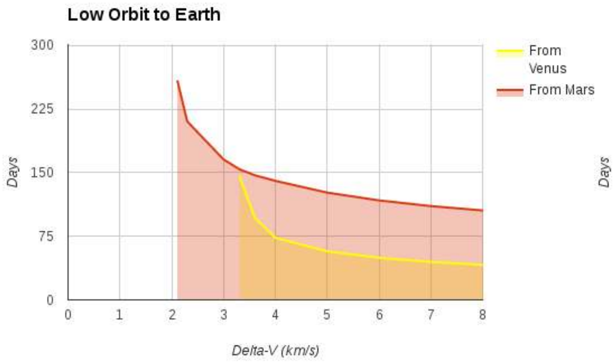
2. Getting There And Back

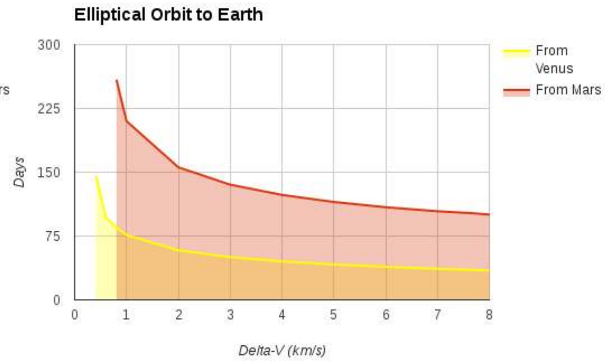
Transfer to and from Venus

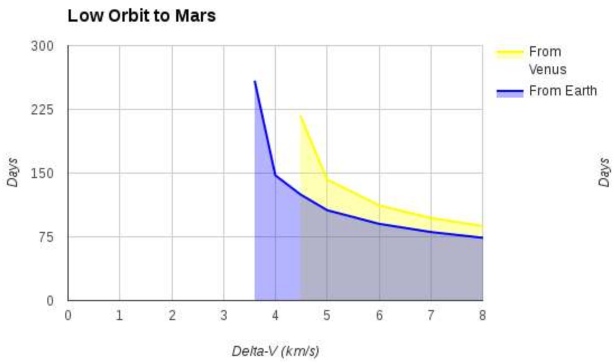
As discussed previously, Venus in an excellent location for reaching other destinations due to the Oberth effect.

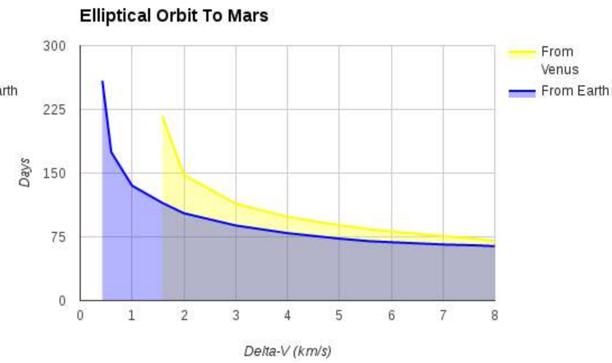












In the above graphs, we plot the time between different destinations versus delta-V on conjunction-class missions. On the left, low orbits are assumed (150km for Mars, 250km for Earth, 350km for Venus). On the right, extremely elliptical orbits are assumed, with apoapsis at the radius of the planet's sphere of influence (57007km for Mars, 911969km for Earth, 606119km for Venus), as an upper bound. Only the energy required to enter a transfer orbit is plotted (that is, as if the transfer stage were aerocaptured[16]).

It becomes immediately clear that Venus is in a very favorable position from an orbital dynamics perspective, while Mars is in a poor one. Excepting minimal energy

[16] Lockwood, M. K., Paulson, J. W., Kontinos, D. A., Chen, Y.K., Laub, B., Olejniczak, J., ... (2006). *Systems Analysis for a Venus Aerocapture Mission*. NASA STI Program, NASA/TM-2006-214291: Concerning the TRL of HYPAS aerocapture to Venus: "*Based on this study there are no enabling technologies required to accomplish this mission. There are, however, strongly enhancing technologies that will significantly help such missions*"

transfers, a transfer from Venus to Mars is nearly as fast as a transfer from Earth to Mars - not accounting for the potential of Earth gravitational assists and the benefit of more frequent launch windows. Unlike Mars, the strong Oberth effect at Venus allows for very fast, efficient return trajectories to Earth.

Like Mars, Venus also has a number of cycler trajectories available to it - although not as well studied as in the case of Mars. Cyclers allow one to have a large amount of mass (such as radiation shielding and passenger facilities) repeatedly making flyby passes. While small spacecraft carrying crew still need to expend the same or greater delta-V as for a direct transfer in order to dock with a cycler, the large shielding / habitation mass does not need to be accelerated each time.

A particularly studied case of cyclers for Venus use is the E-E-V-V-V cyclers - that is, two consecutive Earth passes followed by three consecutive Venus passes. Of the 12 orbits studied in Hollister et al 1970,[17] we select, in order of priority:

- **#3**: This cycler orbit offers the shortest transit times on the Earth-Venus and Venus-Earth legs.
- **#2**: Offering the fourth shortest average transit times, this route is staggered from the #3 cycler by as much as 2 months at times.
- **#8**: Similar to the #3 orbit, this yields the second shortest transit times and occasionally is staggered vs. #3 and #2.

A sample cycler timetable, based on the figures from the above paper, can be seen below, with the day of closest approach indicated and transit times (in days) in parentheses.

	Departure			**Arrival**		
	#3	**#2**	**#8**	**#3**	**#2**	**#8**
E→V		780 *(134)*			914	
			819 *(189)*			
	877 *(132)*			1009		1008
V→E	1462 *(78)*		1458 *(81)*	1540		1539
		1470 *(150)*			1620	
E→V		1979 *(107)*			2086	
	2034 *(115)*		2034 *(115)*	2149		2149
V→E	2599 *(98)*		2599 *(98)*	2697		2697
		2643 *(119)*			2762	
E→V		3127 *(125)*			3252	
	3190 *(118)*		3190 *(118)*	3308		3308
V→E	3758 *(127)*		3758 *(131)*	3885		3889
		3809 *(118)*			3927	
E→V		4293 *(133)*			4426	
	4374 *(118)*		4374 *(118)*	4485		4485
V→E		4873 *(235)*		5039		5039
	4935 *(104)*		4935 *(104)*		5108	
E→V		5473 *(117)*			5590	
	5533 *(108)*		5534 *(111)*	5641		5645
V→E	6091 *(135)*		6095 *(203)*	6226		
		6147 *(112)*			6259	
						6298

More diverse launch windows (sometimes including shorter transfer times) can be achieved by Earth-Venus-Mars three-body cyclers.

[17] Hollister, W. M., & Menning, M. D. (1970). Periodic swing-by orbits between Earth and Venus. *Journal of Spacecraft and Rockets*, 7(10), 1193-1199. doi:10.2514/3.30134

Conversely, if the goal is to deliver maximum payload from Low-Earth Orbit to Venus, solar-electric propulsion can be employed. Delinitz et al (2006) calculated a 1.8 year trajectory (without aerocapture) at slightly less than 4000 m/s dV.[18] Similarly, Kemble (2003) calculated a 1.23 year trajectory requiring 3800 m/s dV and a 2.8 year trajectory requiring 2700 m/s dV.[19]

To determine what sort of trajectories are best to deliver manned and unmanned payloads to Venus, we first must look at what may constrain the size of the habitat, and how that will affect the delta-V requirements of the transit stage.

Airdocks

If one wishes to avoid the expense of constructing a new building, the maximum size of an initial habitat is limited to the size of existing airship hangars. As even a large envelope packs well into a variety of extant rocket fairings without excessive weight, targeting as large of a habitat as possible is desirable for maximizing local capabilities and simplifying transport of manned payloads.

Due to the decline of lighter than air transport on earth in the 20th century, some large airdocks have high availability. Others are in service for various purposes, generally of a far lower value than the cost to construct such a building. The largest airdocks in the world in the world are, in increasing order of height:

Photo: Sam Beebe

1) **Tillamook Hangar B**

59m x 90m x327m

Built in 1942 near Tillamook, Oregon, it remains the world's largest clear-span wooden structure. The reason for its construction was to simultaneously house eight large dirigibles for hunting submarines. Today it functions as the home of the Tillamook Air Museum.

Photo: NASA

2) Moffett Federal Airfield, Hangar One

60m x 90m x 343m

Built in 1933 to house the USS Macon and USS Akron, it is today one of the most recognizable landmarks in Silicon Valley. The hangar is currently owned by NASA and leased to Google; the colocated Hangar Two is apparently being used to build a large rigid airship of unknown purpose.[20]

[18] Dellnitz, M., Junge, O., Post, M., & Thiere, B. (2006). On target for Venus – set oriented computation of energy efficient low thrust trajectories. *Celestial Mechanics and Dynamical Astronomy*, 95(1-4), 357-370. doi:10.1007/s10569-006-9008-y

[19] Kemble, S. (2003). *Interplanetary Missions Utilising Capture and Escape Through Lagrange Points.* 54th International Astronautical Congress of the International Astronautical Federation, the International Academy of Astronautics, and the International Institute of Space Law. doi:10.2514/6.iac-03-a.1.01

[20] Vance, A (25 Apr. 2017) *With Secret Airship, Sergey Brin Also Wants to Fly*. Bloomberg.

Photo: Conring Automation Services

3) Goodyear Airdock
64.31m x 99m x 358m

Built in 1929 in Akron, OH, it served as the construction site for the USS Macon and the USS Akron. The Goodyear Airdock has changed hands many times over the years, and is currently owned by Lockheed Martin.

Photo: Horace Hagen

4) Lakehurst Hangar No. 1
68m x 110m x 294m

Built in 1921 in Lakehurst, NJ and used for storage and maintenance of the largest airships at the time when on the east (including the LZ 127 Graf Zeppelin, USS Macon, USS Akron and the LZ 129 Hindenburg). Today it houses a fake flight deck for naval training.

Photo: Immanuel Giel

5) CargoLifter Aerium:
106m x 220m x 360m

The only large airship hangar constructed after the Second World War, as well as by far the largest ever built and the only of the giant hangars remaining outside the US (with the arguable exception of the old Zeppelin hangar outside Rio de Janeiro). The $110M CargoLifter Aerium in Brandenburg, Germany was completed in 2000 - shortly before CargoLifter's bankruptcy in 2002. It was thereafter purchased by a private company at a small fraction of its construction cost and converted into a tropical theme park; while the company ran at a loss for several years due to disappointing attendance figures, it finally began to turn a profit in 2008.

From looking at existing airdocks that could be used for construction (eg. Hangar One) and assuming that one requires a minimum of ten meters extra on each axis for construction and maneuvering, then we get a maximum sized ellipsoidal airship of ~50x80x330 meters. This has a volume of 691 thousand cubic meters. Floating at a daytime average of 0.5 bar pressure (see *Deployment: Where and How*) and with a 60%/40% N_2/O_2 internal mixture, with the interior temperature at 25°C and the exterior temperature 17°C, the exterior air density is 0.93 kg/m³ and the interior air density s 0.60 kg/m³, yielding a net lift of

0.33 kg/m³. Thus, we arrive at a maximum daytime lift of 228 tonnes. At night, lift drops and the craft descends to denser, warmer air - offsetting Venus's cooler nighttime conditions.

Next, in order to determine our trajectory we must consider how much delta-V an ascent vehicle on the Venus end can provide, to determine whether the Earth-Venus transfer stage must go to a Low-Venus orbit or may enter into an easy-to-escape highly elliptical orbit.

Propellant options

There is no shortage of potential options for propellants that can be used and which have been researched extensively. However, Venus's environment changes the calculus, in a number of manners:

1) Staging and recovery is more complicated
2) Hydrogen is rarer. Fluorine all the moreso. Metallic additives or propellants are difficult to acquire.
3) Cryogenics are challenging to deal with on Venus due to convective heat transfer.
4) ISRU (in-situ resource utilization) requires that all propellants be locally manufacturable without excessively complex production chains

Let us examine a variety of propellant combinations that meet ISRU-simplicity standards.[21]

[21] *All specific impulses cited are vacuum, calculated with CEA2 in equilibrium conditions at a 70 bar and a 40:1 expansion ratio; all are assumed at their boiling point, except propane, which is assumed to share a common bulkhead with LOX be at 100°K, and RP1, which is assumed to be at 25°C. Mixture boiling points and densities assumed to scale linearly, excepting nytrox densities. Listed boiling points are for 1 bar. Mixture percentages are by mass.*

Oxidizer	Boil. °K	ISRU diff.	Fuel	Boil. °K	ISRU diff.	O:F ratio	ISP (sec)	Density (g/cm³)	Comb. temp. °K	% H
LOX	90.2	1	LH	20.7	1	4.70	455	0.31	3197	18
LOX	90.2	1	CH_4	112	1.5	3.37	371	0.82	3566	5.8
LOX	90.2	1	C_3H_8	231	2.6	2.98	365	1.02	3649	4.5
LOX	90.2	1	RP-1	420	3	2.66	356	1.03	3741	4.2
LOX	90.2	1	CO	81.6	1	0.53	281	0.88	3452	0
LOX	90.2	1	C_2N_2	252	3.2	0.85	349	1.03	4431	0
LOX	90.2	1	C_2H_2	191	3	1.79	391	0.87	4196	2.8
N_2O_4	295	2	MMH	364	5	2.37	341	1.20	3125	3.9
N_2O_4	295	2	LH	20.7	1	6.85	397	0.41	3031	13
N_2O_4	295	2	CH_4	112	1.5	5.36	337	1.05	3361	4.0
N_2O_4	295	2	RP-1	420	3	4.32	334	1.26	3524	2.5
N_2O_4	295	2	CO	81,6	1	0.79	276	0.99	3292	0
N_2O_4	295	2	C_2N_2	252	3.2	1.37	330	1.18	4047	0
N_2O_4	295	2	C_2N_2- CH_4 10%	238	3.4	1.77	331	1.18	3767	0.9
N_2O_4	295	2	C_2N_2- CH_4 20%	224	3.4	2.15	332	1.18	3652	1.6
N_2O_4	295	2	C_2N_2- H_2 5%	240	3.3	1.76	337	1.19	3754	1.8
N_2O_4	295	2	C_2H_2	191	3	2.86	357	1.07	3950	2.4
N_2O	303/253/193	2	LH	20.7	1	12.8	348	0.40/0.51/0.56	3065	7.3
N_2O	303/253/193	2	CH_4	112	1.5	10.7	316	0.60/0.91/1.06	3308	2.2
N_2O	303/253/193	2	CO	81.6	1	1.56	281	0.68/0.91/1.01	3247	0
N_2O	303/253/193	2	C_2N_2	252	3.2	3.01	318	0.68/1.00/1.16	3799	0
N_2O	303/253/193	2	C_2H_2	191	3	6.27	331	0.62/0.99/1.09	3777	1.1
Nytrox 20%	253/193	2.2	LH	20.7	1	9.55	374	0.41/0.47	3111	9.5
Nytrox 20%	253/193	2.2	CH_4	112	1.5	7.69	330	0.76/0.98	3392	2.9
Nytrox 20%	253/193	2.2	CO	81.6	1	1.15	283	0.82/0.96	3309	0
Nytrox 20%	253/193	2.2	C_2N_2	252	3.2	2.02	328	0.88/1.10	3996	0
Nytrox 20%	253/193	2.2	C_2N_2- CH_4 10%	238	3.4	2.64	328	0.85/1.07	3744	0.7
Nytrox 20%	253/193	2.2	C_2N_2- CH_4 20%	224	3.4	3.21	328	0.83/1.04	3642	1.2
Nytrox 20%	253/193	2.2	C_2N_2- H_2 5%	240	3.3	2.60	337	0.76/0.92	3741	1.4
Nytrox 20%	253/193	2.2	C_2H_2	191	3	4.19	348	0.79/1.00	3922	1.5
Nytrox 35%	193	2.2	LH	20.7	1	7.83	393	0.41	3108	11
Nytrox 35%	193	2.2	CH_4	112	1.5	6.31	340	0.90	3440	3.4
Nytrox 35%	193	2.2	CO	81.6	1	0.95	283	0.91	3345	0
Nytrox 35%	193	2.2	C_2N_2	252	3.2	1.62	334	1.03	4108	0
Nytrox 35%	193	2.2	C_2N_2- CH_4 10%	238	3.4	2.10	334	1.00	3821	0.8
Nytrox 35%	193	2.2	C_2N_2- CH_4 20%	224	3.4	2.57	335	0.97	3709	1.4
Nytrox 35%	193	2.2	C_2N_2- H_2 5%	240	3.3	2.10	344	0.85	3804	1.6
Nytrox 35%	193	2.2	C_2H_2	191	3	3.38	358	0.93	3998	1.8

Many examples analyzed for this work are not included in the above table. For example, oxidizers such as nitric acid and hydrogen peroxide offer limited performance while involving significant amounts of hydrogen. UDMH involves more complicated production chains than MMH, DETA more complicated than UDMH, Syntin and other strained-ring hydrocarbons more complicated still. Any hydrocarbon fuels, such as varying alkanes, simply have performance intermediary to entries on the above table and are not worth breaking down individually.

Hydrolox famously has a superb specific impulse, tempered by its low density; it is commonly used, particularly effectively on upper stages. On Venus its advantages are further tempered by its extreme use of hydrogen resources and its deeply cryogenic nature.

The various simple alkane mixtures with LOX still require moderate cryogenic conditions for the LOX, regardless of whether the propellant itself requires it. However, they significantly reduce the hydrogen requirement.

We list one conventional hypergolic combination, N_2O_4 / MMH. N_2O_4 is generally utilized as MON (Mixed Oxides of Nitrogen), containing small amounts of NO, ranging from around 1% to 30%. This helps control corrosion, increase vapour pressure and lowers the freezing point, at the cost of a small amount of specific impulse.[22] The main disadvantage to this fuel and oxidizer combination, apart from somewhat poorer specific impulse, is that the dependency chains for MMH production are fairly long.

MON, however, raises interesting possibilities. It's not cryogenic, and thus very storable. Its reduction in specific impulse comes with increased density. It burns with a higher O:F ratio, and thus uses less fuel - including any hydrogen in that fuel. And lastly, it lowers the combustion temperature. A downside is its toxic nature.

When burned with fuels like hydrogen, and to a lesser extent alkanes, its benefits are somewhat tempered. The chamber temperature reduction is not very significant, while the specific impulse reduction can be significant. But with two exotic fuels - carbon monoxide and cyanogen - its benefits really stand out.

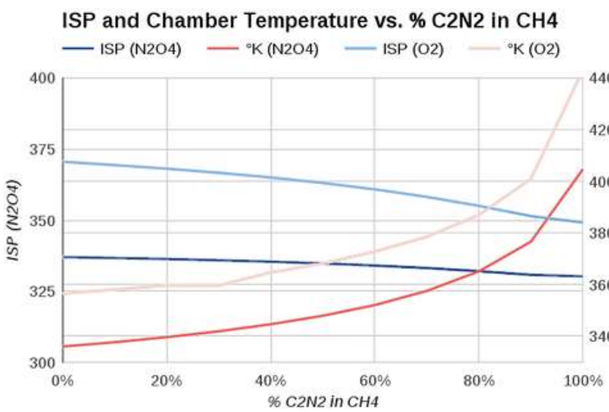
Carbon monoxide is a relatively little studied fuel, with some experiments done for the potential of ISRU on Mars (burned with LOX).[23] It is completely hydrogen free, and simple to produce - for example, via a SOFC similar to MOXIE on Mars 2020.[24] Its benefits somewhat trail off at this point; its density is unimpressive, it is cryogenic (moreso than LOX), and its specific impulse is poor.

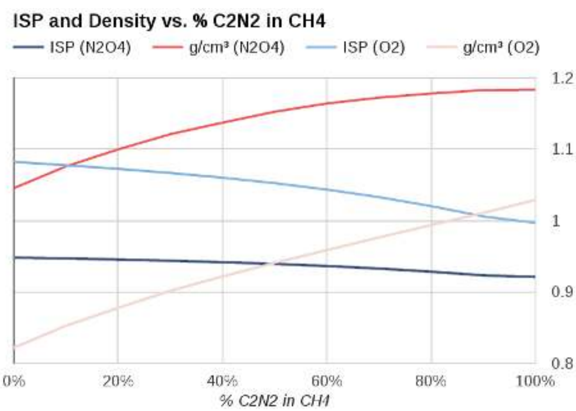
[22] Sutton, G. P., & Biblarz, O. (2001). *Rocket Propulsion Elements* (7th ed.) (pp .254-255). John Wiley & Sons.
[23] Linne, D. L. (1991). Carbon Monoxide and Oxygen Combustion Experiments: A Demonstration of Mars In-Situ Propellants. *AIAA-91-2433*. NASA Technical Memorandum 104473
[24] Mars Oxygen ISRU Experiment (MOXIE). Retrieved from http://mars.nasa.gov/mars2020/mission/instruments/moxie/for-scientists/

The use of cyanogen as a propellant is even less mature than for carbon monoxide, although it has drawn some limited interest.[25] While it too boasts of being completely hydrogen-free and having a decent specific impulse (as well as the ability to be polymerized into a solid/hybrid fuel), it has the second-highest known adiabatic flame temperature of any naturally-occurring compound after dicyanoacetylene[26] (the latter being unsuitable for use as a fuel due to its explosive nature). While high temperature, reusable ceramic engines are possible, they are immature and pose significant challenges. The most significant demonstration of a ceramic engine thusfar was in the Akatsuki spacecraft (ironically, a mission to Venus), which suffered a nozzle failure en route and nearly led to the failure of the mission.[27] While the failure was the fault of out-of-design combustion conditions due to a stuck valve and not of the ceramics themselves, they do expose the risk of a ceramic engine for a Venus habitat: a shattered ceramic nozzle is not a form of damage that could potentially be repaired in-situ.

Two alterations to the propellant mixture, however, make cyanogen much more appealing. One is to burn it with MON rather than LOX, which drops combustion temperatures by 400°, giving up a small amount of ISP in exchange for greater density and a non-cryogenic oxidizer. The other is to burn a small amount of a hydrogen-bearing material, such as methane or hydrogen, along with the cyanogen.

The net effects of these on performance can be seen below. In each of the first two graphs, pure methane is on the left and pure cyanogen is on the right.



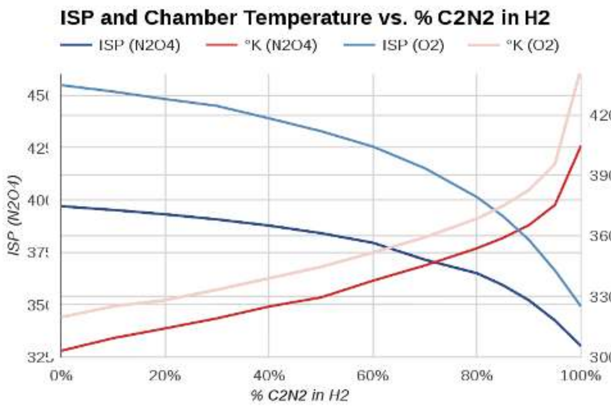


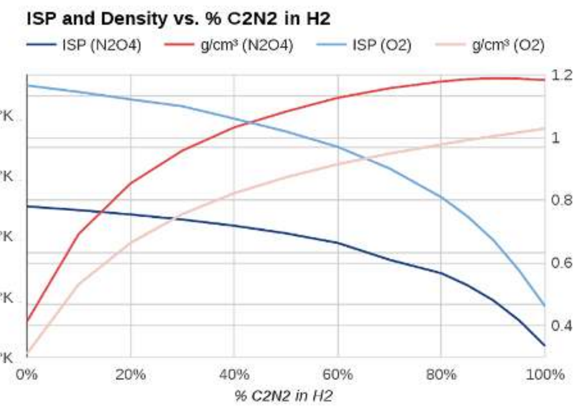
In each of the next two graphs, pure hydrogen is on the left and pure cyanogen is on the right.

[25] Brotherton, T. K., & Lynn, J. W. (1959). The Synthesis and Chemistry of Cyanogen. *Chem Rev., 59*(5), pp 841–883. doi:10.1021/cr50029a003

[26] Kirshenbaum, A.D. & Grosse, A. V. (1956) The combustion of carbon subnitride, C4N2, and a chemical method for the production of continuous temperatures in the range of 5000-6000°K. Journal of the American Chemical Society. *78* (9), 2020-2020. doi: 10.1021/ja01590a075

[27] Lakdawalla, E. (2010, December 10). Akatsuki update: Failure to enter orbit due to insufficient fuel pressure. Retrieved from http://www.planetary.org/blogs/emily-lakdawalla/2010/2821.html





As can be seen, the majority of the benefits occur at only very small amounts of hydrogen addition, while the majority of the negatives do not. These properties make cyanogen + methane (CyMet) and cyanogen + hydrogen (CyHy) appealing options. It is not clear whether MON would be hypergolic with either, although given MON's tendency toward hypergolic ignition, it would not seem unlikely.

An interesting alternative to MON where self-pressurization is desired is nitrous oxide and its mixtures with oxygen (Nytrox). Nitrous oxide is much less toxic than nitrogen tetroxide; mixtures with oxygen increases specific impulse and safety. Pressures range from insignificant (low temperatures and oxygen fraction) to a high 65 bar (room temperature, low oxygen fraction) to a very high 120 bar (low temperature, high oxygen fraction). A downside to Nytrox is its lower density vs. MON; specific impulse is lower at low oxygen fractions but becomes more LOX-like at higher oxygen fractions; the same trend follows for flame temperatures.[28] In general, Nytrox would be more appealing than MON where high levels of self-pressurization and/or use with low temperature fuels are desired.

On the fuel side, acetylene presents an interesting alternative to cyanogen mixtures or triprops. Versus CyHy, for a given propellant hydrogen percentage it offers 10-15 sec greater I_{SP} but 100-150°C higher chamber temperature. Density is around 90% that of CyHy for MON and pure nitrous oxide, but becomes superior as the oxygen fraction increases in Nytrox. Acetylene is moderately cryogenic, with a boiling point 63°C below that of cyanogen at its minimum liquid pressure (1.27 atm). All of these properties suggest that acetylene would be a more preferable fuel for upper stages while cyanogen fuels would be superior for lower stages. Unlike cyanogen, acetylene is not particularly toxic; however, while stable as a liquid, it becomes increasingly unstable and prone to self decomposition at higher temperatures. It has been considered for use as a propellant on Mars.[29]

A note on toxicity: while of relatively limited importance on Venus, the use of toxic propellants can increase development and handling expenses on Earth. Of fuels in the above table, monomethylhydrazine, carbon monoxide, and cyanogen have significant toxicity. Of

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[28] Karabeyoglu, A. (2009). Mixtures of Nitrous Oxide and Oxygen (Nytrox) as Oxidizers for Rocket Propulsion Applications. *45th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*. doi:10.2514/6.2009-4966

[29] Landis, G. A., & Linne, D. L. (1992). Acetylene fuel from atmospheric CO2 on Mars. *Journal of Spacecraft and Rockets*, *29*(2), 294-296. doi:10.2514/3.26350

the latter two, cyanogen has an LC50 approximately 1/10th that of carbon monoxide[30]. However, cyanogen is irritating at low concentrations, while carbon monoxide's symptoms are subtle up to the point of incapacitation. Cyanogen also has, unlike carbon monoxide, an antidote (amyl nitrite) and a better post-exposure prognosis.

Now that we have some of our options for getting off of Venus, let us examine the staging required, and the implications that has for the Earth-Venus transfer stage.

Staging options

Returning to our 228 tonne-lift airship: roughly how much lift do we have for the ascent vehicle? In part, it depends on how many crew we wish it to support. Some visions for colonization seek to start small, with only a few colonists, while others seek to start off with dozens or even hundreds. Let us begin by arbitrarily selecting a 10 person target for the initial habitat.

Most things in the habitat are surprisingly light. Physically largest is the envelope - in this case, taking up 54k m². Typical envelopes for proposed robotic Venus missions range from around 40g/m² for the VEVA balloon/multi-dropsonde concept[31] to 173.2g/m² for VALOR.[32] Ballute entry was estimated by McRonald to only require a 22g/m² envelope for one of their test scenarios (57g/m³ when all of the associated hardware is counted along with the envelope).[33] [34] While envelope design is a complex aspect which will be discussed later, there is some thickness which is required regardless of scale - such as to resist chemical attack and gas permeation - as well as some thickness which scales with the radius of the habitat, such as tensile strength. Tensile stresses also correlate with overpressure (which is much higher for probes than for a habitat). On Earth, airship envelope fabrics range widely in density based on what materials they're made out of, but generally in the low hundreds of grams per square meter (e.g., Zeppelin NT, PVF+polyester at 250g/m²)[35]. Airships on Earth must deal with a high permeation gas (helium). High mass lifting gases (oxygen, nitrogen) and advanced materials can reduce the envelope mass, as can various options for rigid reinforcement (see *Design*). Large scales, hostile environments and the unknowns of Venus can increase it.

Without sufficient data to arrive at a more precise figure, we will for the sake of argument choose a baseline target of 250g/m², including reinforcement. We thus arrive at an envelope plus reinforcement mass of 13.5 tonnes (versus, say, 54.4 tonnes LEO launch

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30 Patnaik, P., & Patnaik, P. (2007). *A comprehensive guide to the hazardous properties of chemical substances* (3rd ed.) (pp. 326-327, 403-404). Hoboken: John Wiley & Sons.
31 Kerzhanovich, V. V., Cutts, J. A., & Hall, J. L. (2003) Low-cost balloon missions to Mars and Venus. 16th ESA Symposium on European Rocket and Balloon Programmes and Related Research. SA Publications Division, ISBN 92-9092-840-9 (pp. 285 - 291)
32 Hall, J., Fairbrother, D., Frederickson, T., Kerzhanovich, V., Said, M., Sandy, C., . . . Yavrouian, A. (2008). Prototype design and testing of a Venus long duration, high altitude balloon. *Advances in Space Research, 42*(10), 1648-1655. doi:10.1016/j.asr.2007.03.017
33 Hall, J. (2000). A review of ballute technology for planetary aerocapture. 4th IAA Conference on Low Cost Planetary Missions, Laurel, MD, May 2-5.
34 McRonald, A.D. (1999). A lightweight inflatable hypersonic drag device for Venus entry. AAS/AIAA Astrodynamics Specialist Converence, Girdwood, AK, August 16-19
35 Achat, D (2008). Zeppelin NT - Technical Data. Retrieved from https://www.carnetdevol.org/zeppelin/Technical.html

capacity for the Falcon Heavy,[36] and 70-130 for SLS[37]). Such an envelope can be readily packed into a typical heavy lift rocket fairing.[38]

We now add payload. Ten people at 75kg each, with 50kg furnished housing with 15kg of water stored and 25kg worth of personal possessions does little to add to the mass (1.7 tonnes). Twenty months of stored food at 3000 kcal/day and 2kcal/g does more to increase the mass, but not tremendously so (9.2 tonnes). As for food production, 2015 US corn harvests were 169.3 dry bushels per acre,[39] or 1.06 kilograms per square meter. Dry corn is approximately 4,200kcal/kg[40] - in short, a person requires the annual caloric output of around 250 square meters. This matches estimates of estimates of land requirements for vegetarian diets on Earth.[41] In the bright, lit-from-all-sides never-winter environment of Venus, we will assume the equivalent of two crops per year, thus halving the area to 125 m².

Assume that on Venus, averaged, between all crops (including less productive ones), and including any animal conversion of agricultural waste, no starting of seedlings in reduced space, that the average person requires the output of 200 square meters (2000 m² total, versus a habitat cross section of around 21000 m²). Let us assume also a running average of 5kg of plant + hydroponics mass per square meter (covered under *Agriculture*). This works out to 10 tonnes. Water, common facilities and hardware, control/propulsion, scrubbing, power storage / lift maintenance, manufacturing, stockpiled materials, ballonet fabric, ISRU / atmospheric control and so forth add at least a few dozen tonnes (see *Mass budget*). In short, a mature habitat of this size with a 10-person crew would mass at least 60 tonnes of dead mass, leaving no more than around 170 tonnes to spare for the ascent vehicle.

Therein lies the rub: one cannot carry a conventional chemical rocket with the potential to take everyone to a highly elliptical, near-escape orbit with a loaded mass of 170k tonnes. Based on existing and proposed crew vehicles on Earth, a 10-person Venus-reusable capsule with no cargo (less if cargo is being returned) is likely to mass 10-12 tonnes fully loaded, even if built light and reentry heating is minimized. The following table lists examples of how a selection of various rockets would perform merely for Low-Venus Orbit (LVO = ~8.6 km/s delta-V, including ascent losses and orbital maneuvering / deorbit).

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36 SpaceX. *Falcon Heavy*. Retrieved from http://www.spacex.com/falcon-heavy
37 Boeing. *Space Launch System*. Retrieved from http://www.boeing.com/space/space-launch-system/
38 At a packing density of 3:1 and a fabric mass density of 1.3g/cm³, the packing size is 42m³, taking up on the order of 10-20% of the volume of a typical heavy lift rocket fairing, and a tiny fraction of the fairing of a super-heavy lift system such as SLS or ITS. See *Fairing limitations* for more details.
39 United States Department of Agriculture (2015, Nov. 10). *Crop Production*. Retrieved from http://usda.mannlib.cornell.edu/usda/nass/CropProd/2010s/2015/CropProd-11-10-2015.pdf.
40 Corn, dried, yellow. Retrieved from http://nutritiondata.self.com/facts/ethnic-foods/10000/3
41 Peters, C. J., Wilkins, J. L., & Fick, G. W. (2007). Testing a complete-diet model for estimating the land resource requirements of food consumption and agricultural carrying capacity: The New York State example. *Renewable Agriculture and Food Systems, 22*(02), 145-153. doi:10.1017/s1742170507001767

Stage	Propellant	Isp	dV (km/s)	Mass frac.	Dry mass (t)	Propellant (t)	Payload (t)
1 2	MON/CyMet MON/CyMet	322 342	3.7 4.9	0.05 0.05	5.9 1.8	117.6 35.6	9.1
1 2	MON/CyMet LOX/CH_4	322 381	2.9 5.7	0.05 0.06	5.2 2.9	103.1 48.1	10.7
1 2	LOX/CH_4 LOX/CH_4	358 381	3.7 4.9	0.06 0.06	6.6 2.3	110.4 38.7	11.9
1 2	LOX/CH_4 LOX/LH	358 455	2.2 6.4	0.06 0.075	4.7 5.0	78.3 66.3	15.6
1 2	LOX/LH LOX/LH	428 455	3.6 5.0	0.075 0.075	7.3 3.3	97.9 43.6	17.9

ISP figures and associated propellant combinations arbitrary; assuming high pressure, high expansion engines; first stage impulse reduced for atmospheric operation starting at ~0.5 atm

As can be seen, while the dry masses of ascent vehicles make them quite deliverable *to* Venus, their performance is a bit disappointing. The easier propellants to make and store yield under 10 tonnes payload, and even the more difficult propellants don't greatly exceed our needs - just to LVO.

Now let's see what happens when we try the same propellant and staging combinations for a highly elliptical HVO (~10.6 km/s delta-V)

Stage	Propellant	Isp	dV (km/s)	Mass frac.	Dry mass (t)	Propellant (t)	Payload (t)
1 2	MON/CyMet MON/CyMet	322 342	4.8 5.8	0.05 0.05	6.7 1.2	133.2 24.7	4.2
1 2	MON/CyMet LOX/CH_4	322 381	4.3 6.3	0.05 0.06	6.3 1.9	125.7 31.0	5.1
1 2	LOX/CH_4 LOX/CH_4	358 381	4.8 5.8	0.06 0.06	7.6 1.7	126.6 28.2	5.9
1 2	LOX/CH_4 LOX/LH	358 455	3.6 7.0	0.06 0.075	6.5 3.3	108.7 43.4	8.3
1 2	LOX/LH LOX/LH	428 455	4.7 5.9	0.075 0.075	8.6 2.3	114.7 34.2	9.9

The problem is actually even worse than this scenario would suggest, as reentry heating and other factors become more challenging. Mass fractions and impulses have not been changed in the above table.

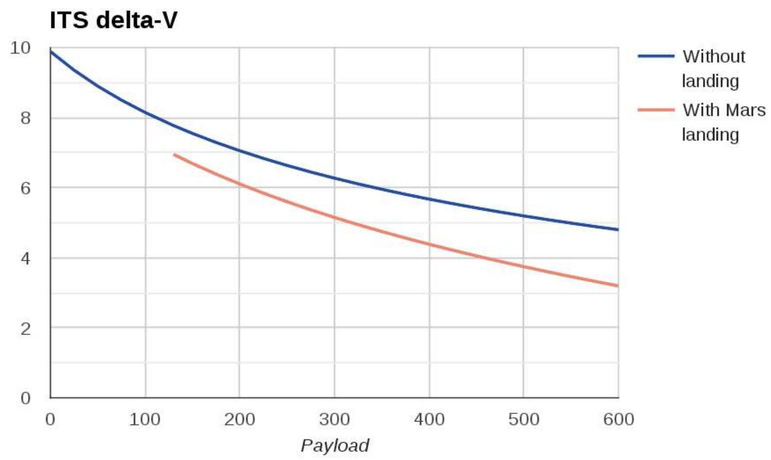
We could add another stage - say, a MON/CyMet booster to get the stack out of the atmosphere where it can be vacuum optimized - but that doesn't help as much as one might hope:

Stage	Propellant	Isp	dV (km/s)	Mass frac.	Dry mass (t)	Propellant (t)	Payload (t)
1 2 3	MON/CyMet MON/CyMet MON/CyMet	322 342 342	2.7 4.0 4.0	0.05 0.05 0.05	5.3 2.6 6.9	96.9 47.3 12.5	4.7
1 2 3	MON/CyMet MON/CyMet LOX/CH_4	322 342 381	2.0 3.6 5.1	0.05 0.05 0.06	4.4 3.1 1.3	80.4 55.9 19.5	5.4
1 2 3	MON/CyMet LOX/CH_4 LOX/CH_4	322 381 381	1.2 4.8 4.8	0.05 0.06 0.06	2.9 5.4 1.2	52.4 82.7 19.2	6.2
1 2 3	MON/CyMet LOX/CH_4 LOX/LH	322 381 455	0.5 3.8 6.3	0.05 0.06 0.075	1.5 5.9 2.7	26.5 91.2 34.0	8.2
1 2 3	MON/CyMet LOX/LH LOX/LH	322 455 455	0.5 5.1 5.1	0.05 0.075 0.075	1.5 7.7 2.1	26.5 96.6 25.7	10.0

In an environment as challenging as Venus, one doesn't want to complicate the ascent any more than necessary. Adding an extra stage for these sorts of marginal improvements does not seem justified.

Given the difficulty in getting to an elliptical orbit from the habitat, we should look into offloading the energy requirements to the transfer stage: having it aerocapture to LVO rather than HEVO. In that case, the question also arises as to what sort of orbit the transit vehicle should utilize on the Earth end.

Since we need at this point to specify a transfer architecture for the sake of argument, we will consider SpaceX's proposed Interplanetary Transport System, which involves a very large stage, refuelled in LEO, and designed for aerocapture at its destinations.



Recalculation of ITS launch capabilities to Mars based on design specs, in comparison to stated payload to dV ratios.[42] *To match the stated Mars landing curve, required landing propellant ranges from 440t (28% of the total) at 130t payload to 940t (48% of the total) at 600t payload.*

[42] Space Exploration Technologies Corporation (2016). Mars Presentation. Retrieved from http://www.spacex.com/sites/spacex/files/mars_presentation.pdf

All transfer stage performance figures below use minimum energy direct transfers :

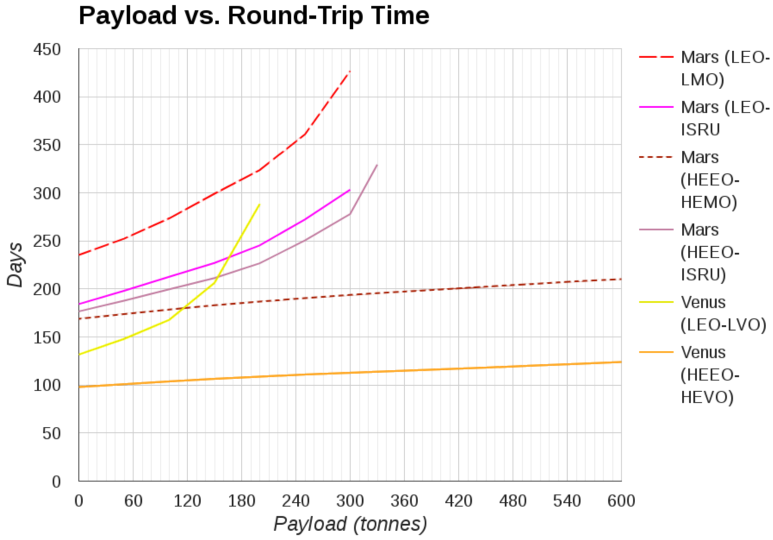
- 250km LEO to VTO aerocapture, plus 125m/s contingency, requires a delta-V of 3.62 km/s.
- 350km LVO to Earth aerocapture, plus 125m/s contingency, requires a delta-V of 3.43 km/s

Thus, from LEO to LVO and back requires around 7.05 km/s delta-V and can deliver approximately 200 tonnes in 146 days outbound and 146 days inbound. There are, however, many possibilities for faster transfers, and hence we will need to create a table (taking into account our reserve propellant requirements).

Tonnes to Venus	Tonnes to Earth	km/s to Venus	km/s to Earth	Days to Venus	Days to Earth	Mars (LMO) days for equiv. payload		Mars (surface) days for equiv. payload	
200	200	3.62	3.44	146	146	177	169	90	161
200	100	3.81	4.02	106	79	144	150	90	137
200	100	4.00	3.81	95	91	125	166		
200	100	4.17	3.62	86	112	111	192		
200	50	3.95	4.43	98	67	137	143	90	127
200	50	4.24	4.06	84	77	116	157		
200	50	4.51	3.73	80	97	104	187		
100	200	3.68	3.63	125	110	151	159	80	161
100	200	3.76	3.57	111	119	131	174		
100	200	3.83	3.50	107	131	115	195		
100	100	4.17	3.98	87	85	116	157	80	137
100	100	4.44	3.71	81	99	102	184		
100	50	4.04	4.69	93	64	133	138	80	127
100	50	4.44	4.26	81	71	108	150		
100	50	4.83	3.84	107	89	97	178		
50	200	3.72	3.73	116	97	151	155	74	161
50	200	3.83	3.64	107	109	128	170		
50	200	3.94	3.54	98	124	110	191		
50	100	3.93	4.37	99	69	137	142	74	137
50	100	4.25	4.07	84	76	113	154		
50	100	4.59	3.76	78	94	98	180		
50	50	4.08	4.82	91	62	131	135	74	127
50	50	4.54	4.36	79	69	104	147		
50	50	5.00	3.90	71	86	93	174		

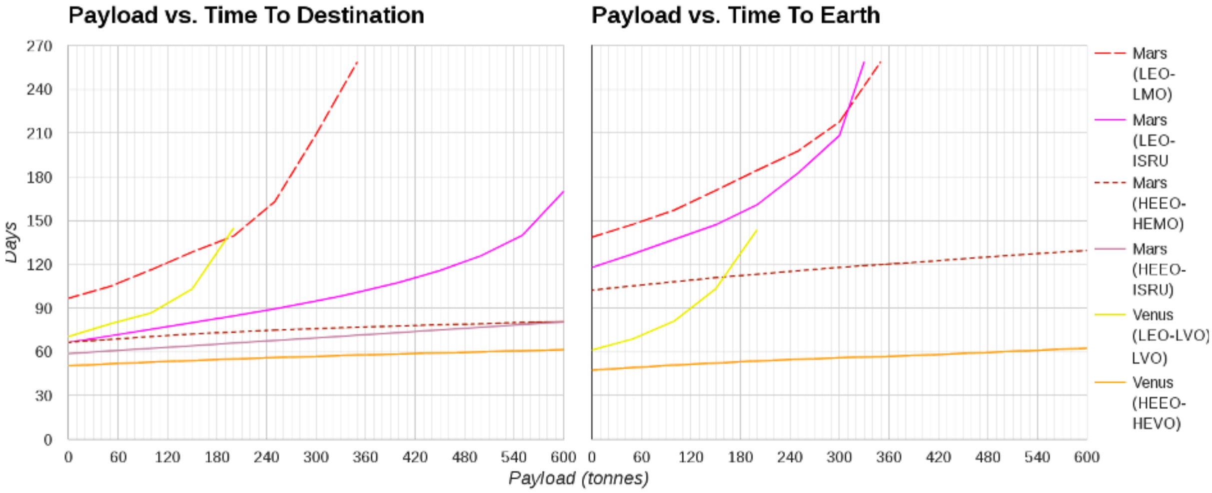
Excepting the 200 tonnes outbound / 200 tonnes inbound case, all payload cases are presented in three options: 1) remaining delta-V given 25% to the outbound (to Venus) / 75% to the inbound (to Earth) leg; 2) 50% to outbound and 50% to inbound; and 3) 75% to outbound and 25% to inbound. Two Mars scenarios are given for comparison: to LMO (without refuelling), and to the surface (with refuelling). The latter implies that the full dV of the spacecraft can be used on each leg, but 0.9 km/s dV is needed for descent and 3.83 km/s dV is needed for ascent.

To the right are plotted round-trip transfers between Earth and Mars or Venus. Payloads are assumed equivalent in both directions. Any extra delta-V is allocated evenly inbound / outbound in the circular-circular transfer cases, 65% / 35% in the Venus elliptical case, and 20% / 80% in the Earth elliptical case (the latter nonetheless still leaving a significant difference between inbound and outbound times).



For the Mars surface ISRU case, the craft can expend all of its propellant in each direction, but is taken to require 3830 m/s dV for ascent and 440-940m/s dV for landing. In the ISRU case, the outbound leg is capable of much more payload, but the return leg is not, thus truncating its curves on the above graph.

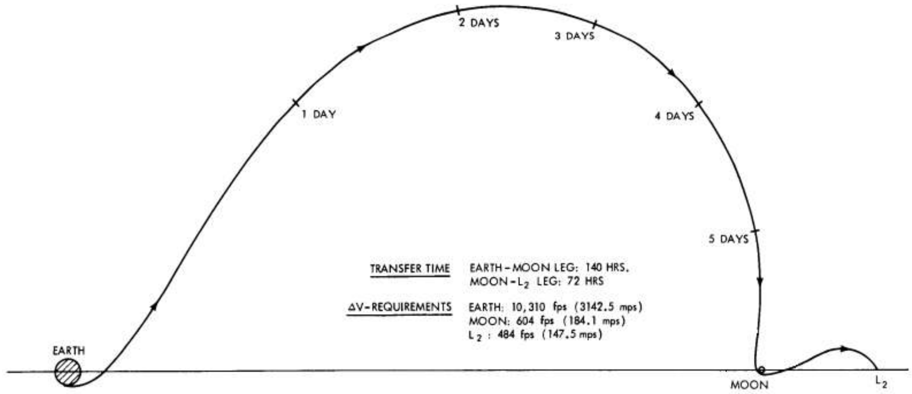
In the below graphs we break down the inbound and outbound legs in the above graph:



It becomes immediately clear that LEO-LVO-Return has hands down a faster transfer versus LEO-LMO-Return in time, but loses in terms of maximum payload. Versus a Mars ISRU scenario, Venus wins easily on inbound times, but the Mars ISRU scenario offers more favourable outbound times. It can additionally be noted that the lower payload / faster transfer scenarios are more favourable to Venus. Lastly, HEEO-HEVO-Return wins in all regards versus all other options, offering the potential for immense payloads and very short transits.

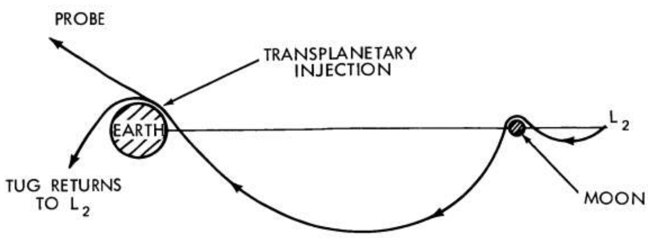
As discussed previously, using a highly elliptical orbit at Venus requires the presence of a large habitat or advanced propulsion concepts in order to be able to carry a sufficiently large ascent vehicle to reach HEVO. However, even the use of a high energy orbit on the Earth end of the transfer would be a great improvement.

Is this prohibitive? In a "HEEO-LVO-Return" scenario, the transit vehicle either remains in a high orbit at Earth, or returns to LEO or the surface and then is later re-launched to a high orbit. Particularly interesting possibilities (not analyzed here) are the Earth-Moon lagrange points, heavily investigated by Farquhar in 1970.[43] L2, for example, can be reached via a 3-day, 4.45 km/s transfer or a 5-day, 3.47 km/s transfer employing a lunar gravity assist.



Reproduced with reformatting from Farquhar 1970.

From L2, a craft can be placed into a highly elliptical low-perigee trajectory for landing or transfer burn to Venus, at a cost of only 335 m/s dV. An unmanned craft could potentially be be returned for as little as 50 m/s, at the cost of a long (~100 day) transit time.



Reproduced from Farquhar 1970.

To fill the ITS spaceship at L1 or L2 requires that two additional tankers be fueled in LEO. Each tanker holds 2500t of propellant.[44] They successively burn to intercept the incoming vehicle, one after the next. At a HEEO intercept, each vehicle has approximately 1045t propellant remaining (not accounting for contingency reserves). After filling the ITS spaceship for its outbound trip to Venus, each has ~70t of propellant remaining for entering an Earth-flyby trajectory for aerobraking to orbit or landing. This equates to 2.15km/s dV remaining for this purpose and contingency.

As SpaceX has not announced their plans for crew and cargo loading / unloading, we cannot analyze whether a crew could be transferred in a high orbit scenario.

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[43] Farquhar, R. W. (1970). The Utilization of Halo Orbits in Advanced Lunar Operations. Goddard Spaceflight Center, X-551-70-449

[44] Space Exploration Technologies Corporation (2016). Mars Presentation. Retrieved from http://www.spacex.com/sites/spacex/files/mars_presentation.pdf

Using SpaceX's cost breakdown, for a high orbit the number of tanker launches increases from 5 to 13; the number of booster launches from 6 to 14; and the ship remains at its current estimate. The resulting cost is $89M per trip, versus their estimated $62M for Mars surface/ISRU. However, the performance improvement is dramatic. For the below figures we will use the same inbound/outbound allocation of delta-V described previously:

- **Maximum payload**: 930 tonnes / 146 days each way (vs. 200t / 146d for LEO-LVO-Return, 350t / 259d for LEO-LMO-Return, and 650t outbound / 330t inbound, 259d for LEO-Mars Surface/ISRU-Return).

- **200 tonnes**: 64 / 65 days (vs 146d / 146d for LEO-LVO-Return, 139d / 184d for LEO-LMO-Return, and 90d / 161d for LEO-Mars Surface/ISRU-Return)

- **100 tonnes**: 59 / 60 days (vs. 87d / 81d for LEO-LVO-Return, 116d / 157d for LEO-LMO-Return, and 80d / 137d for LEO-Mars Surface/ISRU-Return)

- **50 tonnes**: 58 / 56 days (vs. 79d / 69d for LEO-LVO-Return, 105d / 145d for LEO-LMO-Return, and 75d / 127d for LEO-Mars Surface/ISRU-Return)

It should be reiterated that one does not, of course, need to be dependent on any particular system architecture coming to pass; we simply bring up the ITS in order to give a specific transfer stage example. More traditional, smaller, more expensive launch scenarios are possible as well.

Scaling

From the above, delivery options to and from a Venus habitat such as described above can be seen to be quite workable, but ascent vehicle performance is somewhat lacklustre in terms of payload / delta-V in comparison to Mars. How can we alter the scenario to improve our crew delivery to orbit and transfer stage’s throughput? Let us examine how various factors influence it.

- **House fewer people per habitat**. This reduces both mass related to feeding the residents, as well as the required size of the launch vehicle.

- **Not have the ability to launch everyone per cycle**. This allows return stages to be smaller.

- **Sink deeper**. Perhaps counterintuitively, sinking deeper into the atmosphere actually increases the launch capacity. While it means poorer engine expansion and more air mass to go through, buoyancy for a habitat of a given volume is directly proportional to the exterior air pressure; within practical bounds for human heat tolerance, a lower flight altitude yields a greater launch capacity. A habitat taking on a greater-heat environment shortly before launch would go through "seasons", with summer being pre-launch, and winter immediately thereafter. Contrarily, a cooling system could be employed (see *Climate control*)

- **Lifting body.** Discussed in more detail in *Buoyancy control*, a lifting body would allow for more daytime payload capacity at a given altitude - but the habitat would sink down to a lower level at night when propulsion power is reduced. Some degree of day and night altitude differences is desirable, but the balance of this height loss vs. other factors is an implementation-specific detail that must be balanced.

- **Go nuclear**. Nuclear thermal rockets (see *Nuclear thermal*) can have far higher payload fractions, even in a single stage, than chemical rockets. Some nuclear thermal designs can additionally offer the ability for protracted periods of hover when docking.

- **Go big**. One is not restricted to the use of current US hangars. If one were to repurchase the CargoLift hangar in Germany, or to build a similar or larger hangar ($150-300m), larger and more mass-optimally shaped airships could be built. The scaling factors all make "big" more favorable:

    - Lift scales proportionally to the *radius cubed.*
    - Airship structural mass scales *greater than the radius squared* but *less than radius cubed*. Examples:
        - Permeation-resistance envelope layers increase with area, and thus *radius squared.*
        - Chemical / weathering-resistance envelope layers increase with area, and thus *radius squared.*
        - Tensile reinforcement needs increases proportional to area times thickness, and thus *radius cubed*. For a spherical shell, stress equals $\sigma=(P R / 2 t)$; thus, to maintain constant stress at a constant pressure P, the thickness t of material bearing tensile loads must increase corresponding to radius R.
        - Rigid framing, if present, tends to scale at a rate *between the radius squared and cubed*.
    - Agriculture and solar power - and thus crew capacity - scale with the surface area, and thus *radius squared*.
    - Internal hardware ranges from constant to linear to scaling with crew / surface area (*radius squared*)
    - ISRU needs scale with crew and with total airship mass..
    - Rocket mass scales at less than linear with crew capacity, and thus less than *radius squared*.

In short, the larger your habitat is, the easier it is to launch crew and cargo to returning vehicles, as well as doing just about everything else. A large habitat does however come at the cost of higher capital costs / risk, and fundamentally requires a super-heavy launch system.

Improving the situation

As habitat sizes grow, the transit situation improves. Let us examine the case where the lift of the habitat is sufficient to support reusable ascent vehicles that can go to to HVO. For example, a habitat double the radius and four times the population (40 people) has 1824 tonnes lift, with about around 200 tonnes of mass not dedicated to the ascent vehicle. This allows for an ascent vehicle nearly ten times larger than our last calculations. If we 10x our previous case for a two-stage ascent to HEVO, we get:

Stage	Propellant	Isp	dV (km/s)	Mass frac.	Dry mass (t)	Propellant (t)	Payload (t)
1 2	MON/CyMet MON/CyMet	322 342	4.8 5.8	0.05 0.05	67 12	1332 247	42
1 2	MON/CyMet LOX/CH_4	322 381	4.3 6.3	0.05 0.06	63 19	1257 310	51
1 2	LOX/CH_4 LOX/CH_4	358 381	4.8 5.8	0.06 0.06	76 17	1266 282	59
1 2	LOX/CH_4 LOX/LH	358 455	3.6 7.0	0.06 0.075	65 33	1087 434	83
1 2	LOX/LH LOX/LH	428 455	4.7 5.9	0.075 0.075	86 23	1147 342	99

Even the smallest of these is far more than necessary to carry 40 people. Studies on Space Shuttle passenger variants, for example, were to replace its cargo bay (which could carry 27.5 tonnes to LEO) with 30-74 seats for passengers.[45] ascent vehicles such as these - fed by ISRU, fed in turn by Venus's great energy reserves - could take basically whatever cargo is desired wanted offworld - as well as enabling far more than the aforementioned 40 people to live in the habitat.

The improvements need not stop there. As agriculture scales, a habitat can provision food for return trips. With the deveopment of sufficient local ISRU production, the habitat could refuel transfer stages for return trips. Each step taken on the Venus end vastly improves transit times, cargo throughput, and economics.

Analysis

It is naturally compelling to want to starting a project small, eliminate the risk, and then scale up. Indeed, there have been many programmes that one could argue that tried to achieve too much, too soon.

However, the benefits of scale are quite compelling for a Venus habitat. It’s difficult to

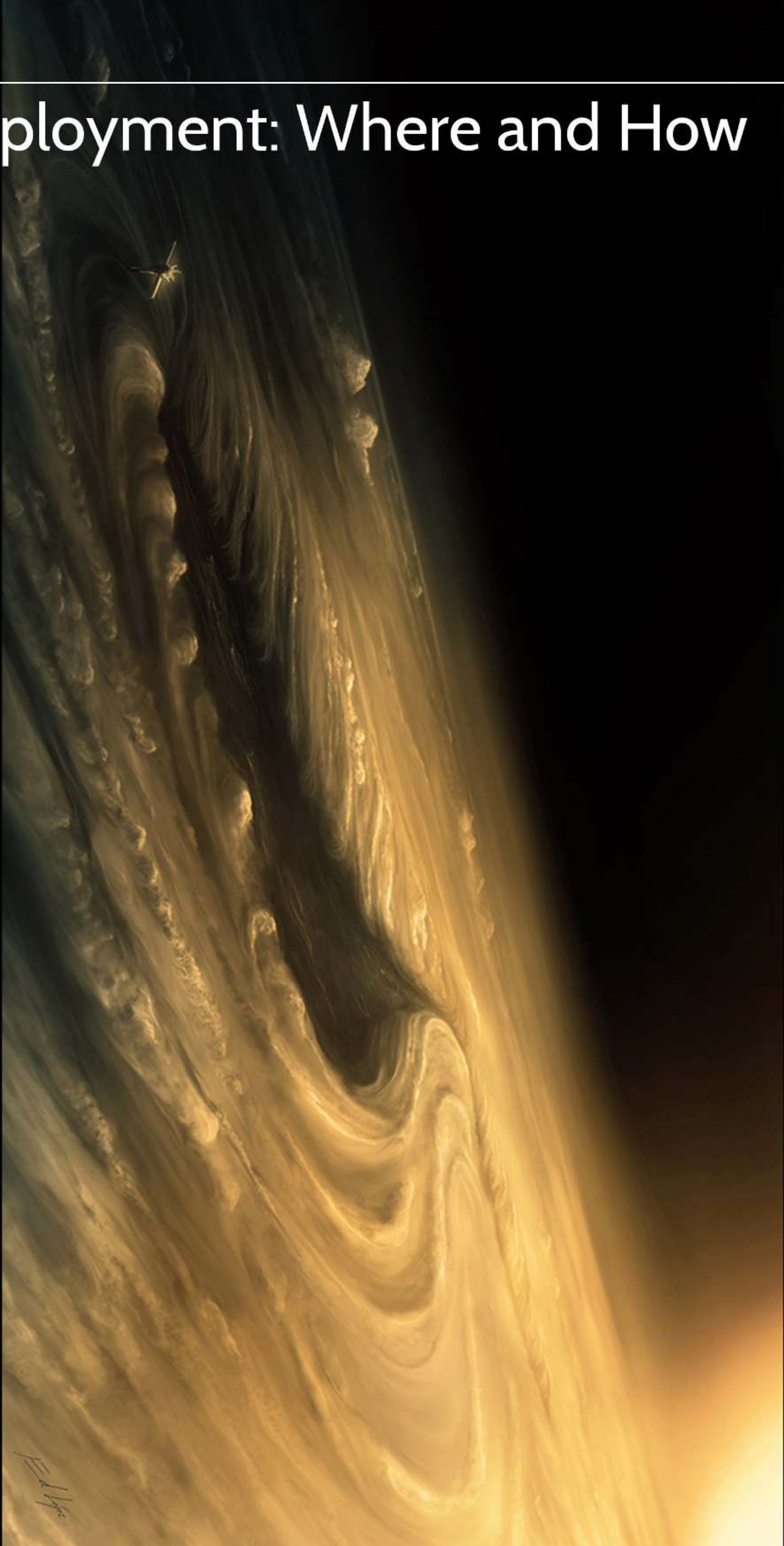
[45]L David, R Citron, T Rogers & C D Walker, April 25–28, 1985, "The Space Tourist", AAS 85-771 to −774. Proceedings of the Fourth Annual L5 Space Development Conference held April 25–28, 1985, in Washington, D.C

avoid the question: is it not worth building a larger hangar, larger assembly hardware, recruiting greater manpower, launching it with a larger launch vehicle, etc? This would yield a habitat that is not only capable of being home to vastly more people and local manufacturing capability, but its larger, higher-dV ascent vehicle would allow for a greater delivery capacity *to* Venus, and/or significantly decrease transfer time per trip. It's difficult to say that this, too, is not compelling. Contrarily, the extra habitat lift could be dedicated to larger scale ISRU and manufacturing capability. If unmanned missions can retire enough risk, is it not worth asking: should the first manned mission not be larger?

Building large airships is not trivial - building them for Venus, all the less so. But at the end of the day, large airships are something that we can and do build, and not at unrealistic expense. Had fixed-wing aircraft proven impractical on Earth, lighter-than-air vehicles are how we would all be engaging in air travel today. And indeed, one of the great advantages of Venus as a destination is that it's similarity to Earth - temperature, pressure, gravity, etc - make it easier to test for on Earth. With minor modifications, the same habitat designed for use on Venus can be lofted on Earth with heliox (a mixture of helium and oxygen used for diving), and support a crew inside of it - just as on Venus. Even ISRU can be effected to some extent, condensing water from the atmosphere as if it were Venus's acid mists. That said, to raise the TRL for habitat hardware to be used in the Venus environment, deploying an unmanned small-scale demonstrator habitat on Venus would be an essential step (in addition to a wide range of other requirements; see *Preliminary steps)*.

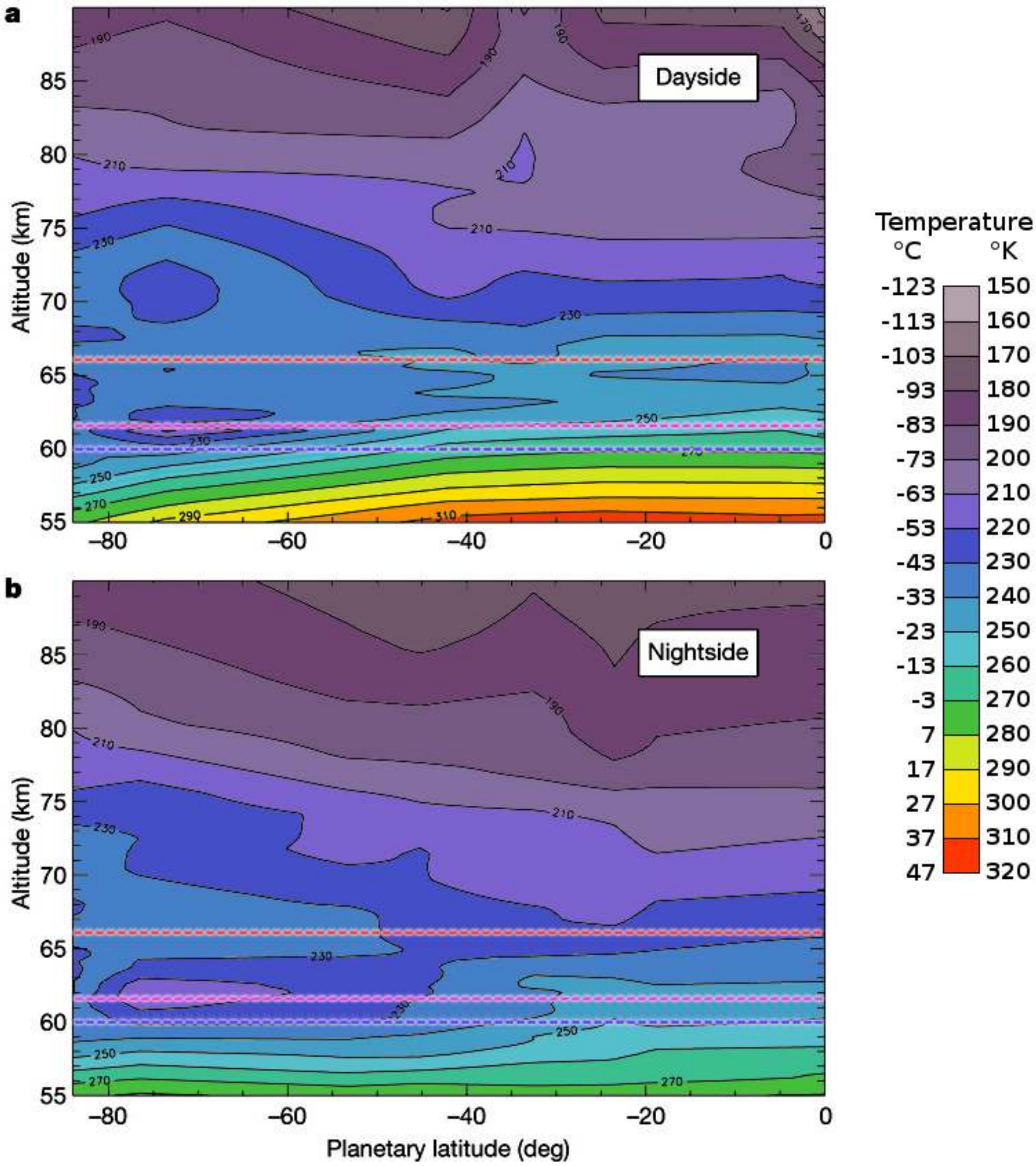
If having a small manned habitat is desirable, however - and potentially even if it's not - a nuclear thermal ascent vehicle presents an appealing alternative to chemical rockets.

3. Deployment: Where and How



While the powerful zonal winds leave one with little control over longitude on Venus, altitude and latitude can be selected. Altitude is determined by buoyancy, while latitude is determined by propulsion against the relatively weak north/south (meridional) winds as necessary. The combination of latitude and altitude determines the daily balance between temperature and pressure, while latitude (and to a lesser extent, altitude) determines the effective day length (via superperrotation).

The balance of these factors can be seen in the following graph (VIRTIS data):[46]

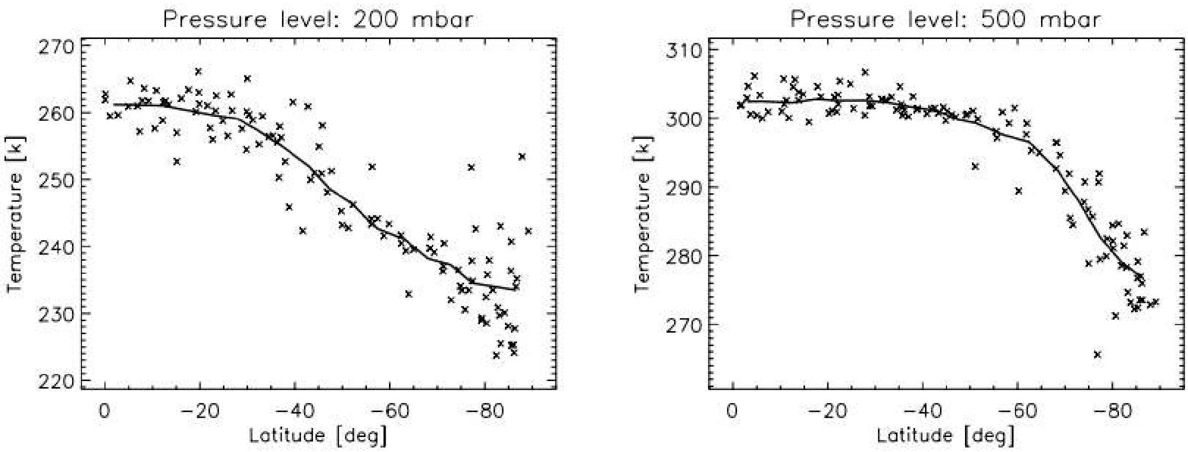


When considering the graph, internal daytime temperatures should be inflated somewhat due to the presence of a greenhouse effect in the habitat. The bottom of the graph, 55 km altitude, corresponds to 0.49 bar.[47] The lifting gas mixture would be approximately 40% oxygen. The blue dashed line corresponds to the level in which a pure oxygen atmosphere has the same O_2 partial pressure as sea level on Earth (0.2 atm). The

[46] Based on Piccialli, A. (2010). *Cyclostrophic wind in the mesosphere of Venus from Venus Express observations*. Berlin: Uni-Edition.
[47] VenusGram (2005) *Venus Global Reference Atmospheric Model (Venus-GRAM)*.

purple dashed line matches the O_2 partial pressure in Quito, Ecuador (2850m altitude) - roughly the maximum comfort limit for your average individual. The top, red line represents the Armstrong limit, the pressure at which water boils at body temperature.

Note that there are other data sources, and they're not entirely in agreement. While VIRTIS data comes from IR cloud tracking, VeRa data comes from radio sounding and yields these results for 60.0 km and 54.8 km, respectively:



Piccialli (2010)[48]

VeRa does not provide a quality day/night breakdown; however, it provides greater sensitivity and spatial resolution within the habitable zone.

We can make a number of general observations from these datasets.

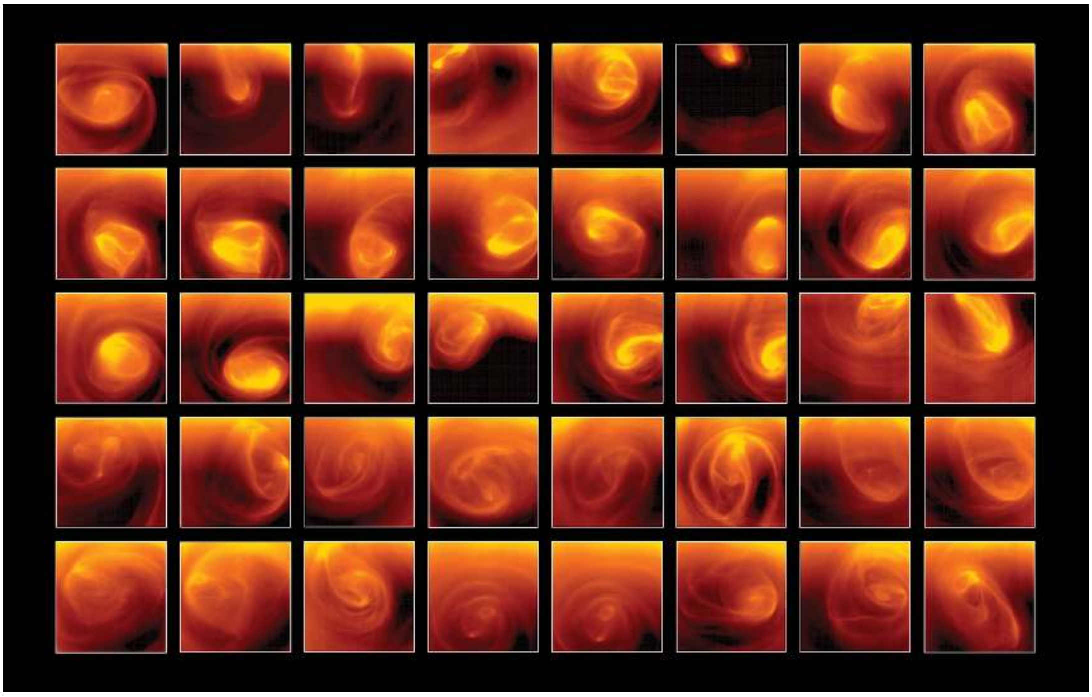
- Staying near the equator is a bad option all around. In addition to a day that is six earth days long, the habitat must be at quite low pressures to be able to have earthlike temperatures after factoring in greenhouse heating. These low pressures mean potential issues for health and comfort (discussed shortly), but more importantly, reduced lift for the ascent vehicle.

- A broader range of latitudes and altitudes could be achieved by use of a climate control system, although such systems are large and consume significant amounts of power (see the sections *Climate control* and *Transpiration*)

- 70° latitude provides an interesting balance, including a 48-72 hour day length (depending on whether VIRTIS or VeRa data is more accurate), little meridional drift, and earthlike temperatures at around 0.5 atm. These sorts of pressures (provided for by losing only nitrogen, not oxygen) correspond with little adverse negative health effects (the only known one of significance is that the lungs are less effective at coughing), and a number of advantages, including easier breathing,[49] reasonable plant growth and longer times for food spoilage (see *Agriculture*).

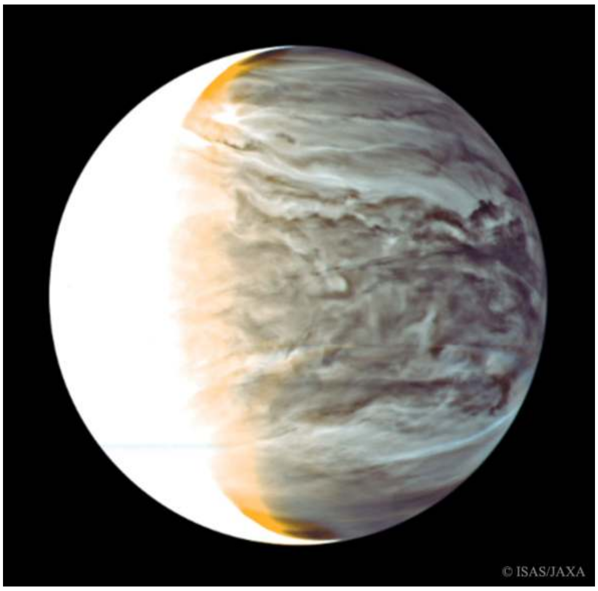
[48] Piccialli, A. (2010). *Cyclostrophic wind in the mesosphere of Venus from Venus Express observations*. Berlin: Uni-Edition.
[49] Parker, J. F., Jr., & West, V. R. (1973). Bioastronautics Data Book. *NASA / BioTechnology, Inc.* NASA SP-3006

- Further poleward allows for even shorter days and even higher pressures. However, in addition to further reducing sunlight from the 70° environment, this places the habitat close to the polar vortices:



(Photos: ESA/VIRTIS-VenusX/INAF-IASF/LESIA-Obs. de Paris (G. Piccioni, INAF-IASF)

How dangerous is turbulence in the polar vortices? It is difficult to say; no probe has ever passed through them. While efforts continue to correlate our limited probe data with longer-term satellite observations, without a longer-term presence in the clouds, our ability to make firm conclusions is limited.



Shifting weather systems observed in infrared by Akatsuki. Photos: ISIS / JAXA

To sum up, it appears that around 70° latitude and around 54-55km, around 0.5 atm, appears to be an optimal location for an initial habitat. The climate is favorable and lift significant. The geology around 70°N is arguably more interesting and diverse than 70°S, including passing over Ishtar Terra. This considered a possible granitic remnant,[50] has conductive/semiconductive "frosts" in certain areas, is the location of Venus's highest mountain (Maxwell Montes),[51] and high terrain in general (least hostile surface conditions). Consequently, would appear to be the preferred hemisphere for initial insertion. However, transfer across the equatorial regions to the opposite hemisphere should be possible when ascent vehicle propellant masses are low, allowing the habitat in order to float at higher altitudes.

Entry and deployment

The traditional approach for Venus atmospheric entry - used by Vega, and proposed for use in future unmanned balloon probes (such as VME) - is to use an aeroshell, a small parachute, and a source of inflation gases to inflate the airship.

This system is functional, at least on the small scale. However, a typical deceleration profile for a habitat tends to involve either problematically high velocities during deployment or problematically high air density. As noted in the manned HAVOC habitat proposal:

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[50] Shellnutt, J. G. (2013). Petrological modeling of basaltic rocks from Venus: A case for the presence of silicic rocks. *Journal of Geophysical Research: Planets, 118*(6), 1350-1364. doi:10.1002/jgre.20094

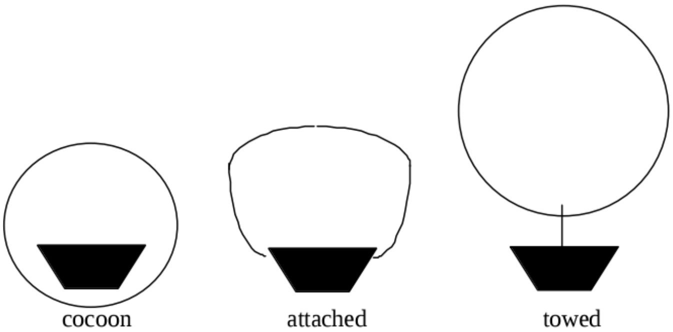
[51] Treiman, A., Harrington, E., & Sharpton, V. (2016). Venus' radar-bright highlands: Different signatures and materials on Ovda Regio and on Maxwell Montes. *Icarus, 280*, 172-182. doi:10.1016/j.icarus.2016.07.001

"Analysis of point cases drawn from the human mission design space showed that dynamic pressures at parachute deployment exceed the valid environment due to the relatively low altitude at which the vehicle reaches Mach 2.1, and resultant high density. The high dynamic pressure is beyond the survival capability of commonly used parachutes (such as disc-gap-band) used in current planetary exploration. Thus a different technology such as a ribbon parachute or ballute must be used to slow the vehicle enough to permit the airship to inflate while under parachute"[52]

Mark 82 high-drag bombs utilize a ballute for deceleration from high speeds. Photo: USAF

This is a key issue worthy of consideration; if you have to engineer a new entry/deployment system regardless, you might as well focus on the version that provides the greatest potential benefit to the mission. And in this case, this is arguably a ballute (deceleration device based on a self-inflating balloon), for two main reasons.

Venus is arguably the most suitable body in the solar system for direct ballute entry. TRL (technology readiness level) on ballutes for in-atmospheric use is high;[53] for ballute entry, it remains low, as such a system has never been deployed. However, ballutes allow for much lighter system mass versus aeroshell entry, with much lower reentry temperatures and somewhat lower decelerations.[54] [55] The ballute could remain a fully independent system ("towed"), or involve an integrated portion of the airship's envelope that is retained after full inflation ("attached" or "cocoon"), optionally including the burble fence.



Reproduced from Hall (2000)

The other benefit is the provision of an initial inflation of the ballonets during reentry, a concept previously researched for inflatable reentry systems. The gas is warmed by entry

[52] Lugo, R. A., Ozoroski, T. A., Van Norman, J. W., Arney, D. C., Dec, J. A., Jones, C. A., Zumwalt, C. H.. High Altitude Venus Operations Concept trajectory design, modeling and simulation. AAS 15-223.
[53] Numerous examples in parachutes and air-dropped weaponry. As a spaceflight-related example, non-reentry ballutes were used as a parachute stabilization system on Gemini; see http://www.hq.nasa.gov/office/pao/History/SP-4203/ch8-4.htm
[54] Hall, J. (2000). *A review of ballute technology for planetary aerocapture*. Presented at the 4th IAA Conference on Low Cost Planetary Missions, Laurel, MD, May 2-5, 2000.
[55] McRonald, A. (1999). A light-weight inflatable hypersonic drag device for Venus entry. Presented at the AAS/AIAA Astrodynamics Specialist Converence, Girdwood, AK, August 16-19, 1999.

heating, providing temporary buoyancy[56] - and thus helping reduce the time pressure to complete inflation.

A ballute design is additionally useful one considers lift requirements. The mass of a Venus habitat is overwhelmingly dominated by the heavy ascent vehicle slung underneath, which is in turn overwhelmingly dominated by the mass of the propellant used by it. Other significant sources of mass, such as plants and water, likewise come later. Thus, the entry mass - and lift required to loft it - is far lower than the final mass and final lift requirements. As a consequence, at arrival the ballonets need to be filled to their maximum inflation level, with the initial lifting gas[57] only needed to fill the small habitable space not taken up by the ballonets. Using a ballute system for inflation speeds the time to full deployment versus relying only on the ballute fans.

In order to advance the tech readiness level for ballutes, it will be necessary to demonstrate reliable deployment after months of storage packed, with aerodynamic stability and heating in line with calculations. Successful demonstration of ballute entry for an unmanned Venus probe would not only aid in the deployment of a Venus habitat, but additionally be of use for payloads to Earth, Mars, Titan, and the gas and ice giants. NASA's Low Density Supersonic Decelerator project is actively working to develop ballutes for use on Mars.[58]

Photo: NASA

We will cover ballutes in more detail under *Ballute considerations*. A great deal of additional information about ballute design and construction can be found in Griebel (2010).[59]

A somewhat similar alternative to ballutes has been proposed for the VAMP concept (Venus Atmospheric Maneuverable Platform), and researched in general under the LEAF (Lifting Entry / Atmospheric Flight) project.[60] In this scenario, the craft is fully inflated in

[56] NASA / Duvant, J. C., & Scher, S. H. (1970). *U.S. Patent No. US 3508724 A*. Washington, DC: U.S. Patent and Trademark Office.

[57] While initial gas in the habitable area would be helium from Earth, over time, local production of gases ultimately yields the desired $O_2 + N_2$ atmosphere therein. As an example, for 400 tonnes of the higher-energy-to-produce gas fraction, (oxygen from CO_2, ΔH=393509 J/mol, byproduct CO, ΔH=−110525 J/mol, $2\ CO_2 \rightarrow 2\ CO + O_2$, 1 MJ/mol-$O_2$, 31.5 MJ/kg) is 12.6 GJ. Produced at 50% efficiency with 200kW peak power at 25% capacity factor would require only 2.9 Earth days to produce. Practical limitations lie more on the production sdte - see In-Situ Resource Utilization.

[58] Clark, I (2014). Low Density Supersonic Decelerator. Retrieved from https://www.nasa.gov/sites/default/files/files/IClark_LDSD(1).pdf

[59] Griebel, H. (2011). *Reaching high altitudes on Mars with an inflatable hypersonic drag balloon (Ballute)*. Wiesbaden: Vieweg Teubner Verlag.

[60] Lee, G., Polidan, R.S., Ross, F. (2016). Venus Atmospheric Maneuverable Platform (VAMP) - A Low Cost Venus Exploration Concept. *American Geophysical Union*, Fall Meeting 2015

space, with no openings/burble fence as in a ballute. The inflated shape then acts as a hypersonic lifting body to maintain altitude as long as possible, while steadily adding gas from tanks as it descends. While not providing for the filling of the ballonets, a lifting body offers the potential to reduce peak envelope heating during entry.

There are many options for initial gases for inflation. For spacecraft, hydrogen and helium are the most common inflation gases; however, tankage masses are typically much higher than the mass of the gases themselves, a factor only worsened by increasing pressures. Hydrogen can be produced from the decomposition of hydrogen-bearing compounds, but the hydrogen only makes up a minority fraction of the mass. However, if the remaining fraction is useful, then this seems a convenient means to transport hydrogen. For example, ammonia decomposition over a catalyst (investigated as a means to generate hydrogen for a “hydrogen economy”)[61] proceeds as:

$$2\ NH_3 \rightarrow N_2 + 3\ H_2$$

The hydrogen (useful for fuel cell power generation, water production, and many other applications) can be separated for the nitrogen (an important lifting gas) by a molecular sieve or selective membrane. There is an almost unlimited number of compounds which can be decomposed to yield lifting gases; most are exothermic, additionally increasing lift via heating. Additional moles of light gas could be created via the endothermic reverse water gas shift reaction (up to the maximum saturation vapour pressure of water in the envelope):

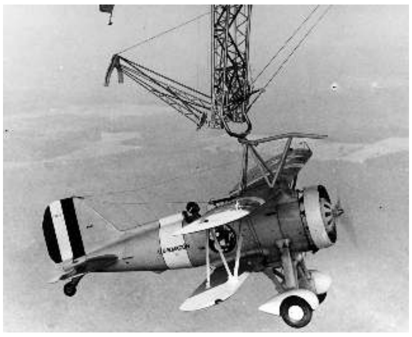
$$CO_2 + H_2 \rightarrow H_2O + CO$$

Alternatively, accelerated atmospheric CO_2 removal (e.g. ethanolamine stripping) could potentially yield nitrogen fast enough to inflate the habitat during its descent.

Docking, ascent and descent

As discussed previously, one of the greatest challenges with Venus is getting people to and from the habitat. Beyond simple considerations of propellants and staging, we must consider the details of docking, fuelling, and restaging.

There are many problems with docking a heavy object anywhere but the underside of the habitat - including weight balance, increased risk of damage, greater difficulty mounting docking hardware on the upper side, and so forth. An underside docking location would be equivalent to the “trapeze” docking of airplanes on the USS Macon and USS Akron.



F9C-2 Sparrowhawk fighter docked with the airship USS Macon. The USS Macon and Akron served as airborne aircraft carriers in the 1930s. Photo: Naval History Center.

Analysis argues against many means of maintaining lift and maneuvering into docking position.

[61] Bell, T. E., and L. Torrente-Murciano. H2 Production via Ammonia Decomposition Using Non-Noble Metal Catalysts: A Review. *Topics in Catalysis* 59.15-16 (2016): 1438-457. Web.

Rockets (traditional or rotary), battery- powered propellers (rotary or fixed wing craft) turboprops, and so forth always yield short flight times, high system masses, and have catastrophic failure modes. In practice, only one sort of non-nuclear system combines low mass, long flight times and gentle failure modes: lighter-than-air vehicles. A lighter than air vehicle can maneuver to underneath the habitat, where an arm or tethered drone can connect a docking cable to a mast on the top. Once tethered, the arriving vehicle reduces its lift to tension the cable and is then winched into place.

Assuming that crews must climb, suited up into the habitat, this implies an airlock on the bottom of the habitat. Thankfully, since there is little pressure differential between inside and outside, an airlock on Venus is quite simple, comprised of 1) a section of framed, loose, doubled-up envelope film; 2) a platform to stand or rest cargo on inside; and a 3) system to evacuate air out of the space between layers, then blow in air from the opposite side. A person or cargo inside briefly becomes “shrink wrapped” before being free to open the seal and emerge on the other side.

Implementing docking by means of lighter-than-air vehicle means that it faces the same requirements as the habitat itself faced on arrival, and thus the ideal solutions are the same. While disposable vehicles are possible and potentially economically viable in the short term, for long-term viability, ascent vehicles need to be able to be used multiple times. Thus, we will consider the sort of ascent and descent cycle that could take crew and supplies to orbit for rendezvous and return back to the habitat for reuse.

One of the first challenges faced by the ascent vehicle is to provide an abort scenario. If the vehicle is dropped from the habitat and then needs to abort, it cannot be recovered. A balloon, sized to bring an empty returning vehicle to the habitat, will not have the lift to counter the mass of a fully fuelled vehicle, and would face a heavy wind load in free fall. There is grossly insufficient time in which to empty the stage of propellant. Stages could potentially be jetisoned as an abort scenario, but would thus be lost.

Another problem arises with launching the ascent vehicle, this time for the habitat: the ascent vehicle represents a large portion, if not the majority, of the habitat’s mass. This sudden change in the mass/buoyancy of the habitat and the resultant stresses pose a serious risk to the its structural integrity.

The solution to both of these is to provide an equivalent to “hold-down” for a launch by having the ascent vehicle tethered to the habitat on a winch - for example, with 500m of cable available. As the brake is let off, the vehicle begins falling, building up inertia while the habitat begins accelerating upward. Once the two are sufficiently far apart, and with sufficient downward velocity in the ascent vehicle, the engines can be ignited without risk to the habitat. If ignition is successful, the cable can be detached; the ascent vehicle finishes cancelling its downward velocity and ascends (at an angle), while the habitat vents gas to reduce lift and uses its upward velocity to funnel air into its ballonets. If instead an abort is required, within seconds[62] the engine can be shut off, the vehicle (and habitat) braked to a

[62] Free fall without accounting for wind resistance: t =sqrt(2d/a). In 8.7 m/s² gravitational acceleration with 250m for acceleration and 250m for deceleration at the same rate yields 7.6 seconds, more than ample for a go/no-go decision.

stop, and then winched back up. The cable and winch masses in such a scenario are reasonable.[63]

Boost stages of ascent vehicles appear to present a frustrating scenario: that new stages would have to be continually imported from Earth. Building a rocket stage locally is anything but a near-term scenario. Working from this, one arrives at moderately-term in-situ alternative: drop tanks. Unlike a full stage, a drop tank - lacking engines - can be a very simple structure to build, requiring relatively little imported hardware. Hence, a “stage and a half” approach would appear to be an improved ascent architecture. Any drop tanks produced in the habitat must be able to fit through the central channel and out the bottom airlock. Despite such tanks being much simpler than building a rocket locally, they still represent a significant manufacturing challenge and are not a near-term solution.

A potentially superior solution arises when one considers what happens when you drop a tank or stage on Venus. It descends in the atmosphere, which becomes progressively denser and hotter, heating up the residual propellant and oxidizer[64] and thus providing counterpressure on the stage; sufficient pressure to resist collapse is easy to achieve.[65] Should it have a net density lighter than Venus’s 67 kg/m³ median surface density - which most empty rocket stages and tanks do - it eventually hits an atmospheric layer in which it floats. So long as the heat does not compromise its structural integrity, it could be recovered.[66]

Taking this even further, we arrive at the concept of deliberately floating returning tanks or stages in middle cloud layer - akin to how returning crew vehicles would dock with the habitat. As with before, the best way to do that would be a restowable balloon or ballute. Hence all of our stages follow the same principle: a tank or rocket that returns to the habitat by inflating an envelope of light gas, redocks, restows its envelope, and is carried underneath the habitat for future use. As unusual as a buoyant rocket may sound, the concept is not new; it was investigated for ROOST, intended as a VTVL successor to the Saturn V.[67]

Concept artwork from the 1960s Douglas OOST / ROOST / ROMBUS design study.
Image: San Diego Air & Space Museum.

[63] For example, a 100kW Emrax 268 motor at 12kg paired with a 8kg inverter yields a power density of 5kW/kg. To raise a 140 tonne loaded ascent vehicle against a gravitational field of 8.7 m/s^2 for 0.5km requires ~609MJ. To do this in 1 hour thus requires a motor + inverter mass of 34kg. 0.5km of cable at a static loading of 1GPa (allowing for dynamic loadings several times higher, plus a reasonable safety margin) holding said mass requires 3.5cm² of cross section; at 2g/cm³ the added mass is 1.2 tonnes. While structural and braking hardware adds to the total, there is little complication to the mass budget.
[64] NASA MSFC (1971) *Saturn V launch vehicle flight evaluation report AS-509: Apollo 14 Mission*, MPR-SAT-FE-71-1: Saturn V S-IVB residual/reserve propellant = 3.4% of total; Saturn V S-II = 1.3%
D. R. Jenkins (1993),*"Space Shuttle: The history of developing the National Space Transportation System; The beginning through STS-50*. Waldworth Publishing Company, Marceline: Space Shuttle residual propellant = 0.7% of total
[65] As an example, 1% residual propellant at 1 g/cm³ and a molecular weight of 16, boiled off at 25°C, yields (PV=nRT) a pressure of ~1.52MPa (~15 atm) - not accounting for residual pressurant.
[66] Based on calculations from Jonathan Goff; retrieved from http://selenianboondocks.com/2013/11/venusian-rocket-floaties/
[67] OOST. Encyclopedia Astronautica. Retrieved from http://www.astronautix.com/o/oost.html

Before refilling and relaunch, stages must be remounted to each other. In a conventional mounting configuration, this would require the importation of an interstage, or at least explosive bolts, for each launch. Unconventional staging options, such as clamping or magnetic connections, can also be considered during the design phase.

While there may be some initial inflation potential from residual fuel or oxidizer (having boiled off while the craft was in orbit / on reentry), calculations suggest that this would be insufficient in most cases.[68] Hence, the rocket needs to have extra propellant or pressurant onboard for inflation. The same factors that govern initial habitat inflation affect the initial lifting gas choice, and thus the optimal solution is likely the same: catalytically decomposed ammonia, optionally combined with the reverse water gas shift reaction or atmospheric nitrogen.

Lastly, the balloon has to be able to be restowed if the vehicle is to be reused. Various systems for automatically restowing parachutes on aircraft have been considered in the past.[69] [70] Manual balloon restowing is also possible, within the constraints discussed under *Chemical Environment and Resource Considerations*.

In addition to vehicles designed for crew ascent/descent, it would be beneficial to have a small cargo vehicle for use in sending unmanned payloads from Earth. The same design principles apply to it as to manned designs. Such a vehicle would be much simpler and cheaper by means of not needing to return to orbit. It could likewise be disassembled for parts after being emptied.

As discussed previously, a number of good-performing propellants are cryogenic, raising the issue of storage. On Earth, LOX is generally stored in vacuum tanks, which tend to be very heavy and would need to be imported from Earth. Vacuum tanks are used not only because of the high degree of insulation required, but because traditional insulations perform poorly at cryogenic temperatures.[71]

An interesting alternative presents itself naturally on Venus: carbon dioxide. Carbon dioxide has a low thermal conductivity (half that of oxygen and nitrogen, 8% that of helium)[72] and, by nature of freezing directly to a solid at pressures below 5 atm, does not flow away like oxygen or nitrogen and is thus immune to cryopumping. These properties have led to research on the use of carbon dioxide as a rocket insulation even for applications on Earth:[73]

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[68] A tank with a 5% mass fraction containing 1% residual propellant weighs five times as much as its propellant, meaning that every kilogram of propellant must provide at least five kg of lift for the tank and one for itself: that is, the ratio of atmospheric density to propellant density must be at least 6:1. As carbon dioxide has a molecular weight of 44g/mol, this implies that the residual propellant (fuel and oxidizer combined) must have a molecular weight of 7.3g/mol or less - a generally unrealistic scenario.

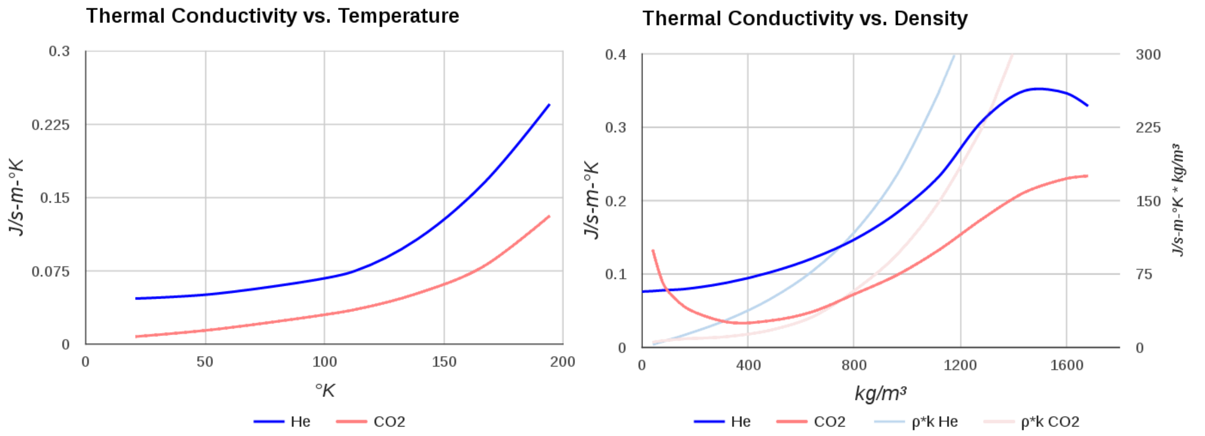
[69] Heffernan, R. C. (1950). *U.S. Patent No. US 2513867 A*. Washington, DC: U.S. Patent and Trademark Office.

[70] Bowden, M. K., & Buck, J. C. (1965). *U.S. Patent No. US 3222014 A*. Washington, DC: U.S. Patent and Trademark Office.

[71] Technifab Products. *Cryogenic Insulation*. Retrieved from https://technifab.com/cryogenic-resource-library/cryogenic-thermodynamics/cryogenic-insulation/

[72] Engineers Edge. *Thermal Conductivity of Gases Chart*. Retrieved from http://www.engineersedge.com/heat_transfer/thermal-conductivity-gases.htm

[73] Sharpe, E. L., Jackson, L. R. (1975). *Performance of a hypersonic hot fuselage structure with a carbon dioxide frost protected, nonintegral cryogenic tank.* Langley Research Center Hampton, Va.



*Data from Anderson and Jackson (1967),[74] illustrating the effect of temperature (left) and density (porosity) on the thermal conductivity of loose-fill fibre insulation (72kg/m^3) with either helium (blue) or CO_2 (red) in the pore space. Both are at 1 ATM. The left graph is at a constant 400kg/m^3 frost density, while the right is averaged across 21°K to 167°K (CO_2) / 195°K (He). Figures of merit (density * conductivity, faint lines) are also illustrated on the right.*

CO_2 insulation can range from a light, porous fluff to dense ice; left for long periods, it tends to slowly densify. Porous CO_2 ice is created by condensing the carbon dioxide in the presence of significant amounts of a dilutant gas. For deep cryogenic storage (e.x. LH_2), only helium is a practical dilutant. For milder cryogenic storage (e.x. LOX or warmer), gases with higher boiling points, such as nitrogen, can be used.

While porous CO_2 performs significantly better than dense CO_2, even the latter provides significant insulation as its thickness increases. Hence, one option for insulated tanks on Venus may be the air itself. A thick layer of CO_2 would build up on the tank over time, until the heat flow matches the rate of heat loss at CO_2 sublimation temperatures. At those temperatures, regular insulations work well; hence, to reduce heat loss further the rocket could be stored “docked” into cocoon of loose-fill insulation. During launch, any CO_2 that did not remain attached to the cocoon can be expected to break free (akin to what happens to ice with rockets on Earth); carbon dioxide frosts are notably fragile, and without a matrix to hold it onto, tends to spall off.[75]

Regardless of the insulation system, any cryogenic coolant system would be a relatively large, heavy piece of hardware. Hence, avoiding or minimizing the use of cryogens remains desirable.

While either fuel or oxidizer may be stored inside a stage while it is stowed close to the habitat, the vehicle must be positioned well away from the habitat when both are loaded, in order to limit the potential damage to the habitat in the event of an accident.

Development of the ascent vehicles will likely prove to be among the most expensive and challenging aspect of the entire programme.

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[74] Anderson, M. S., Jackson, L. R. (1967). A carbon dioxide purge and thermal protection system for liquid hydrogen tanks of hypersonic airplanes. NASA NSF GK-1116.
[75] Sharpe, E. L., Jackson, L. R. (1975). *Performance of a hypersonic hot fuselage structure with a carbon dioxide frost protected, nonintegral cryogenic tank.* Langley Research Center Hampton, Va.

Advanced Concepts

A number of advanced concepts developed for Earth have applicability on Venus as well.

- ## Airbreathing engines

Despite the lack of oxygen, airbreathing engines - both subsonic and supersonic (scramjets) are possible in Venus. For example, CEA2 simulation of burning hydrogen with atmospheric air (100 bar, 50:1 expansion ratio, 250°K ambient air temperature) begins with the Bosch reaction ($CO_2 + 2\ H_2 \rightarrow C + 2\ H_2O$), transitioning to the additional synthesis of methane and then ammonia at high hydrogen ratios. At low hydrogen:air molar ratios, thrust is poor but specific impulse excellent, and vice versa; for example, at 0.2:1, effective I_{SP} (impulse scaled by the fuel-air ratio) is 10417 sec; at 1:1, 3147 sec; and at 10:1, 752 sec. This however does not account for the drag involved accelerating the incoming air mass, which is particularly problematic at low hydrogen ratios; increasing thrust (and thus hydrogen) is required with increasing speed. As the Bosch reaction is less energetic than hydrogen-oxygen combustion, performance for Venus scramjets can be expected to be lower than scramjets on Earth.

- ## Air augmentation

The rocket equivalent of a high-bypass jet engine, air augmentation increases efficiency of a rocket engine by converting a high velocity / low mass exhaust stream into a low velocity / high mass exhaust stream. This comes at the cost of the mass of the duct to draw air into the exhaust stream.[76] For a given atmospheric pressure and velocity, such a duct on Venus would yield a greater mass of air than it would on Earth due to the higher molecular weight of Venus's atmosphere.

- ## Nuclear thermal

Technicians manufacture a nozzle for the Kiwi B-1-B nuclear rocket engine as part of the NERVA programme. Photo: NASA / GRC

As developed under the NERVA programme between 1952 and 1972, nuclear thermal propulsion - using a fission reactor to heat propellant - has demonstrated a specific impulse of 850 sec with hydrogen propellant, albeit at a low thrust to weight ratio. Modern designs, such as with a pebble bed core, can be expected to achieve around 1000 sec I_{SP}. However, the specific impulse drops off with increasing molecular weight. As potential non-hydrogen propellants on Venus are 14-22 times heavier than hydrogen, alternative propellants are generally not realistic choices. This is not a limitation for NTR ramjet (e.g. Project Pluto) bimodal nuclear thermal designs, but the added mass for airbreathing operation further limits the thrust to weight ratio.

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[76] Sutton, G. P., & Biblarz, O. (2016). [Rocket propulsion elements](). John Wiley & Sons.

A number of NTR concepts exist. In LANTR, a LOX “afterburner” lowers the I_{SP} by a third when in use, but triples the thrust, allowing for a much improved thrust-to-weight ratio. The afterburner can be shut off partway through ascent to improve the impulse when high thrust is no longer needed.[77]

In-between airbreathing and NTR or LANTR modes there also exist air augmented (NEAR)[78] and scramjet (NTTR)[79] designs (Bosch reaction on Venus). Some possible rough performance figures from a habitat to HEVO can be seen in the following table:

	ISP (sec)	T:W	Engine	Misc inert	Dry mass (t)	Propellant (t)	dV (km/s)	Payload (t)
NTR	900	11	9.1%	18%	32.2	118.9	10.6	18.9
NTR Ramjet	500/∞ /3.5k/900	10	10%	0% / 18%	29.2	104.5	0.4/1/1.2/8	36.3
LANTR	550 / 900	37	2.7%	6.5%/18%	24.9	120.2	3 / 7.6	25.0
LANTR+NEAR	550/3.5k/900	23	2.9%	6.5%/18%	21.3	108.3	0.4/2.2/8	40.4
NTTR	1k / 3k / 900	31	3.2%	18%	17.5	82.3	0.4/6.3/3.9	70.2

1g acceleration (lifting body design) at liftoff; thrust:weight ratio is at liftoff and relative to Venus gravity; “engine” (incl. neutron shield and intakes) and “misc inert” fractions are relative to vehicle wet mass; “misc inert” includes tankage, plumbing, etc. NTTR ISP reduced due to Bosch reaction rather than H_2/O_2 combustion.

The ramjet concept above is assumed to use pure NTR to accelerate up to ram speeds, but could utilize a LANTR-style LOX afterburner to achieve a lower engine mass at the cost of some specific impulse. All processes incorporating the external air are particularly interesting, as they yield significant extra reaction mass; the hardware to utilize it comes at a mass penalty, but offsets an even greater amount of reactor mass.

While public fears of atmospheric contamination have hindered NTR development on Earth, opposition would likely be reduced for a craft that only operates on Venus. Overall, the payload figures to a high orbit are quite impressive. While the amount of hydrogen consumption is very high, and hydrogen is difficult to acquire on Venus, the ascent vehicle could simply be scaled down, reducing both payload and propellant consumption. This has the side benefit of allowing the initial habitat to be smaller, as it does not have to loft such a heavy ascent vehicle. A caveat must be added, however, in that NTR performance and thrust-to-weight ratios decline as the reactor size decreases.

Techniques have been proposed to improve NTR specific impulses further. Examples include a thin-film fission fragment reactor (propellant heated directly by fission fragments in fine channels, thus avoiding its energy transfer through the fuel) or a “nuclear lightbulb” plasma or misty core (core meltdown is allowed but the fuel is kept suspended in a transparent channel, radiatively heating the propellant outside). The higher hydrogen temperature provided for by such concepts can increase the pure NTR to 2000-4000 sec I_{SP}; however, they present more challenging design issues. Fission fragment reactors require extremely narrow fuel elements (films / wires) and high neutron economy, while the transparent medium on a nuclear lightbulb tends to suffer from radiation blackening.

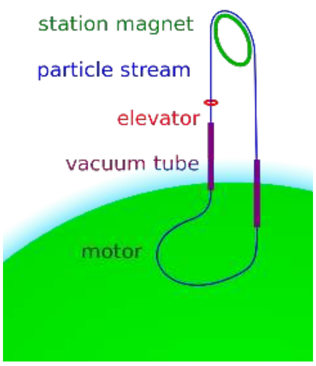
[77] Davis, E. W. (2004) Advanced Propulsion Study. Warp Drive Metrics / Air Force Research Laboratory. AFRL-PR-ED-TR-2004-0024

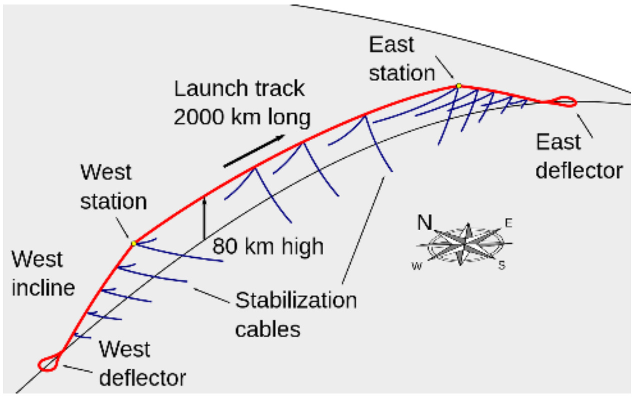
[78] Adams, R., & Landrum, D. (2001). Analysis of a nuclear enhanced airbreathing rocket for earth to orbit applications. *37th Joint Propulsion Conference and Exhibit*. doi:10.2514/6.2001-3205

[79] Bucknell, J. R. (2015). The Nuclear Thermal Turbo Rocket - A Conceptual High-Performance Earth-to-Orbit Propulsion System. *51st AIAA/SAE/ASEE Joint Propulsion Conference*. doi:10.2514/6.2015-3958

* ## Kinetic suspended structures

While current material technology is 1 ½ orders of magnitude from the requirements of a realistic space elevator on Earth,[80] the problem is far worse on Venus, where slow rotation rates (with respect to the cloud layer, or particularly with respect to the surface) makes the challenge even greater. High latitude space elevators are even more complicated. However, an alternative exists in the form of structures suspended by kinetic energy. Two notable examples of this are the space fountain and the launch loop. Neither are "near-term" options on Earth, let alone on Venus; however, they present interesting possibilities for the long-term.





Left: space fountain (Credit: Pengo). Right: launch loop (Credit: Keith Lofstrom).

In a space fountain, particles (microscopic or macroscopic) are accelerated around a curve at a base station As they reach the target altitude, they are redirected back down via a magnet, transferring their kinetic energy to the station. Elevators likewise can tap into the force up the upflowing particle stream to hitch a "free" ride. The in-atmosphere portion of the particle stream must be protected in a vacuum tube, but outside of the atmosphere it can fly unshielded. The only energy requirements are to make up for lifting payloads and losses in the system (such as from an imperfect vacuum). The whole weight of the system, including the space station, is borne by the base magnets. On Venus, these would be located on a large (potentially toroidal) airship.

In a launch loop (sometimes called "Lofstrom loop", after its designer), an iron band rotates between two base stations which magnetically deflect it back; the loop flies in an effectively ballistic trajectory, shaped by stabilization cables with material requirements achievable with today's technology and via ISRU. Like with the space fountain, the in-atmospheric portion must be protected by a vacuum sheath. Unlike a space fountain, a launch loop does not just lift vehicles up, but also propels them onto an orbital or transfer trajectory.

A variety of other such concepts exist, such as skyhooks, electrotubes, guns (combustion and magnetic varieties), and many others.[81] While all such technologies are at

[80] Edwards, B. (2003) *The Space Elevator: NIAC Phase II Final Report*.
[81] Davis, E. W. (2004) Advanced Propulsion Study. Warp Drive Metrics / Air Force Research Laboratory. AFRL-PR-ED-TR-2004-0024

this point in time only concepts, they present interesting potential for the long-term on not just Earth, but Venus as well.

Buoyancy control

A lighter than air vehicle faces issues related to an ever-shifting balance between buoyancy and mass. External temperature and pressure changes, and particularly internal temperature changes due to daytime solar heating, can dramatically alter this balance. One common reason for aluminizing aerial vehicle skins is to help maintain a more constant internal temperature and thus buoyancy. For a Landis habitat, this is not an option. On Earth, even the presence of a cloud passing over an airship or moving from snow reflection to bare ground can reduce lift by significant amounts.[82] An airship operating at roughly ambient pressure with excess lift will continue to rise until its ballonets are completely deflated (where it must either vent the primary envelope or burst); an airship with insufficient lift will continue to descend until it is destroyed.

We will examine some of the various means to control buoyancy.

Venting and addition of gases: This is commonly used by airships on Earth, where resupply is readily available. On Venus, the only gases available are produced locally. To some extent, this is possible to do; return vehicle oxidizers (such as boiled-off LOX or MON decomposed to O_2 and N_2) can be used to quickly provide more lift in the habitat, while distilled atmospheric nitrogen can be added more slowly. However, lift conditions will strongly vary between day and night, particularly due to the greenhouse effect within the envelope; repeatedly venting large amounts of gas every day is not a practical solution, and should only be done in emergency situations.

Active propulsion and lift: Upwards or downwards thrust can - at a cost of power - compensate for buoyancy changes. To reduce the mass and energy cost of active propulsion, new airship designs known as hybrid airships maintain a shape as a lifting body. By varying their amount of lift they can compensate for any buoyancy changes.[83]

Airlander 10, the first large-scale hybrid airship. Photo: Philbo Bagshot.

While this works well on Earth for airships transporting goods between different locations and thus always under thrust, a Venus habitat generally has reduced power on hand at night and thus reduced ability to provide lift. That said, a lifting body remains worthy of consideration for one significant reason: it is acceptable, and in fact desirable, to sink to a lower altitude at night when the ambient temperature drops (as covered previously). Hence a lifting body

[82] Khoury, G. A. (2012). *Airship technology*. Cambridge: Cambridge University Press. doi:9781107019706
[83] Khoury 2012.

could allow for a degree of additional payload capacity, of assistance in lofting a heavier return stage.

European Venus Explorer concept art.
Photo: ESA

Superpressure balloons: Rather than remaining the same pressure as their environment, superpressure balloons maintain significantly higher internal pressures and keep a roughly constant volume. Akin to a party balloon, superpressure balloons were used in the Vega programme and are popular proposals for unmanned Venus probes:

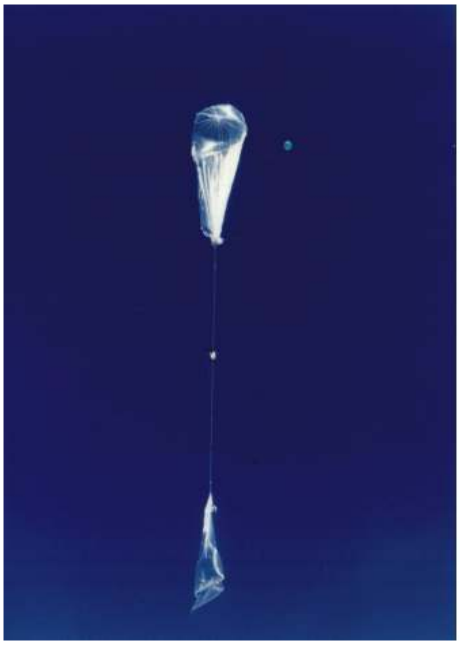
The gas mass inside the volume of a superpressure balloon, as it lacks ballonets, remains constant. As it descends, the surrounding atmosphere becomes denser and its lift increases. As it rises, the reverse happens. Hence, superpressure balloons are passively stable, and present a simple solution for buoyancy control. While this is an excellent solution for small probes, it does not scale up well. As discussed previously, envelope mass is proportional to the tensile load which it must bear due to the pressure differential. On the scale of an entire manned habitat, this would make for a tremendous mass penalty.

Mechanical compression balloons: Similar to superpressure balloons, mechanical compression balloons are able to exert varying pressure and thus greater lift control. They function as a high altitude analogue of the bellows balloon.

Venus altitude cycling balloon concept. Photo: NASA

Phase-change balloons: Also known as "reversible-fluid zero-pressure" balloons. For every stable substance, there are varying temperature and pressure conditions in which it will change phase between a solid or liquid and a gas. It is common for substances to shift phase naturally at different points in an atmospheric column relative to the local temperature and pressure conditions. Wherein a substance boils off lower in the atmosphere and condenses at higher altitudes, or is absorbed into / boiled off from another compound, it provides a passive, semistable form of buoyancy control. This has been demonstrated on

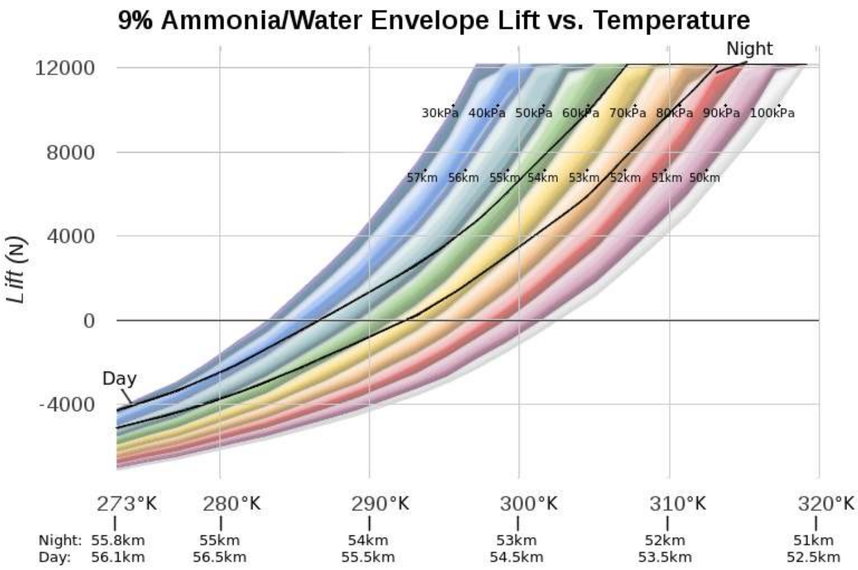
Earth in the ALICE project, which launched reversible methylene chloride balloons between 1993 and 1997.[84]



Balloon ALtItude Control Experiment (ALICE). Photo: NASA

While this approach overcomes all of the disadvantages of the aforementioned concepts, it does have some issues of its own. While initially assumed to provide a stable altitude, it has since been determined that phase change balloons inherently oscillate in the atmosphere relative to their rate of heat exchange with the surrounding air. Interestingly, some proposals for unmanned Venus balloon probes plan to take advantage of this fact to allow the same balloon to passively explore multiple levels of the atmosphere.[85]

In selecting the working fluid, one can choose the stabilization altitude in the atmosphere. By containing the phase change fluid in its liquid state, ascent can be prevented until the liquid is released (useful for landers that need to ascend back up to a target altitude).[86] The optimal fluid for the middle cloud level on Venus is an ammonia-water mixture - the exact ratio determining the stabilization altitude.[87]



Left: A phase-change envelope containing 1000kg of ammonia-water mixture and 20000kg of Venus air. The color bands correspond to different external pressures (top labels), which in turn corresponds to specific altitudes. Plotted over this is the actual temperature/ pressures at 70° latitude during day and night. Lift ranges from negative at low temperatures, as the fluid is overwhelmingly liquid, to very positive as it displaces CO2. The lift curves truncate abruptly as all of the fluid is evaporated.

[84] Nock, K., Aaron, K., Jones, J., Mcgee, D., Powell, G., Yavrouian, A., & Wu, J. (1995). Balloon ALtItude Control Experiment (ALICE) project. *11th Lighter-than-Air Systems Technology Conference*. doi:10.2514/6.1995-1632
[85] Nock, K., Anderson, J., Bachelder, A., Balaram, J., Cameron, J., Heun, M., . . . E, A. (1997). The development of a Planetary Aerobot Testbed. *International Balloon Technology Conference*. doi:10.2514/6.1997-1444
[86] Nock et al, 1997.
[87] Jones, J. (1995). Reversible fluid balloon altitude control concepts. *11th Lighter-than-Air Systems Technology Conference*. doi:10.2514/6.1995-1621

The greater the surface area and thus rate of exchange with the outside atmosphere, the lower the degree of oscillation. The entire lift does not need to be provided by the phase change system - only the difference between daily peak and minimal lift conditions. Hence, the system represents a small “mini-balloon” system within part of the envelope, ideally covering a large surface area but minimal thickness in order to allow for rapid heat exchange.

Substance	Altitude
Water	42 km
50% Ammonia / 50% Water	Begins 49 km, 90% condensed at 55km
88% Ammonia / 12% Water	Begins 54 km, 90% condensed at 60km
Fe0.8Ni0.2Ti(H)x chemisorption	50 km
$CaCl_2(NH_3)x$ chemisorption	57 km
Methylene chloride	58 km

Both ammonia and water are readily produced from Venus’s atmosphere, as will be discussed under *In-Situ Resource Utilization*. Hence an aerial vehicle can arrive with only a minimal stabilization system, facing wilder, high-altitude swings, and produce more before the crew arrives.

A phase-change balloon was proposed for the European Venus Explorer (EVE).

Other options include allowing the humidity to vary within the habitat itself by throttling the transpiration condensers; humidity fluctuations however come at the cost of comfort.

Climate control

As noted under *Deployment: Where and How*, the ability to control the interior temperature would allow for increased lift via flight at lower, hotter altitudes. However, this comes with mass and power constraints which bear examination. As environmental control systems (ECS) for spacecraft involve radically different environments than a Venus aerial habitat, and ECS data for airships on Earth is limited, we will first examine ECS for large commercial aircraft.

Centrifugal impeller blade. Photo: S. J. de Waard

To provide for climate control in a commercial aircraft, bleed air (150°-220°C / 250-450 kPa) is directed into the air cycle machine (ACM). Therein it passes through a heat exchanger, cooling it to ambient. A centrifugal compressor then compresses the air, raising its temperature to around 250°C. After a second heat exchanger cools it to ambient, the air is expanded, cooling it to below ambient. The air is then demisted with a cyclonic separator and provided to the cabin - for a typical commercial aircraft, around 2 kg/s airflow rate,[88] with a system mass of around 80kg.[89] Such a unit can generate temperatures as low as -20 to -30°C

[88] Guo, W., Ke, P., & Zhang, S. (2015). Effects of Environment Control System Operation on Ozone Retention Inside Airplane Cabin. *Procedia Engineering, 121*, 396-403. doi:10.1016/j.proeng.2015.08.1084
[89] Torhorst, S., Hölzel, N., Gollnick, V. (2014) *Identification and evaluation of the potentials of Prognostics and Health Management in future civil aircraft*. European Conference of the Prognostics and Health Management Society 2014.

Unfortunately, this does not work out well for our needs. Aircraft generally use an ACM due to the availability of a bleed air stream (the engines) and a direct compressor drive, sacrificing efficiency (air cycle cooling being inefficient) for reduced mass and simplicity. Lacking jet engines aboard a habitat and requiring efficiency, other options would appear to be superior.

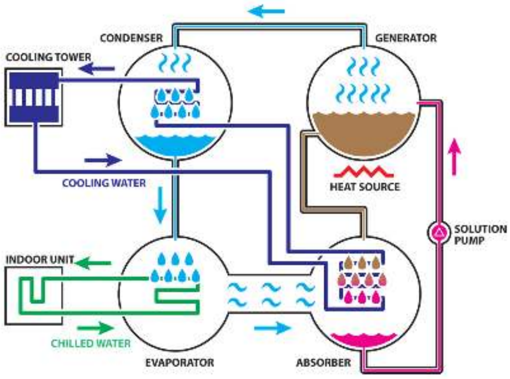
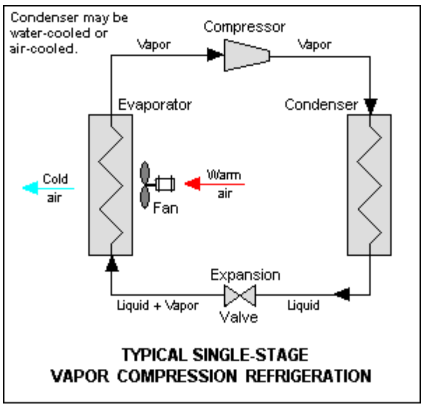


Image: R718.com

On the simplicity side, absorption chilling appears to be a winner, with no moving parts. In an typical absorption chiller, a mixture of fluids is heated in a high pressure chamber, driving off the volatile phase to condense onto the radiator feed and transfer to it the heat of condensation. The pure volatile phase moves to a low pressure chamber where, through evaporation, it chills the cooling feed, then condenses back into the non-volatile phase. A single-pressure variant using three fluids (such as H_2, NH_3 and H_2O) also exists. While a mature technology, absorption chillers unfortunately have poor coefficients of performance (COP), under 2,[90] moving the power requirements to unrealistic levels.

A number of other technologies exist. Thermoelectric (Peltier) cooling systems are very small and light, but have terrible COP (typically 0.4-0.7).[91] Vortex tube systems convert a compressed gas into a hot and cold stream - while turboexpander variants have theoretical maximum COPs as high as 20, traditional real-world vortex tubes have COPs of only 0.03-0.05.[92] Of cryocooling technologies with high-COP room-temperature potential, magnetic refrigeration shows promise, but is still immature in this role.[93] Thermoacoustic refrigeration (standing wave gas cycle), while with potential for advancement, currently does not compete with more traditional systems in terms of COP.[94] In short, the best option appears to be the most mundane: vapour- compression cycle.



Familiar in the form of air conditioners, refrigerators, and large industrial chillers, vapour-compression cycle chillers involve. A compressor takes incoming warmed vapour and compresses it to high pressures, heating it further in the process. Passing through a radiator, it loses heat, condensing the liquid. As the collected liquid passes

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90 *Triple Effect Chiller*. Thermax. Retrieved from http://www.thermaxglobal.com/thermax-absorption-cooling-systems/vapour-absorption-machines/triple-effect-chillers/

91 *How efficient is a thermoelectric cooler?* IV-VI Marlow. Retrieved from http://www.marlow.com/resources/general-faq/14-how-efficient-is-a-thermoelectric-cooler.html/

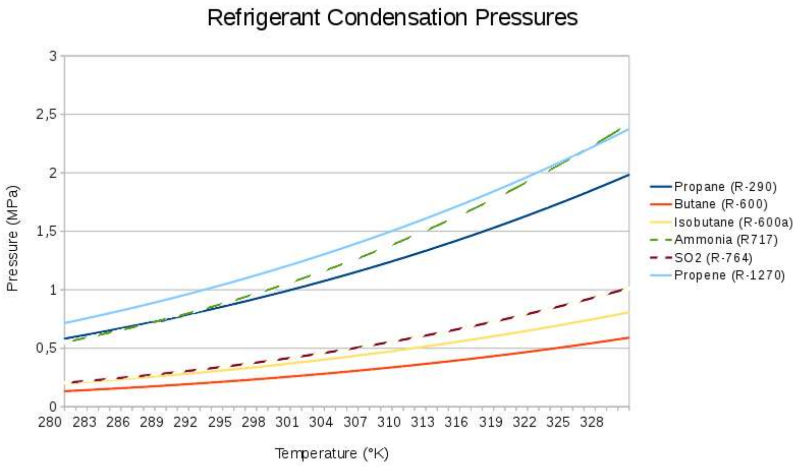
92 Polihronov, J. G., & Straatman, A. G. (2015). The maximum coefficient of performance (COP) of vortex tubes. *Canadian Journal of Physics, 93*(11), 1279-1282. doi:10.1139/cjp-2015-0089

93 Aprea, C., Greco, A., & Maiorino, A. (2014). *Magnetic refrigeration: a promising new technology for energy saving. International Journal of Ambient Energy*, 37(3), 294-313. doi:10.1080/01430750.2014.962088

94 Zolpakar, N. A., Mohd-Ghazali, N., & El-Fawal, M. H. (2016). Performance analysis of the standing wave thermoacoustic refrigerator: A review. *Renewable and Sustainable Energy Reviews*, *54*, 626-634.

Image: Keenan Pepper

through an expansion valve, a fraction of the liquid flashes off, chilling the remainder in the process.



Based data from the NIST Chemistry Webbook. [95]

While the compression requirement increases the complexity and maintenance, vapour cycle coolers are mature and highly efficient. A variety of refrigerants are available that can be produced locally without requiring rare elements such as fluorine.

Even carbon dioxide can be used as a refrigerant; however, it requires very high pressures and is suboptimal for the temperature range at hand.[96] Of the above refrigerants - if properly isolated to prevent the risk of leaks, due to their toxicity - ammonia and sulfur dioxide are the most interesting. Both are readily producible locally, with high heats of vaporization and high volumetric specific heat capacity. Sulfur dioxide is more toxic but less prone to permeation through polymer membranes; it is also produced as a byproduct of direct water and oxygen production from sulfuric acid (see *In-Situ Resource Utilization*). Ammonia is lighter and is one of the most common industrial refrigerants.

Before we can look at mass and power considerations, we need to decide on an architecture. While traditional heat exchanger options exist, an appealing alternative would be to integrate pressurized tube rigidization into the airship on the exterior (such as fins or portions of the envelope), thus having the radiators double as structural elements. The ratio of liquid to gas in the tubes would also vary with altitude, acting similar to a phase-change altitude stabilization envelope. Such tubes would need to drain back toward the interior and be tolerant of changes in airship pitch. Another consideration is the use of the cooling system to drive dehumidification, rather than requiring a separate closed-cycle dehumidifier.

While single-stage chillers with reciprocating compressors as used in home refrigerators and air conditioners may have a dry-air COP of around 3.5 for a relatively small lift, centrifugal and screw industrial chillers often have a COP of 5 or higher for small temperature differences, and top-end magnetic bearing VFD centrifugal compressors can exceed 10.[97] As our needs are both large-scale and aerospace (high budget), we will assume a relatively high dry-air COP of 7 for a lift of 30°C (just under half the Carnot efficiency), with outlet air of 283°K (10°C) chilling the envelope to 293°K (20°C) versus a 313°K (40°C) exterior temperature during the daytime at 0.5 bar. How large of a system would be needed and how much power would it require?

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[95] *NIST Chemistry Webbook*. National Institutes of Standards and Technology.
[96] (2015) *Commercial CO2 Refrigeration Systems*. Emerson Climate Technologies.
[97] (2009) *Energy Efficiency Best Practice Guide - Industrial Refrigeration*. Sustainability Victoria. State Government Victoria, Australia.

Ideally the entire structure would be modeled for CFD simulation, but for now we will do a simple radiation balance and convection calculation. Radiation for a grey body is defined by:

$$j^* = A\ \varepsilon\ \sigma\ T^4$$

Where:

- j^* is the total radiative power across all wavelengths
- A is the surface area
- E is the emissivity
- σ is the Stefan-Boltzmann constant, 5.670373e-8 W/m²-K^{-4}
- T is the temperature in Kelvin

We face a challenge in the presence of transparency with varying internal elements radiating through it; for approximation purposes will simply model it as a 130 meter diameter sphere with an average emissivity of 0.2 and a surface temperature halfway between the exterior and interior (303°K / 30°C). Outbound radiation is thus 5.08 MW. For the incoming radiation, we will treat it as representing a scenario where the equilibrium interior temperature due to sun exposure would be 15° over ambient (328°K / 45°C); this yields 6.97 MW incoming radiation, for a net difference of 1.89 MW.

For convective losses, we will use Newton's Law of Cooling:

$$P = h\ A\ \Delta T$$

Where:

- P is the heat energy transferred per second (power)
- h is the heat transfer coefficient
- A is the surface area, $4\ \pi\ r^2$
- ΔT is the temperature difference (20°K)

Subsequently, we calculate the heat transfer coefficient as:

$$h = Nu\ k\ /\ L$$

Where:

- Nu is the Nusselt number
- k is the fluid's thermal conductivity - for CO_2, 0.01784 W/m-K
- L is the characteristic length (for a sphere, the diameter) - 130m

Using the Churchill correlation for a sphere:

$$Nu = 2 + 0.589\ Ra^{1/4}\ /\ (1 + (0.469\ /\ Pr)^{9/16})^{4/9}$$

Where:

- Ra is the Rayleigh number
- Pr is the Prandtl number

$$Ra = Gr\ Pr$$
$$Pr = c_p\ \mu / \mathrm{k}$$
$$Gr = g\ \beta\ \Delta T\ L^3 / \nu^2$$

Where:

- Gr is the Grashof number
- c_p is the specific heat - for CO_2, 844 J/kg-K
- μ is the dynamic viscosity - for CO_2, 1.65e-5 Pa-s = N-s/m²
- g is the local gravitational acceleration - at altitude, 8.7m/s²
- β is the coefficient of thermal expansion - for CO_2, 3.2e-3 1/K.
- ν is the kinematic viscosity - for CO_2, 1.844e-5 m²/s

Putting this all together we get:

$$Gr = 3.60e15$$
$$Pr = 7.81e15$$
$$Ra = 2.81e15$$
$$Nu = 3300$$
$$h = 0.452$$
$$P = 481kW$$

Combining radiative with convective power, we get a cooling need of 2.97MW.

A common alternative formula for the Nusselt number involves moving flow, although it is only valid for a Reynolds number of 3.5 to 70000. For an airflow velocity of u=10m/s:

$$Re = u\ c_p / \nu \mathrm{\ {\sim}= 70{,}500{,}000}$$
$$Nu = 2 + (0.4\ Re^{1/2} + 0.06\ Re^{2/3})\ Pr^{0.4}\ (\mu_\infty / \mu_s) \sim= 12300$$
$$h = 1.69$$
$$P = 1.79MW$$

This yields a total cooling need of 4.61MW. In the two cases, the cooling power needs at COP=7 are around 424kW and 659kW, respectively. A typical ammonia chiller, made from steel and including traditional heat exchangers may run around 20W/kg. We will assume that via optimization (such as carbon overwrap vessels, composite lines, heat exchange via reuse of structural elements, mass savings from integrating dehumidification into cooling, etc), we can bring this to 80W/kg; the system mass would come in at 5.3 to 8.2 tonnes. The refrigerant charge would be on the order of 1-2 tonnes if the primary loop is small.

Moisture in the air - and thus dehumidification - increases power requirements but does not dramatically increase the required system mass. Using the Buck equation for saturation vapour pressure in pascals:

$$P = 611.21\ e^{(18.678\ -\ T°C\ /\ 234.5)\ (T°C\ /\ (257.14\ +\ T°C)}$$

Saturation pressure at 20°C is thus 2338 Pa, while at 10°C it is 1228 Pa. At 60% relative humidity (the upper recommended bound for interior spaces[98] [99]), water vapour would be 1.3g/m³.

Higher humidity levels cause a greater proliferation of dust mites and have a higher heat index, but reduce problematic transpiration from crops. Higher humidity levels increase the rate of water vapour recovery via air conditioning. At 70% humidity, condensation would be 3.1 g/m³; at 80%, 4.9 g/m³; at 90%, 6.7 g/m³; and at 100%, 8.5 g/m³; this is relative to an air mass of around 600g/m³. For 4 MW of cooling, airflow is around 80 m/s; dehumidification rates are thus 0.88 kg/s (60% RH), 2.04 kg/s (70% RH), 3.19 kg/s (80% RH), 4.33 kg/s (90% RH), and 5.45 kg/s (100% RH). These are very significant water recovery figures, in line with or exceeding transpiration rates (see *Transpiration*), and thus with potential to reduce or eliminate the need for a separate condenser.

Producing the refrigerant charge in-situ is not implausible. However, the mass of the chiller itself appears likely to be uncomfortably high, and the power requirements are very significant. That said, none of these extremely rough mass and power figures are fundamentally prohibitive - and may be justifiable with certain design configurations, either due to temperature or dehumidification constraints.

[98] Balaras, Constantinos A.; Dascalaki, Elena; Gaglia, Athina (2007). *HVAC and indoor thermal conditions in hospital operating rooms*. Energy and Buildings. 39 (4): 454. doi:10.1016/j.enbuild.2006.09.004.
[99] Wolkoff, Peder; Kjaergaard, Søren K. (2007). *The dichotomy of relative humidity on indoor air quality*. Environment International. 33 (6): 850–7. doi:10.1016/j.envint.2007.04.004. PMID 17499853.

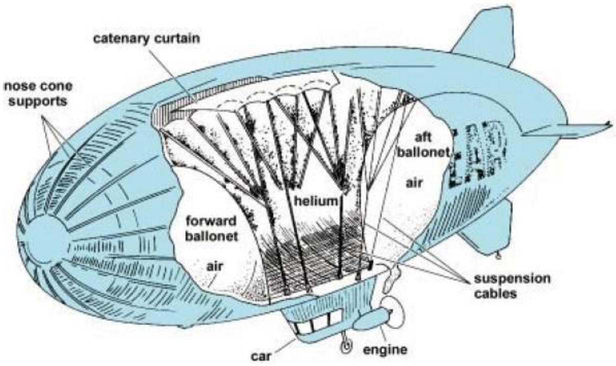
4. Design

Structural integrity

In a Landis habitat, the crew lives within the envelope of an airship,[100] rather than slung underneath it as in the early-phase HAVOC designs.[101] However, this provides only a general concept of what needs to be present and where it should be located within the structure. First one should consider airship types.

- **Rigid**: A structural frame, rather than overpressure, maintains the shape. Lift against the envelope is immediately transferred to the frame
- **Non-rigid**: No rigid structural reinforcement is utilized; all loads are directly supported by catenary curtains and transferred by cables. Commonly called a “blimp”.
- **Semi-rigid**: Loads are transferred from catenary curtains to a rigid keel, on which other loads are supported.

Non-rigid and semirigid airships contain ballonets - variable-sized envelopes of external gas that respond to changes between external and internal pressure. In rigid airships, an outer skin maintains the form, inner gas cells provide lift, and the void space between them functions as ballonets.



Stockbridge et al 2012.[102]

In non-rigid and semi-rigid airships, *catenary curtains* are used to spread out the load of structures across the upper envelope fabric. In rigid airships, lift is transferred from the gas cells to the frame, which in turn bears loads.

As a general rule, non-rigid airships tend to be the most economical at smaller sizes, while rigid airships tend to be the most economical at larger sizes, as a result of scaling factors. The formula for stress in a spherical shell, as noted previously, is:

$$\sigma = PR/2t$$

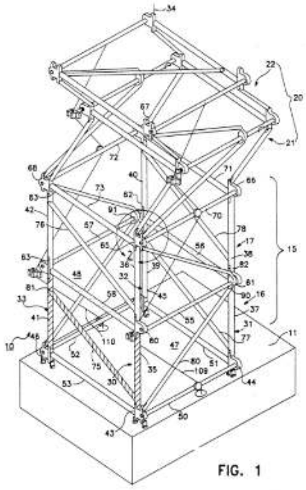
Where:

- σ is stress
- P is pressure
- R is the radius
- t is the shell thickness

[100] Landis, G. A. (2003). Colonization of Venus. AIP Conference Proceedings. doi:10.1063/1.1541418
[101] Arney, D. C., & Jones, C. A. (2015). High Altitude Venus Operational Concept (HAVOC): An Exploration Strategy for Venus. *AIAA SPACE 2015 Conference and Exposition*. doi:10.2514/6.2015-4612
[102] Stockbridge, C., Ceruti, A., & Marzocca, P. (2012). Airship Research and Development in the Areas of Design, Structures, Dynamics and Energy Systems. *International Journal of Aeronautical and Space Sciences, 13*(2), 170-187. doi:10.5139/ijass.2012.13.2.170

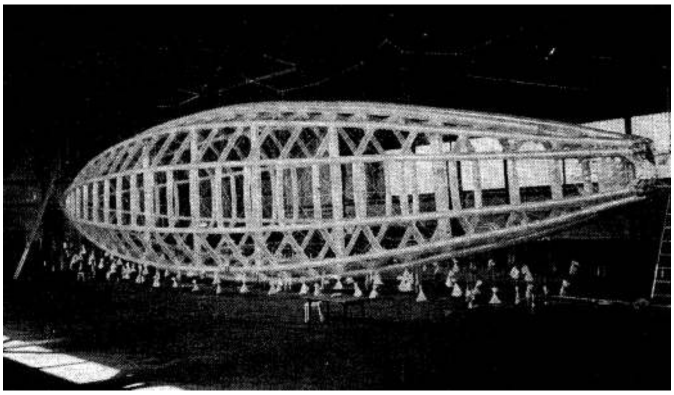
Hence, as the radius rises, the thickness must also rise linearly in order for stress to remain constant. Hence, envelope mass increases approximately in accordance with the radius cubed, the same as the lift.

A way to work around this is to reduce the overpressure. However, the overpressure is what maintains the airship's shape against applied forces. Hence the use of a rigid frame, which resists deformation. In the large scale, rigid-framed airships tend to yield better payload margins.[103]



Patent image for the ADAM collapsible truss system by the AEC-Able Engineering Company (since acquired by ATK)[105]

Therein lies a problem: rigid-framed airships don't historically pack down well or deploy quickly. While collapsible trusses have long existed,[104] they tend to leave significant amounts of airspace, both between tubes and within tubes themselves. Furthermore, a rigid airship doesn't use linear booms, but rather a latticework of trusses. Even a simpler, partially-rigid modern structure such as that of the Zeppelin NT (75m long, 1.1 tonne) still contains dozens of truss interconnections.



Bracher et al (1997)

An alternative rigidization system worth noting is the pressurized tube concept pioneered with the Airboat.[106] In this system, a frame is used, but instead of being comprised of rigid members, it is comprised of collapsible film tubes, pressurized for rigidity. In the prototype implementation, the tube material was 20μm Nalophan (PET), no fibre reinforcement, and with a rupture pressure of 200kPa.

Perhaps the most exciting form of rigidization is that of locking rollable composite trusses, built around rollable tubes (which themselves have been an active research topic since the 1960s). Akin to a tape measurer, a rolling tube uses an internal tension in the unreeling sheet to achieve the desired shape - good for resisting bending loads but suboptimal in handling torsion. More recent designs, such as those from Roccor and Composite Technology Development, utilize locking systems to overcome this weakness.

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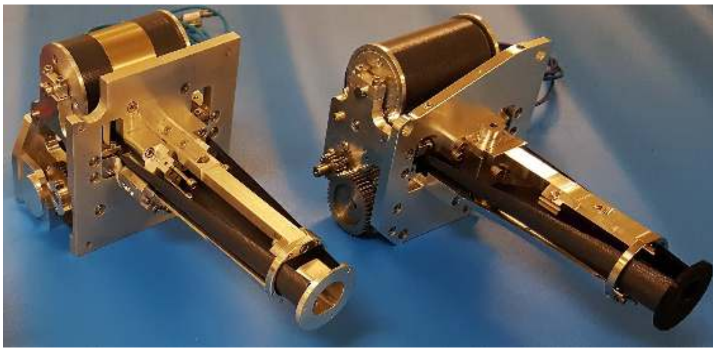
[103] Khoury, G. A. (2012). *Airship technology*. Cambridge: Cambridge University Press. doi:9781107019706
[104] Tibert (2012). *Deployable Tensegrity Structures for Space Applications*. Kungl Tekniska Högskolan, doctoral thesis. TRITA-MEK. ISSN 0348-467X
[105] Warden, R. M. (1993). *U.S. Patent No. US5184444 A*. Washington, DC: U.S. Patent and Trademark Office.
[106] Bracher, J., & Steibli, M. (1997). The airboat, a chance for environmentally compatible transportation. *12th Lighter-Than-Air Systems Technology Conference*. doi:10.2514/6.1997-1458



Above: Roccor rollable tubes, in various stages of deployment.

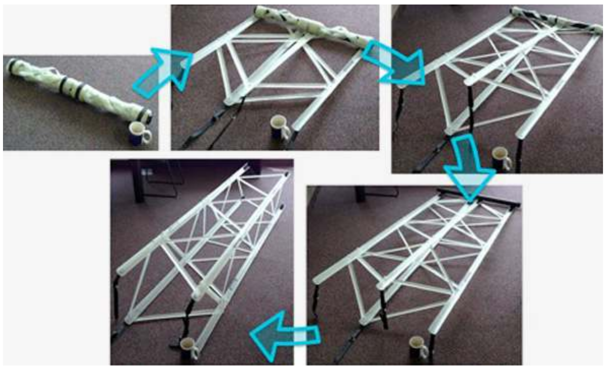
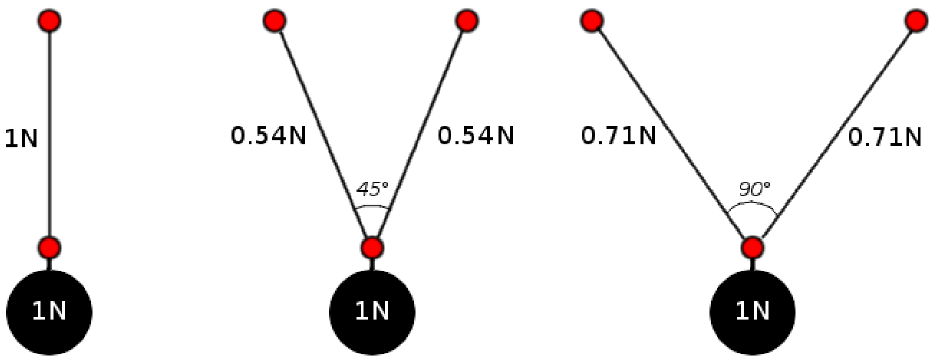


Photo: Roccor

Roccor's design allows one to achieve approximately half the torsional stiffness of a fully sealed composite tube.[107] Individual tubes can, in turn, be formed into more complex structures such as trusses. Embedded elements can be co-deployed with trusses and tubes, such as wire harnesses. In the case of an aerial habitat, further developing such a technology to co-deploy structural supports with hydroponics conduits inside would be of great utility.

All rigidization comes with some disadvantages versus a fully flexible envelope - greater complexity and more light obstruction to the interior being examples. However, offering a potential means for reduction of system mass, rigidization systems are worth investigating. An additional reason that rigidization bears consideration: if we are confined in our construction to existing hangars (long but narrow), then the return stage's mass will be borne across a long span - meaning that it either must be a very long distance beneath the habitat (implying extra cable masses and reduced crew accessibility), or that its support cables will be highly angled and thus imposing excess stresses that need to be countered.



Above: Vector forces increase the stress in supporting cables relative to the loading angle.

[107] Davis, B. L., Francis, W. H. (2014) *Big Deployables In Small Satellites*. SSC14 VII-4.

Some degree of rigid rigidization can be used to reduce this problem.

Components

As described previously, in non-rigid airships, loads are borne from catenary curtains. Even in rigid airships, the frame is sparse, often with few to no rigid components away from the skin; cables give access to interior areas. This top-down orientation provides a key difference in construction: on Earth we're used to bearing loads from the ground up, and likewise with Mars. On Venus you're dealing with structures primarily in tension rather than compression. From a mass perspective, this is advantageous; however, it does require a rethink of how we consider design - in particular, where each element should be located within the habitat.

- **Ascent vehicle***:* There is only one option for where to house this element; to ensure habitat stability, such a large mass must be slung underneath the airship. An ideal scenario allows for multiple empty ascent vehicles to be stowed at once, but only one fully fuelled (due to lift constraints well discussed elsewhere) - and when both fuel and oxidizer are aboard, it must be slung at a safe distance beneath the habitat for explosion safety.

- **Human habitation**: Three factors argue that this should be located near the top. The first is a common factor: the minimization of the length of support cables, particularly in the case of a non-rigid airship. A second factor is that the ballonets are located on the bottom, as the air in them is heavier than that used for lift; if ballonets were located near the top, the habitat would roll when the ascent vehicle was launched. As ballonets undergo a great degree of expansion and contraction due to the varying lift requirements, this leaves only a proportionally small horizontal slice at the top unthreatened by their expansion. Lastly, in the event of a major envelope leak, the external carbon dioxide atmosphere will pool at the bottom, posing a risk of smothering the occupants if they were located in that environment. By contrast, a leak poses little risk to "sinking" the habitat, as the vast majority of the mass of the airship can be jettisoned - in the worst case, including the ascent vehicle.

  Note that there must be a pathway - regardless of ballonet inflation level - from the crew habitation areas down to the bottom where the ascent vehicle must be slung. Cables / netting or rigid structure must prevent the ballonets from closing off this "central channel".

- **Agriculture**: The same factors as for habitation apply to agriculture. To enable ease of access, human habitation should be largely central, with agriculture radiating out from it. Since agriculture involves the movement of water (such as in ebb and flow hydroponics), agriculture should arguably be done in an even number of vertical layers, flowing outwards at a slight downward angle, then inwards, such that the nutrient solution ends up collecting in the center underneath the crew areas, ready to be pumped back up.

- **Livestock**: While the same factors apply to livestock (if present) as to humans, other factors such as noise and odor argue for locating them away from people. A reasonable “compromise” location thus might be a platform located in the central channel which yields access to the bottom of the habitat - that is to say, somewhere beneath the crew area but above the bottom of the envelope. Contrarily they could be located in upper areas away from crew habitation, so long as mass is distributed evenly.

- **Industrial hardware**: Industrial hardware serves many purposes, including envelope gas scrubbing and in-situ resource production (ascent vehicle propellant, oxygen, water, and various industrial chemicals for uses discussed under *In-Situ Resource Utilization*). As the gathering of external gases/mists for ISRU is likely to be done either on the underside (runoff from the envelope, if present) or near the propulsion system (maximum airflow for scrubbing), the feedstocks are located underneath the habitat. Likewise, the main demand for the output - the ascent vehicle - is located underneath the habitat. Lastly, increasing local production invariably leads to the use of a number of highly toxic compounds which could potentially leak (hydrogen fluoride, phosgene, hydrogen cyanide, etc), as well as explosion hazards. Hence a reasonable location for most industrial systems could be to locate them near propulsion underneath the envelope in their own enclosed environment, rather than in the primary envelope. Another option would be to locate it in an underside empennage element. The greater the separation between the industrial section and the habitat, the better - but it still must be accessible.

- **Manufacturing**: Maintenance and expansion of a habitat invariably involves local manufacture, which involves processes that create noise, fumes, sparks, and other factors that one generally does not want located near crew areas. The areas most in need of the outputs of manufacturing are located underneath the envelope. Therefore it might be reasonable to locate manufacturing in the bottom-access channel just above the bottom of the envelope. As nobody would sleep in a workshop, the aforementioned smothering risk is reduced.

- **Phase-change buoyancy control**: In order to respond quickly to external temperature changes, if any phase-change gas envelopes are used, they should run along the exterior envelope. Since ammonia is offensive-odored, toxic, prone to permeation, and because the envelopes presents such a large surface area, it should be located up inside the ballonets.

- **Fuel cell stacks**: In addition to providing better energy density than batteries, fuel cells help deal with the deuterium issue (see *Deuterium and power storage issues*). Due to their higher efficiency, longevity, power density, and chemical storage options, HCl fuel cells appear more appropriate than H_2O fuel cells.[108] Wiring and tubing mass

[108] Huskinson, B., Rugolo, J., Mondal, S. K., & Aziz, M. J. (2012). A high power density, high efficiency hydrogen–chlorine regenerative fuel cell with a low precious metal content catalyst. *Energy & Environmental Science, 5*(9), 8690. doi:10.1039/c2ee22274d

would argue for a location as close to the industrial section as possible. Since toxic chemicals are involved, they should not be co-located within the habitable portion of the envelope.

Beyond location, we should take into account considerations beyond what is needed during “typical” habitation on Venus. One such element is the presence of a rigid “shelter”.

While most “buildings” in the habitat have no need for rigid walls or pressure-tight structures - which pose a great mass and packing penalty - having one such room available is worth consideration. While the habitat is en-route, having a section to slightly pressurize internal cargo means the ability to transport ordinary consumer goods that do not have vacuum compatibility, rather than having to re-engineer every item sent to the planet. It would also provide a convenient environment for packing loose items. When the habitat is deployed, in addition to serving as a functional room in its own right, it could provide an area for people to shelter in the event of dangerous conditions within the envelope (toxic gases, insufficient oxygen, etc), with its own oxygen tank and CO_2 scrubbing.

If we operate on the premise of such a shelter, then we need to colocate the toilet within it. We also need to look at its size. Unlike rooms with no rigid walls, which can include fold-out leafs to expand their size, the shelter can be no larger than the rocket fairing’s internal diameter minus some overhead. So we need to examine fairing internal dimensions:

Fairing limitations

Rocket	Variant	Width (mm)	Height (mm)	Nom. LEO Payload (kg)
Long March 3[109]	4000F 4000Z 4200F 4200Z	3600 3650 3850 3850	6420 6662 6850 7331	6000
Long March 5[110]	-	*<5200*	*<12500*	*14000*
H-IIB[111]	4S 5S	3700-3750 4600	10230 9124.5	8000
Ariane 5[112]		4570	15589	16000 (5G)[113]
Atlas 5[114]	4-m LPF 4-m EPF 4-m XEPF 5-m Short 5-m Medium 5-m Long	3750 3750 3750 4572 4572 4572 *<7200*	9397.0 10311.4 11225.8 10184.4 12927.6 16484.6 *<32300*	8123 (0 SRBs) to 18814 (5 SRBs); *29400 (HLV)*
Delta IV-Heavy[115]	Long Metallic	4572 4572	~16200 16484	28790
Proton-M[116]	PLF-BR-13305 PLF-BR-15255	3866 3865	11305 15225	22000[117]
SLS[118]	*Block 1* *Block 1B 5m* *Block 1B 8.4m* *Block 2B*	*4600* *4600* *7500* *9100*	*<19100* *<19100* *<19100* *<31100*	*70000* *105000* *105000* *130000*
Falcon[119]	F9 v1.2 *Heavy*	4600	11000	22800[120] *54400*[121]
ITS[122]	-	*<12000*	-	*300000*
New Glenn[123]	*2-stage* *3-stage*	*?* *<7000*	*?*	*45000* *?*

Long March 7 uses similar diameter fairings as 3 but different lengths and greater payload.[124] *All instances where only outer diameters are known are listed as “<X” where X is the outer diameter; subtract approximately 0.5m. Italics indicates that the design has not yet been flown. ITS based on spacecraft core dimensions.*

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[109] *LM-3A Series Launch Vehicle User’s Manual, Issue 2011*. China Great Wall Industry Corporation.
[110] *Cheng Zheng 5 (Long March 5)*. China Space Report. Retrieved from https://chinaspacereport.com/launch-vehicles/cz5/
[111] *H-IIA User’s Manual Ver. 4.0 2015*. MHI Launch Services.
[112] *Ariane 5 User Manual*. Arianespace. Issue 5, Revision 2, October 2016
[113] *Ariane 5G*. Encyclopedia Astronautica. Retrieved from http://www.astronautix.com/a/ariane5g.html
[114] *Atlas V Launch Services User’s Guide*. United Launch Alliance. March 2010.
[115] *Delta IV Launch Services User’s Guide*. United Launch Alliance. June 2013.
[116] *Proton Launch System Mission Planners Guide*. International Launch Services. Data as of 2009.
[117] Proton-M / Briz-M - Launch Vehicle. Spaceflight 101. Retrieved from http://spaceflight101.com/spacerockets/proton-m-briz-m/
[118] *Space Launch System (SLS) Program Mission Planner’s Guide (MPG) Executive Overview*. NASA. SLS-MNL-201 ver. 1. 22 Aug, 2014.
[119] *Falcon 9 Launch Vehicle Payload User’s Guide*. SpaceX.
[120] *Falcon 9*. SpaceX. Retrieved from http://www.spacex.com/falcon9
[121] *Falcon Heavy*. SpaceX. Retrieved from http://www.spacex.com/falcon-heavy
[122] *NINA 5 Final Draft Mars Talk Revised v4*. SpaceX. Retrieved from http://www.spacex.com/sites/spacex/files/mars_presentation.pdf
[123] Foust, J. (7 Mar. 2017). *Eutelsat first customer for Blue Origin’s New Glenn.* Space News.
[124] *Long March 7 Launch Vehicle*. Spaceflight 101. Retrieved from http://spaceflight101.com/spacerockets/long-march-7/

If one doesn't care about mandating the use of a super-heavy launch vehicle then they can design to SLS, ITS, or other proposed / in-development systems with large fairings. However, such a launch vehicle is not a fundamental requirement. As discussed previously, the envelope itself packs down into a surprisingly small volume regardless of what thickness and packing ratio parameters one chooses, and most required habitation structures - requiring no rigid walls or ceilings - collapse into a small space. Hence, designing for a 4-5m diameter fairing seems the most logical solution. A <4.5m diameter shelter sounds like a reasonable compromise, being compatible with the Ariane 5, Delta IV-Heavy, Falcon Heavy, H-IIB, and future systems such as the SLS and ITS.

Accounting for the space for the bathroom - which should ideally open to both the inside and outside so that people don't have to interrupt others' work to use the toilet - you're left with a room that's a reasonable size for a laboratory / control center. Let us examine some of the other types of rooms that should be considered. Most should have a flexible solar "tent" as walls that can be raised or lowered as desired for light and privacy, as well as surge battery packs, power wiring / outlets, and room lighting.

- ***Kitchen***: Accounting for food storage space, which should be colocated, this room requires fold-out leaves or a roll-out floor design to increase the area. Since tensile loads are ultimately borne from overhead, and food and liquid storage is heavy, these should be supported directly from cables rather than resting on a floor which must in turn be supported. A large refrigerated area can be provided by use of a collapsible tent of flexible aluminized bubble plastic or aluminized foam. Ovens can likewise be collapsible, although the material must tolerate prolonged operation at up to 250°C. The kitchen, as the location food is to be stored, is a logical location for food processing, including winnowing, grinding, drying, etc. Enclosed food production systems with a small footprint, such as mushroom cultivation on agricultural waste, could likewise be slung from support cables. While it may be tempting to locate some livestock in the kitchen for the same convenience reason, hygiene and noise argue against this possibility.

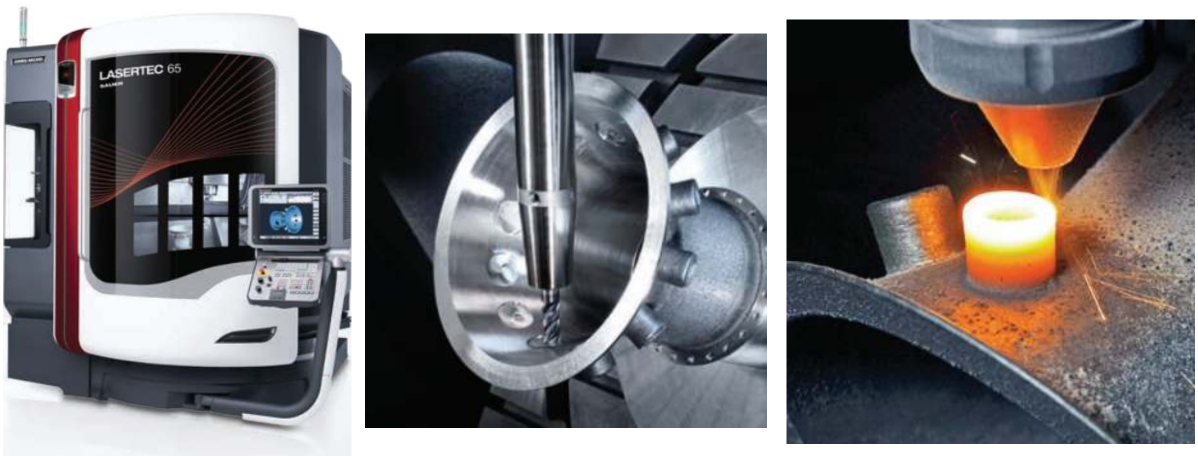
- ***Common area***: A society needs a place to gather. A common area with fold-out leaves can allow for socializing and entertainment, with (ideally hanging, detachable) sofas and chairs; a television for movies, games and video messages; and a multipurpose gaming table. This can double for use in medical procedures via isolation with a plastic curtain and covering with plastic sheeting. Shelving is required. Such a room could be located in a hanging stack between the shelter/lab (top) and kitchen (bottom).

- ***Bedrooms***: One of the great advantages of a Landis habitat is the fact that it has extensive room for people to move around in, and bedrooms should be designed to exploit this. Each bedroom should consist of a composite floor, a solar tent, a composite bed frame (ideally hanging), a lightweight mattress, shelving, a sink fed from a dehumidifier / condenser (see *Transpiration*) and a small water tank (ideally gravity-fed, hung above the room). As a bedroom would be light enough to move, a crew member could hang their room up from catenaries anywhere they wanted, whether right in the center or far from everyone else.

- ***Shower***: Only one shower should be required in the beginning - ideally an isolated solar tent-encircled structure with a water recycling system (similar to the OrbSys[125] or EcoVéa[126] systems). Water recycling translates to to not simply a reduction in water tankage and collection requirements, but also heating requirements. If located on the "outskirts" of the inhabited area, showering could be done with tent open to the outer envelope, providing a view while still maintaining privacy.

- ***Livestock platform***: With the large amount of room provided by a Venus habitat, raising livestock becomes much more practical than on a Mars habitat (see *Animal products)*. Aquaponics is ideally collocated with livestock, since many of the outputs from livestock can be inputs to aquaponics (manure fertilizes algae growth and tilapia consume it directly, for example). Contrarily, if at least sections of aquaponics are kept hygienic, low density algae/fish farming could additionally be used for swimming.

- ***Manufacturing platform***: Beyond a solar tent, manufacturing additionally requires a durable safety tent to resist sparks, molten metal droplets and fast-moving debris, such as bits of metal or shattered cutting discs. The floor surface must be able to withstand drips of molten metal from welding and resist spilled corrosive chemicals. Shelving and flooring should be heavy-duty, as very heavy systems may be temporarily or permanently located there. A particularly heavy floor element would be a multi-material 3d printer / CNC miller.



The DMG MORI Lasertec 65 combines CNC milling with laser deposition welding. With this printing technique, the sprayed powder gets absorbed and melted into a melt pool created by the laser, to rapidly produce parts with excellent mechanical properties..[127]

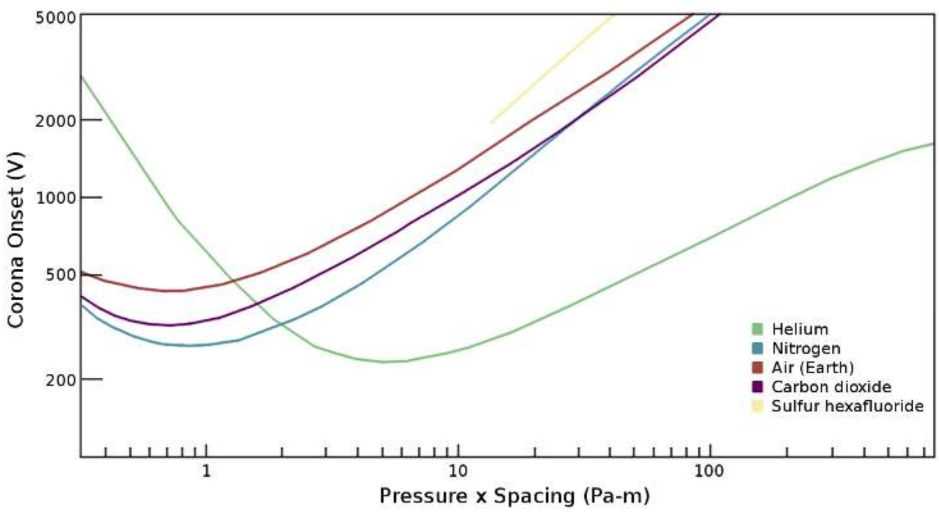
Such a system could easily amass a large fraction of a tonne or more even after weight reduction, and take up 5-10 square meters of floor space on its own.

[125] Orbital Systems. Retrieved from https://orbital-systems.com
[126] Reveeco. *EcoVéa*. Retrieved from http://www.reveeco.com/ecovea.html
[127] ALL IN 1: Laser Deposition Welding & Milling Additive Manufacturing in Milling Quality. 2014, DMG / MORI SEIKI Europe AG

Lightning

A design issue worthy of consideration is lightning. Lightning has been detected on Venus, and appears to be at least as common as on Earth.[128] However, its nature and location has as of yet not been established; it is difficult to say much more than that it does not appear to be very high altitude,[129] and that it is probably weaker than lightning on Earth.[130]

Large helium airships generally avoid flight near storms and typically utilize simple one-wire lightning protection systems, but lightning strikes on aerostats tethered with conductive cables are common.[131] On Earth, helium - having 15% the dielectric strength and ⅓ the breakdown voltage of air - tends to encourage lightning to flow through its volume rather than around it. However, a Landis habitat, filled with oxygen and nitrogen, has a similar dielectric strength[132] and breakdown voltage to the outside environment.



Based on Dunbar (1966)[133]

Gas	Dielectric Strength*
Air	0.97
CO_2	0.85
He	0.15
N_2	1
O_2	0.92

** Relative to nitrogen*

If carbon fibre is used as a reinforcing or catenary cable material, any electrical discharges would tend to flow through it, due to its higher electrical conductivity.[134]

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[128] Russel, C. T., Hart, R. A., Zhang, T. L. (2014) Venus Express Contributions to the Study of Planetary Lightning. *European Planetary Science Congress*. Vol. 9, EPSC2014-34, 2014
[129] Moinelo, A. C., Abildgaard, S., Muñoz, A. G., Piccioni, G., & Grassi, D. (2016). No statistical evidence of lightning in Venus night-side atmosphere from VIRTIS-Venus Express Visible observations. *Icarus, 277*, 395-400. doi:10.1016/j.icarus.2016.05.027
[130] Gurnett, D. A., Zarka, P., Manning, R., Kurth, W. S., Hospodarsky, G. B., Averkamp, T. F., . . . Farrell, W. M. (2001). Non-detection at Venus of high-frequency radio signals characteristic of terrestrial lightning. *Nature, 409*(6818), 313-315. doi:10.1038/35053009
[131] Plumer, A., Perala, R. A., & Jaeger, D. (2001). Lightning and Electrostatic Charge Effects And Protection Design Approaches For Large Transport Airships.
[132] Berger, L. I. (1998). Dielectric strength of insulating materials.
[133] Dunbar, W. G. (1966). Corona onset voltage of insulated and bare electrodes in rarefied air and other gases. *Boeing*. Technical report AFAPL-TR-65-122
[134] Elimat, Z. M., Hamideen, M. S., Schulte, K. I., Wittich, H., Vega, A. D., Wichmann, M., & Buschhorn, S. (2010). Dielectric properties of epoxy/short carbon fibre composites. *Journal of Materials Science, 45*(19), 5196-5203. doi:10.1007/s10853-010-4557-6

Damage to blimps from lightning strikes on Earth tends to be surprisingly low, despite the fact that most Earth blimps are not made from oxidation-resistant fluoropolymers like the skin of a Venus habitat. Rather, lightning strikes tend to create a series of pinholes in the impacted area(s).[135]

Movement around the habitat

In designs employing rigidization, large amounts of the habitat can be accessed by utilizing the structural elements as walkways. However, even with rigidization this will not give access to all parts of the envelope for maintenance and repairs.

Relocatable walkways could provide temporary access between reinforcing trusses, as could mobile cranes, designed to be affixed to structural elements. However, these provide no access to structures away from rigid elements.

“Personal flying machines” or drones could potentially provide an option to access any location, inside or out - albeit one with numerous drawbacks and potential for damaging the habitat or envelope itself. The best option for general purpose access may be cable ascenders, an increasingly mature technology.

In a non-rigid airship, ascenders could climb support cables hanging from horizontal cables strung up near the top of the envelope (with sheaves to bypass supporting catenary curtains, akin to a ski lift’s tower sheaves). In a rigid airship, cables can be strung from the framework as needed. Hanging from cables strung from multiple points and adjusting the lengths between them would allow one to reach any location in 3-space between those points. A hand crank or simple prusik would provide an emergency backup climbing method in case of equipment failure.

The Atlas APA-5 rope ascender weighs 9.1kg (including a swappable battery), lifts 270kg, can climb 213 meters per charge, and can be operated by remote control.[136] Photo: Atlas Devices

[135] Plumer et al 2001
[136] *APA-5 Powered Rope Ascender*. Atlas Devices. Retrieved from https://atlasdevices.com/products/ascenders/apa-5-powered-rope-ascender-std-config/

Regardless of the mechanism to maneuver around the envelope, tools on poles could be used to reach any hard-to-reach areas, such as sections of envelope located above the highest accessible locations.

In addition to moving people around, heavy cargos need to be able to be moved - new equipment, locally produced hardware, dredged materials from the surface, etc. This suggests the presence of one or more interior winches, ideally designed to be readily relocated to different parts of the habitat. As described in *Docking, Ascent and Descent*, an additional large, high power winch is needed underneath the habitat for stowing and launching docked rockets.

Gas sensors and alarms should be present at varying points around the envelope, to alert people working near them of leaks. While Venus's atmosphere does not pose acute toxicity if diluted into breathable air (and none if sufficiently diluted),[137] its primary threat is suffocation by displacing oxygen in low-lying areas. It is unknown at this point as to how strong of an odor the atmosphere has; however, the levels of sulfur dioxide should be above the human odor threshold.[138] All outlying inhabited areas (such as bedrooms) as well as the laboratory / shelter will require gas masks and emergency oxygen.

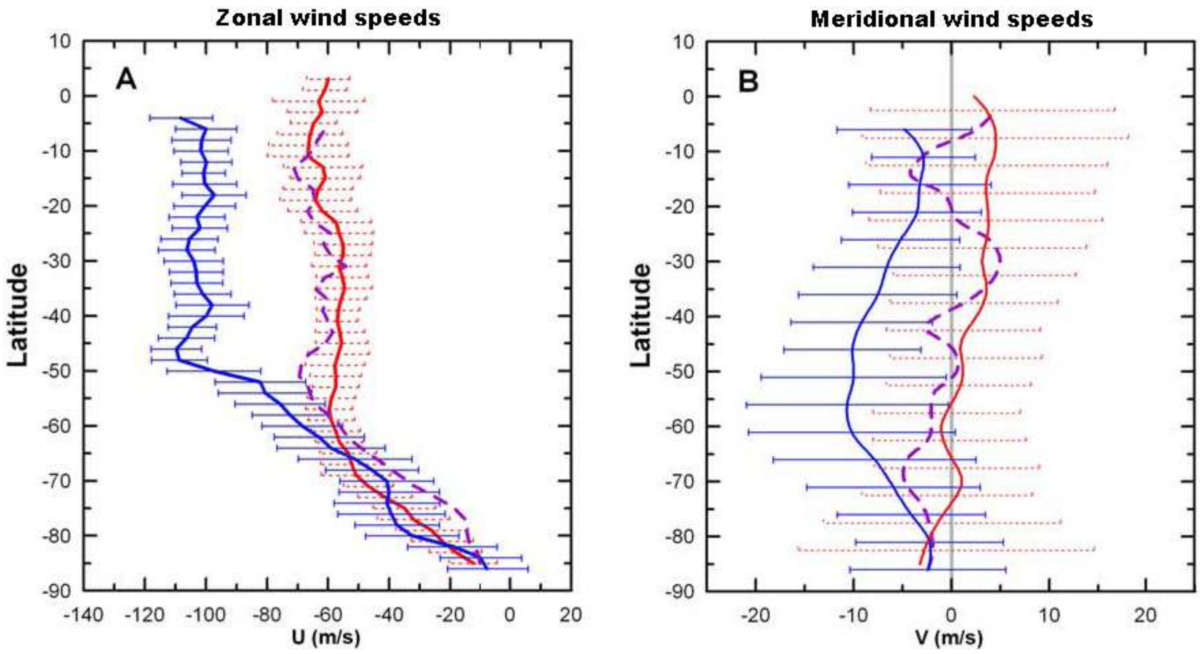
Habitat propulsion

Propulsion is needed in order to:

- Present an minimal drag profile to hazardous turbulence
- Rotate the craft to the angle in which forward motion is desired
- Move the craft to resist meridional winds
- Move the craft to target surface features for study
- Move the craft to assist in docking
- Assist in altitude maintenance
- Relocate the habitat between the northern and southern hemispheres, in combination with high altitude excursions
- Keep the day length consistent, in order to track the orbital period of any relay satellites

In no realistic situation, however, can propulsion overcome the immense zonal (east to west) winds, except in the extreme polar locations.

[137] CO_2 (97%): LC50 47% (rat), TCLo 1% (rat)
SO_2 (150 ppm): LC50 2520 ppm (rat, 1h), TCLo 3000 ppm (human, 5m), 12 ppm (human, 1h), 3ppm (Human, 5d)
CO (17 ppm): LC50 1807 ppm (rat, 4h), LCLo 5000 ppm (human, 5m), 650 ppm (human, 45m)
H_2SO_4 (~1-30 mg/m^3): LC50 18mg/m^3 (guinea pig), LCLo 1mg/m^3 (human, 3h)
[138] Kleinbeck, S., Schäper, M., Juran, S. A., Kiesswetter, E., Blaszkewicz, M., Golka, K., . . . Thriel, C. V. (2011). Odor Thresholds and Breathing Changes of Human Volunteers as Consequences of Sulphur Dioxide Exposure Considering Individual Factors. *Safety and Health at Work*, 2(4), 355-364. doi:10.5491/shaw.2011.2.4.355



Wind speed estimates from VIRTIS (blue = ~66km, violet = ~61km, red = ~47km). VeRa zonal windspeeds are higher. Image reproduced from Picalli (2010).[139]

The nature of the propulsion system depends in part on the nature of ISRU required, which in turn depends on factors that are as of yet unknown. In particular, various types of ISRU collection can include:

- **Precipitation**: While the Vega data was initially interpreted as indicating no precipitation or condensation, some later research have argued that it instead shows the opposite. For example, in Dorrington (2013), it was argued that Vega 1 accumulated 0.25-0.35 kilograms total on its surface, causing a reduction in altitude, before the collected liquid began to drip off. Peak collection rates on Vega 2 were claimed at 40 mg/s. The mass change was stated to be highly uneven, corresponding with storms measured by other instruments.[140]

- **Condensation**: Rather than precipitation, condensation could be encouraged by the use of a hydrophilic envelope. Fluoropolymers tend to become increasingly hydrophilic after plasma treatment in a N_2/O_2 environment.[141]

- **Absorption**: The highly hygroscopic gases of Venus middle cloud layer are ready targets for direct absorption by water or other solvents with similar properties, either directly or through a membrane.

It's important to note that the types of recovery are expected to be different between different collection techniques. While absorption would be expected to capture all hygroscopic compounds, precipitation would be expected to be predominantly H_2SO_4, as the

[139] Piccialli, A. (2010). *Cyclostrophic wind in the mesosphere of Venus from Venus Express observations*. Berlin: Uni-Edition
[140] Dorrington, G. E. (2013). Preliminary evidence for drizzle in the middle cloud layer of Venus. *Advances in Space Research, 52*(3), 505-511. doi:10.1016/j.asr.2013.03.026
[141] Vandencasteele, N., Merche, D., & Reniers, F. (2006). XPS and contact angle study of N2 and O2 plasma-modified PTFE, PVDF and PVF surfaces. *Surface and Interface Analysis, 38*(4), 526-530. doi:10.1002/sia.2255

higher latitude middle cloud is dominated by sulfuric acid droplets at around 89% concentration,[142] while most other acidic compounds such as hydrogen chloride exist in the gas phase.[143] A precipitation or condensation collection system would be expected to utilize the entire envelope to channel drainage to the underside.

How does propulsion design depend on resource collection? For scrubbing, maximum air flow rates - and thus capturable resources - occur through the propulsion system. The absorption system could hence be designed to make use the higher airflow by ducting all or part of the slipstream through an absorption duct.

If propulsion is to assist ISRU, this alters the calculus. Maximizing mass flow rate implies props of larger radius and slower angular velocity, by the equation:

$$\Delta T = \rho\ 4\ \pi\ r\ V^2\ (1 + a).a.dr$$

Where:

- ΔT is the elemental thrust
- ρ is the fluid density
- V is the free stream velocity of the air moving past the propeller
- r is the radius of the blade segment
- a is the axial inflow factor

Thus, for a given thrust, increasing radius means not only a greater volume of air (which is relative to prop radius squared times the flow velocity), but a lower flow velocity (which is relative to the square root of the prop radius). In short, a greater resource mass moves across absorbing elements with less drag and a longer time in contact with them.

Dense structured packing for use in scrubbers. As Venus's gravity is similar to Earth's, the Ergun equation for calculating the pressure drop through a packed bed can be expected to be roughly valid.[144]
Photo: Luigi Chiesa

The potential propeller scaleup is, however limited - not just by mass, but dimensions. A single prop can be generally expected to be limited to the inner diameter of the payload fairing, e.g. ~4 ½ meters. However, a collapsible prop could allow that limit to be exceeded.

Discounting scrubber pressure drops (whose effect will be discussed under *Atmospheric scrubbing*), we will examine the following scenarios to achieve 10 m/s

[142] Krasnopolsky, V. A. (2015). Vertical profiles of H2O, H2SO4, and sulfuric acid concentration at 45–75km on Venus. *Icarus, 252*, 327-333. doi:10.1016/j.icarus.2015.01.024

[143] Barsukov, V. L., Khodakovskii, I. L., Volkov, V. P., Sidorov, I. I., Dorofeeva, V. A., & Andreeva, N. E. (1982). Metal chloride and elemental sulfur condensates in the Venusian troposphere - Are they possible. Lunar and Planetary Science Conference, 12th, Houston, TX, March 16-20, 1981, Proceedings. Section 2. (A82-31677 15-91) New York and Oxford, *Pergamon Press*, 1517-1532.

[144] St. Onge, T. (2015) "PBRE". *Space Flight Systems*. NASA Glenn Research Center.

maximum flight speed. All will assume a 80x50m cross section, 0.03 drag coefficient airship flying in 0.95 kg/m³ air, lift coefficient = 6.2x angle of attack, drag coefficient = $0.008 - 0.003\ C_L + 0.01\ C_L^2$, hub diameter 10% of prop diameter, 92% net powertrain efficiency and two blades per prop. Calculations are via basic blade element theory.[145]

# of props	Diameter (m)	Chord (cm)	Blade angle (hub : tip)	Power (kW)	Flow (kg/s)	Wake (m/s)	RPM
1	2	14.1	40.6° : 12.5°	194.0	101	33.9	2368
2	2	13.4	41.9° : 12.9°	146.3	154	25.8	1708
3	2	12.9	43.0° : 13.2°	125.5	197	22.1	1415
1	4.2	25.6	44.2° : 13.5°	109.4	254	19.3	566
2	4.2	22.2	48.0° : 14.4°	88.0	410	15.6	418
1	*8*	37.2	51.3° : 15.5°	75.4	645	13.5	170
2	*8*	31.2	56.0° : 17.4°	65.6	1142	11.9	128

The large (8m) props are assumed to be collapsible; such a large prop would more resemble a wind turbine due to its scale, with twin 8m props rotating only twice per second.

In addition to varied propeller designs, there exist alternatives to propellers - most notably:

- **Arcjets**:

  A relatively simple type of electric thruster, arcjets have thusfar primarily found use in satellites, where they can boost propellant specific impulse by hundred seconds (such as Aerojet Rocketdyne's MR 510).[146] In an arcjet, an electric arc heats a gas (either inert or combustible) so that it can be expanded through a nozzle. Thruster mass per unit power can be favorable - however, power consumption in current systems is prohibitively high, with typical consumption figures around 25 kW/N.[147] This would imply dozens of megawatts to provide equivalent speeds to the above propellers. Efficiency improvement is possible. Arcjets, like jet and rocket engines, perform best when heating is conducted at high pressures and with high bypass, and would thus favour integration into scrubbing units.

- **Electrohydrodynamic propulsion**:

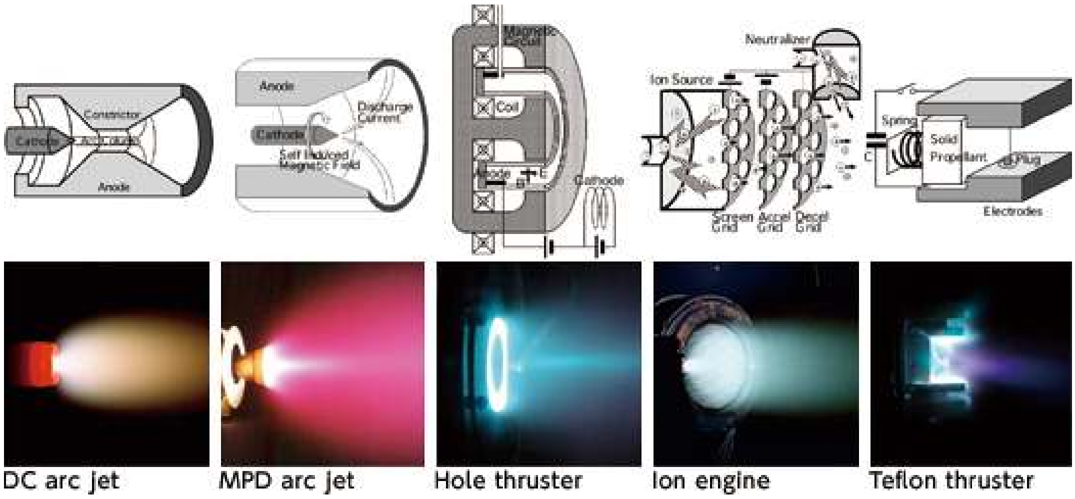
  Also known as "ion wind" thrusters, "ionocraft" or "lifters", electrohydrodynamic propulsion has gained a unfavorable reputation due to fringe claims that simple homemade EHD thrusters operate by antigravity.[148] The

[145] *Analysis of Propellers: Glauert Blade Element Theory*. AMME, University of Sydney.
[146] *MR-150*. Encyclopedia Astronautica. Retrieved from http://www.astronautix.com/m/mr-510.html
[147] Auweter-Kurtz, M., G-Ograve, T., L., Habiger, H., Hammer, F., Kurtz, H., . . . Sleziona, C. (1998). High-Power Hydrogen Arcjet Thrusters. *Journal of Propulsion and Power, 14*(5), 764-773. doi:10.2514/2.5339
[148] Tajmar, M. (2004). Biefeld-Brown Effect: Misinterpretation of Corona Wind Phenomena. *AIAA Journal, 42*(2), 315-318. doi:10.2514/1.9095

technology is nonetheless a legitimate method for propulsion, under study for aircraft usage.[149]

An EHD thruster operates by using a high voltage source to create coronal discharge, ionizing the surrounding air so that it is drawn to a downstream electrode. They can offer thrust efficiency superior to even propellers at low flight speeds (such as a habitat), but thrust per unit area is exceedingly low, requiring a very large thruster. While in heavier-than-air aircraft this may be prohibitive, integrating an EHD thruster around the envelope of an airship might prove a more reasonable goal. The high voltages utilized lower the required wiring masses.

An interesting side effect of EHD thrusters is chemical changes in the atmosphere in which they operate; on Earth, this primarily generates ozone, while on Venus it would primarily generate carbon monoxide and ozone.[150] If process alterations could instead induce the production of stable carbon particulate, the very act of propulsion would double as carbon sequestration. Another side effect is that particulate in the atmosphere tends to precipitate out on the anode,[151] presenting a potential means for resource collection.



Above: A variety of non-mechanical propulsion systems. Teflon thrusters are a variety of arcjet. EHD thrusters are a variety of ion engine. Photo: JAXA

Due to its advantages, we will investigate EHD closer. First off, how does the Venus environment affect it? The theoretical efficiency (generally tracked closely by experimental data[152]) is described by the formula:[153]

$$F / P = 1 / (\mu E + v)$$

[149] Gilmore, C. K., & Barrett, S. R. (2015). Electrohydrodynamic thrust density using positive corona-induced ionic winds for in-atmosphere propulsion. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences,471*(2175), 20140912-20140912. doi:10.1098/rspa.2014.0912

[150] Dors, M ., & Mizeraczyk, J. (1996). Conversion of nitrogen oxides in N2:O2:CO2 and N2:O2:CO2:NO2 mixtures subjected to a dc corona discharge. *Czechoslovak Journal of Physics, 46*(10), 943-952. doi:10.1007/bf01795143

[151] Parker, K. R. (2012). *Applied electrostatic precipitation*. Blackie Academic and Professional.

[152] Gilmor et al 2015

[153] Masuyama, K., & Barrett, S. R. (2013). On the performance of electrohydrodynamic propulsion. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences, 469*(2154), 20120623-20120623. doi:10.1098/rspa.2012.0623

Where:

- F is force (N)
- P is power (W)
- F / P is the force to power ratio, or power efficiency
- μ is ion mobility (m² / V s)
- E is the voltage gradient (V / m)
- v is the free stream air velocity

For peak efficiency (rather than thrust), E should be minimized to the lowest level to maintain coronal discharge, around 15-20 kV per electrode,[154] divided by a long electrode spacing (such as ~35cm). Ion mobility on Earth is 2.155×10^{-4} and 1.598×10^{-4} for dry and saturated (100% RH) air, respectively (the latter being more efficient). Ion mobility in carbon dioxide is lower (that is to say, more efficient) - 1.09×10^{-4}.[155] Ion mobility increases roughly proportionally to the the square root of pressure - that is to say, reduced pressure decreases efficiency.[156] Hence a ~0.5 bar EHD thruster on Venus has roughly the same efficiency as a saturated air thruster on Earth at sea level.

For a habitat moving at 13 m/s, using 17.5 kV per electrode, the estimated efficiency is thus 64 N/kW, compared to 23-68 N/kW in our above table for propellers of different sizes. This can be improved by increasing the spacing between electrodes, at the cost of requiring more electrode area. At lower speeds, such as 3 m/s, the above EHD efficiency becomes 118 N/kW.

What would be required to overcome the habitat's 3.59kN air resistance at 10 m/s? Taking 10mN per meter as a thrust density, we can calculate a required electrode length of 359km. Versus a habitat surface area of ~54k m², this equates to 6.7 electrode pairs per square meter for a single-stage design (isolated negative-positive pairs) which - at a spacing of 35cm between anode and cathode - would require 4.7 layers of electrodes covering the whole envelope. Contrarily, the corona could be maintained with protrusions extruding X mm from the surface every (X / 4.7) mm, where X can be any value. For a dual-stage design (alternating negative-positive electrodes), half as many layers of electrodes (or equivalent protrusions) are needed. Dual stage thrust comes at around a 20% efficiency penalty vs. single stage.[157]

Can a single-layer approach be achieved? One can certainly reduce electrode spacing to achieve higher thrust density; reducing electrode spacing to 20cm the efficiency drops to 51 N/kW but packing density increases threefold. At an electrode spacing of 10cm, efficiency drops to 34 N/kW but packing density is 12.3 times higher than the baseline case. In short, one can trade packing efficiency for packing density at will - but this comes at a cost. We will note that for a multilobed lifting body habitat design, the surface area to volume

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[154] Gilmore, C. K., & Barrett, S. R. (2015). [Electrohydrodynamic thrust density using positive corona-induced ionic winds for in-atmosphere propulsion.](#) *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences,471*(2175), 20140912-20140912. doi:10.1098/rspa.2014.0912
[155] Sharma, A. (1998) [Properties of some gas mixtures used in tracking detectors](#). SLAC-J-ICFA-16-3, SLAC-JOURNAL-ICFA-16-3.
[156] Liu, Y., Huang, S., & Zhu, L. (2015). [Influence of humidity and air pressure on the ion mobility based on drift tube method.](#) *CSEE Journal of Power and Energy Systems, 1*(3), 37-41. doi:10.17775/cseejpes.2015.00033
[157] Masuyama et al 2013

is higher than for the elliptical-habitat considered, and thus there is more room to place thrusters. Likewise, we do not consider the area of any empennage elements (rudders, elevators and stabilizers). On the other hand, we're also not considering thrust angles; not all of the surface area of the habitat would direct thrust straight back. The net aerodynamic effects of thrust along the entire surface of a habitat regardless of angle are not considered here.

How much mass would such a thruster add? Let us examine whether our low-E coating itself could act as an electrode (see *Other additives* under *In-Situ Resource Utilization*). A "thick" coating of ITO is 1 micron,[158] and normal thicknesses are 0.1-0.3 microns.[159] Assuming 5cm strips of ITO of 0.3 microns thickness, the cross section is 1.5 x 10^{-8} m². With an electrical conductivity of around 1e4 S/cm[160] (around the same as mercury), a 200 meter run equates to a resistance of 13 kΩ. With a voltage of 17.5kV and 10cm spacing, the current required is ~0.1 mA/m, or 20mA total.[161] From this, $V = IR$ yields a voltage drop of 260V - a relatively insignificant value compared to the operating voltage. Consequently, usage of ITO as an electrode (or at least a conductor to the electrodes) appears to be a quite favourable option.

Another option for power transfer is carbon fibre envelope reinforcement (see *Reinforcement*). Resistivity of common carbon fibre tows ranges from 50 to 205 mΩ-cm[162] (similar to drinking water). In order to match the ITO, the cross sectional area would thus have to be at least 0.75 to 3 m². Hence, this option appears unrealistic, with the caveats that high conductivity carbon wires are possible (see *Wiring*), and standard carbon reinforcement can be utilized for short runs (such as a coronal discharge electrode).

Electrode longevity against erosion is a concern for EHD propulsion, and has not received sufficient study to be considered mature. Estimates for rates range from logarithmic [163] to exponential[164] with charge transfer; in one test, the longest-lived silver-copper alloy corona wire was only 78 days, and most were significantly shorter. Electrode layering appears to provide significant lifespan benefits over single-material wires.[165] Ionic conductive polymers, such as iongels (ionic liquid gels), possess significant self-healing properties[166] and may prove suitable. Regardless, further research is required, and simple ITO conductors are unlikely to met longevity requirements on their own.

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[158] Oyama, T., Hashimoto, N., Shimizu, J., Akao, Y., Kojima, H., Aikawa, K., & Suzuki, K. (1992). Low resistance indium tin oxide films on large scale glass substrate. *Journal of Vacuum Science & Technology A: Vacuum, Surfaces, and Films, 10*(4), 1682-1686. doi:10.1116/1.577769

[159] *Indium Tin Oxide (ITO) (In2O3):(SnO2)*. Indium Corporation. Retrieved from http://www.indium.com/inorganic-compounds/indium-compounds/indium-tin-oxide/

[160] *Material: Indium Tin Oxide (ITO)*. Retrieved from http://www.mit.edu/~6.777/matprops/ito.htm

[161] Gilmore, C. K., & Barrett, S. R. (2015). Electrohydrodynamic thrust density using positive corona-induced ionic winds for in-atmosphere propulsion. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences,471*(2175), 20140912-20140912. doi:10.1098/rspa.2014.0912

[162] Šafářová, V., Grégr, J. (2010). Electrical conductivity measurements of fibres and yarns. th International Conference - TEXSCI 2010 September 6-8, Liberec, Czech Republic

[163] Islamov, R. S., & Krishtafovich, Y. A. (2013). Lifetime and erosion of silver-based wire electrodes in an ultracorona in air. *Journal of Electrostatics, 71*(2), 109-115. doi:10.1016/j.elstat.2012.12.019

[164] Islamov, R. S., & Krishtafovich, Y. A. (2013). Erosion and Lifetime of Tungsten, Gold, and Nichrome Wire Anodes in an Ultracorona in Air. *IEEE Transactions on Plasma Science, 41*(7), 1787-1793. doi:10.1109/tps.2013.2263513

[165] Gao, G., Jewell-Larsen, N., & Humpston, G. (2013). *U.S. Patent No. US20130056241 A1*. Washington, DC: U.S. Patent and Trademark Office.

[166] Cao, Y., Morrissey, T. G., Acome, E., Allec, S. I., Wong, B. M., Keplinger, C., & Wang, C. (2016). A Transparent, Self-Healing, Highly Stretchable Ionic Conductor. *Advanced Materials,* 1605099. doi:10.1002/adma.201605099

Should longevity be addressable, it appears that highly efficient EHD thrust could be utilized on a habitat. However, due to the relative immaturity of alternative means of electric propulsion, we will operate on the presumption of the use of propellers, with the caveat that advances in EHD technology may warrant reconsideration.

Control

Control and stability for the habitat must be provided by some combination of differential thrust, thrust vectoring and/or aerodynamic control surfaces. As the entire habitat deploys from a stack launched in a rocket fairing, keeping large systems in line with each other is simplest from a deployment and maintenance perspective. This would tend to argue for either one or a pair of props directly underneath the central access channel. Centralized empennage and propulsion would also simplify airworm-style habitat expansion (see *Expansion*) and the use of the habitat as its own atmospheric entry ballute (see *Ballute considerations* under *Envelope design*). Contrarily, the further that propulsion and empennage are from the center of the mass, the greater the net torque they exert on the craft.

Not all means of control function at all times. Active propulsion systems can exert full torque regardless of airspeed (as defined relative to the average local wind velocity, not the surface); however, torque from the empennage is dependent on the relative airspeed. However, empennage provides passive stabilization; a “tail” structure helps maintain the craft pointing into the wind.

A final factor worthy of consideration is the difficulty in accessing remote areas for maintenance. This is of relatively little concern for relatively static systems such as stabilizers, but important for systems with moving parts such as rudders/elevators and propulsion systems.

One approach to increasing torque without excessively decreasing accessibility would be to locate propulsion systems at the ends of collapsible trusses or inflatable tubes which begin at a readily accessible location. Contrarily, with a ducted thrust system, duct inlets and/or outlets could be located in less accessible areas so long as the propulsion and vectoring system itself is located in a readily accessible location. Other options exist to locate mechanical systems in accessible areas while the systems that they control are in relatively inaccessible areas - for example, connecting accessible actuators to inaccessible actuated surfaces.

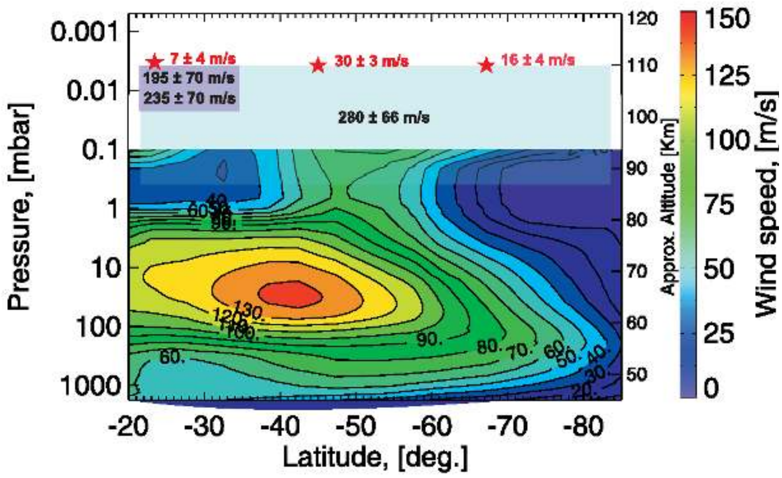
A final possibility for propulsion and control: it is technically possible to use altitude-based zonal wind differentials to exert force on the habitat (as well as simultaneous wind power generation). However, this imposes a number of difficulties that are generally prohibitive for an early-phase habitat (see *Wind power*).

We will operate on the baseline assumption of the central core (laboratory / shelter, common area, kitchen, livestock platform, workshop) being over the industrial section and surrounded by a trilobate tail structure to simplify deployment. In this scenario, propulsion would be directly connected with the industrial section, and the bottom stabilizer would be the access route to it - thus keeping it at a fair distance from the primary envelope. For stability reasons, thus, this would all be located near the rear of the envelope. This implies that the front of the habitat would be dedicated to bearing the weight of the ascent vehicle - and as a consequence, that the front ballonet(s) would be highly inflated in the beginning, only emptying as ISRU propellant production increases the rocket mass.

Power considerations

Venus is blessed with abundant sources of wind and solar energy. Various complications come up in their usage which need to be addressed.

Wind power



VeRa zonal windspeeds from Piccialli 2010 demonstrating the high difference in windspeeds between altitudes.[167].

As one can see in the VeRa data, there is an approximately 3 meters per second wind differential per kilometer altitude difference. With cables dozens of kilometers in length, one can reach into the very dense lower haze layer. Reaching from ~55km to ~45km (at an angle determined by factors such as turbine/cable mass and turbine lift angle) yields a 50 m/s (112 mph / 180 kph) windspeed differential with the turbine at 2 ATM, at a temperatures around 115°C. The windspeed differential is nearly constant, including a good degree of diurnal stability. So long as the turbine does not lose significant energy to lift, and so long as the drag it experiences is well less than the drag the habitat experiences under tension from the turbine, most of that energy can be harnessed. By contrast, most wind turbines on Earth are not even designed to handle windspeeds greater than 25m/s at 1 ATM. Wind drag force corresponds to the square of the windspeed, and capturable energy to its cube.[168] In short, a small turbine on a cable can yield a tremendous, reliable source of energy on Venus.

There are, however, some problems with the use of wind as a near-term power source on Venus. First, let us examine the physics (assuming a slack-free carbon fibre cable):

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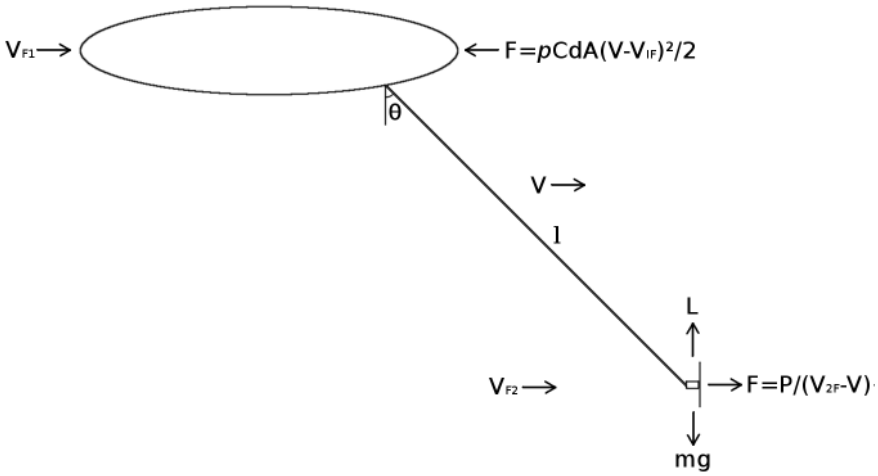
[167] Piccialli, A. (2010). *Cyclostrophic wind in the mesosphere of Venus from Venus Express observations*. Berlin: Uni-Edition
[168] Physics of Wind Turbines. *Energy fundamentals*. Retrieved from http://home.uni-leipzig.de/energy/ef/15.htm



Where:

- **V_{F1}** is the freestream wind velocity at habitat altitude
- **V_{F2}** is the freestream wind velocity at turbine altitude
- **V** is the velocity of the habitat-turbine system
- **θ** is the angle of the tether
- **l** is the tether length
- **mg** is the force of gravity (~8,7m/s²) on the turbine and half of the cable
- **F** is force
- **L** is lift (can be negative, to hold the turbine down)
- **P** is the power that would be generated by the turbine at 100% efficiency
- **ρ** is the air density at habitat altitude
- **CdA** is the drag area of the habitat

We additionally define:

- **R_{LD}** is the lift-drag ratio of the turbine
- **Δh** is the the altitude difference between the habitat and the turbine (meters)
- **σ** is the stress in the cable
- **r** is the radius of the cable
- **m_T** is the mass of the turbine
- **m_C** is the mass of the cable
- **σ_{max}** is the maximum allowable static stress on the cable (e.g. 500 MPa)
- **ρ_C** is the density of the cable

To this we add the following equations:

$$L = F\, R_{LD}$$
$$l = \Delta h / \cos(\theta)$$
$$\Theta = \mathrm{atan}(F / (mg - L))$$
$$\sigma = ((mg - L) / \cos(\theta) + F / \sin(\theta)) / (\pi r^2)$$
$$m = m_T + 0.5\, m_C$$
$$m_C = \rho_C\, \pi\, r^2\, l$$

We add in a loose estimate of turbine mass relative to air density and windspeed:

$$m_T = m_{blades} + m_{generator} = 3\,P / (V^{1.5}\,\rho_2) + P / 40$$

And high voltage wiring mass:

$$M_W = P\,l^2 / 3e10$$

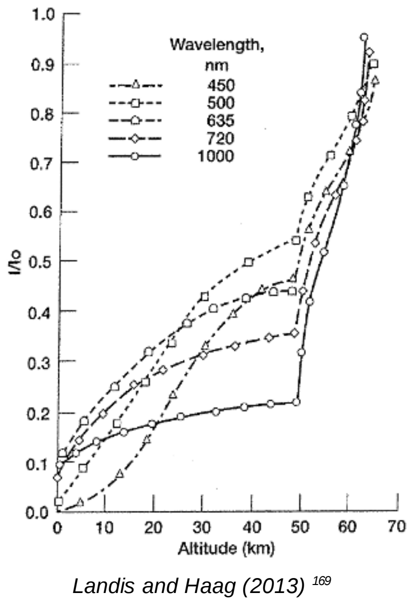
Operating with habitat altitude h_1 = 55000m, cable density ρ_C = 1850 kg/m³, σ_{max} = 500 MPa, Cd = 0.03, A = 3142, P = 20000W; a 50um coating at 2000 kg/m³; assuming actual power generation is 80% efficient; and letting R_{LD} and h_2 vary - we arrive at the following:

- **Total mass**: 1252 kg
    - **Turbine**: 731 kg
    - **Cable**: 425 kg
        - **Length**: 9739 m
        - **Diameter**: 0.55 cm
        - **Tensile**: 329 kg
        - **Wiring**: 79.0 kg
        - **Coating**: 16.9 kg
- **Turbine altitude**: 45.5 km
- **ΔV**: 45.3 m/s
- **L:D ratio**: 1.34
- **Cable angle (*θ*)**: 12.6°

For a point of comparison, we shall next examine the same amount of solar power.

Solar power

What about a comparable amount of solar energy? First we must look at the light profiles on Venus.

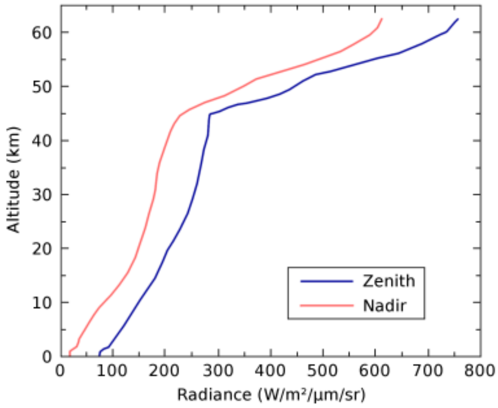


Landis and Haag (2013) [169]

The solar constant in space at Venus is 2635 W/m² - 193% that of Earth and 446% that of Mars. However, the light has already well attenuated by the time it reaches the middle cloud layer. At 54.5km, subject to direct overhead radiation, the middle cloud layer experiences about 1600W/m². This is further reduced by the solar angle, which causes sunlight to have to penetrate through a greater amount of the atmosphere. At 70° latitude, simple cosine scaling suggests around 540W/m² peak daytime lighting, although in practice transmission fares better than simple cosine scaling would suggest. These levels of light are fairly average by Earth surface standards. At 70°

[169] Landis, G. A., & Haag, E. (2013). Analysis of Solar Cell Efficiency for Venus Atmosphere and Surface Missions. *11th International Energy Conversion Engineering Conference*. doi:10.2514/6.2013-4028.

latitude the light come in a somewhat long day-night cycle - most probably around two days (VeRa data), but possibly upwards of three days (VIRTIS data).[170]



Zenith and nadir light , based on Moshkin et al (1983) / ESA[171]

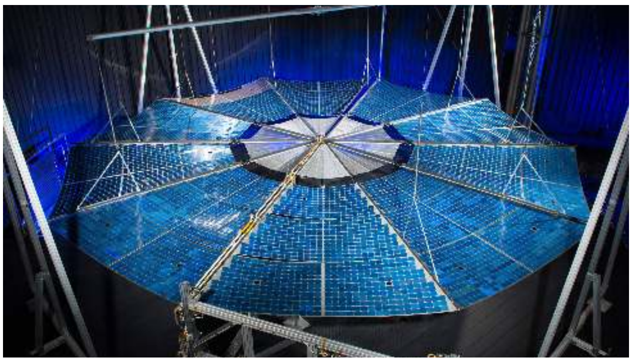
A particular curiosity of Venus's light is its relatively anisotropic nature. In the middle cloud layer, light coming from underneath is approximately 70-80% as strong as light coming from overhead.

This has a number of interesting consequences. Firstly, it means that it cannot be effectively concentrated, ruling out solar thermal heating, due to conservation of étendue. Secondly, it means that clouds visible outside the habitat will be low contrast, although it is expected that it will still be possible to see individual shapes.[172]

Third, it means that to capture the maximum amount of energy, light must be captured from all directions rather than simply overhead. The advantage of this is that a double-sided cell presents two square meters of exposure to the cloud deck per square meter of physical area.

We return to power source comparisons. The top of the line in space-based solar systems today is along the lines of the ATK Megaflex and Ultraflex series. Ultraflex yields a nameplate 150W/kg[173] under standard Earth testing conditions, while Megaflex is designed for up to 200W/kg.[174] Ultraflex was used on the Mars Phoenix lander, the (cancelled) Mars 01 lander and New Millennium ST8, and several pending systems (NASA Orion/MPCV, Orbital ATK CRS Cygnus, and the Mars Insight lander).

However, on a Venus habitat, the situation is far superior. In the ATK systems, the system must provide its own structural strength - generally the majority of the mass of a flexible solar system. On Venus, with solar cells embedded into the envelope, structural support is already provided by the envelope itself. The next largest portion of the mass of a flexible solar system is the substrate. Again, this



ATK MegaFlex. Photo: NASA / GRC

[170] Piccialli, A. (2010). *Cyclostrophic wind in the mesosphere of Venus from Venus Express observations*. Berlin: Uni-Edition
[171] Grieger, B., Ignatiev, N. I., Hoekzema, N. M., & Keller, H. U. (2004). *Indication of a near surface cloud layer on Venus from reanalysis of Venera 13/14 spectrophotometer data*. Proceedings of the International Workshop Planetary Probe Atmospheric Entry and Descent Trajectory Analysis and Science, 6-9 October 2003, Lisbon, Portugal. ISBN 92-9092-855-7
[172] Wilson, C. F., Chassefière, E., Hinglais, E., Baines, K. H., Balint, T. S., Berthelier, J., . . . Szopa, C. (2011). The 2010 European Venus Explorer (EVE) mission proposal. *Experimental Astronomy, 33*(2-3), 305-335. doi:10.1007/s10686-011-9259-9
[173] *UltraFlex™ Solar Array Systems*. Orbital ATK. Retrieved from https://www.orbitalatk.com/space-systems/space-components/solar-arrays/docs/FS007_15_OA_3862%20UltraFlex.pdf
[174] MegaFlex Solar Array Scale-Up, up to 175kW per Wing. NASA SBIR. Retrieved from https://www.sbir.gov/sbirsearch/detail/388526

is provided by the envelope itself. Additionally, solar cells on Venus are illuminated from both sides, doubling the number of effective square meters per physical square meter of fabric. Hence, we can consider the ATK systems to give us what should be by far the worst case.

Let us take a pessimistic tack and assume that the addition of photovoltaic and wiring mass over the already-required mass of the envelope is 600W/kg. We'll target the same 20kW as before in wind, but with the added need to generate enough power during a 24-hour day to store 30 hours of power at 70% net storage efficiency. We'll credit our cells with a 30% daytime (0% night) capacity factor - that is, to account for the different light levels over the course of the day as well as structural shading within the habitat - again, pessimistic figures. Thus we have:

$$P = (20000W / 0.3) * (1 + (30/24) / 0.7)$$

This 20kW thus requires a nameplate capacity of 186kW, massing at 310kg. Note that this does not include the mass of the energy storage system, but this is relatively lightweight (discussed under *Deuterium and power storage issues*)

It is clear that the solar system comes in at a far lower mass than the wind system, even with arguably pessimistic solar mass assumptions. In terms of technology readiness level, it is also far beyond that of a blimp-towed wind system which can handle Venus conditions (many of which are unknown, and some of which, such as lightning, could prove hazardous to an object dangling on a tether). Solar represents a much cheaper development path which can be very readily tested on Earth, and almost invariably greater reliability.

In the long term, wind has the potential to provide massive amounts of local power, including nighttime generation, as well as to provide a "towing" force, allowing a lifting body habitat to gain greater lift. It additionally provides interesting options for resource collection, discussed under *In-Situ Resource Utilization*. However, for an initial habitat, solar appears to be the superior option.

The question arises as to where solar power systems should be located. As noted, by embedding solar production into the already-required envelope rather than having it as external systems, you provide it a substrate and shelter it from the external corrosive environment and weather. Indeed, high-tensile multilayer plastic substrates with fluoropolymer coatings have long been a mainstay in thin-film photovoltaics.[175]

However, all parts of the envelope are not created equal. A first instinct might be to place solar cells on the top, as we would on Earth; however, that is the location where agriculture is conducted. Agricultural outputs are strongly correlated with light levels.[176] The light reaching any point in space in a simple isotropic illumination environment can be thought of as the percentage of its sky sphere that is obstructed; hence, the closer the cells are placed to the plants, the less light plants and solar cells receive. The logical conclusion is that they should be apart from each other.

[175] Debergalis, M. (2004). Fluoropolymer films in the photovoltaic industry. *Journal of Fluorine Chemistry, 125*(8), 1255-1257. doi:10.1016/j.jfluchem.2004.05.013
[176] Hunt, R. (1990). *Basic growth analysis: plant growth analysis for beginners*. London: Unwin Hyman.

Additionally, while light is largely isotropic in the middle cloud environment, the zenith angle still receives more light than the nadir. Likewise, the underside of the habitat contains the ballonets, propulsion, and other obstructions. So the best “real estate” remains at the top. To some degree there is a competition between agriculture and solar for the best light positioning. Which should win? A strong argument can be made for agriculture. Agriculture presents a much greater embodied mass per square meter than solar power, and consumes vastly more human labour and produced resources. Hence it’s much easier to provide more area of solar cells than more cultivated area.

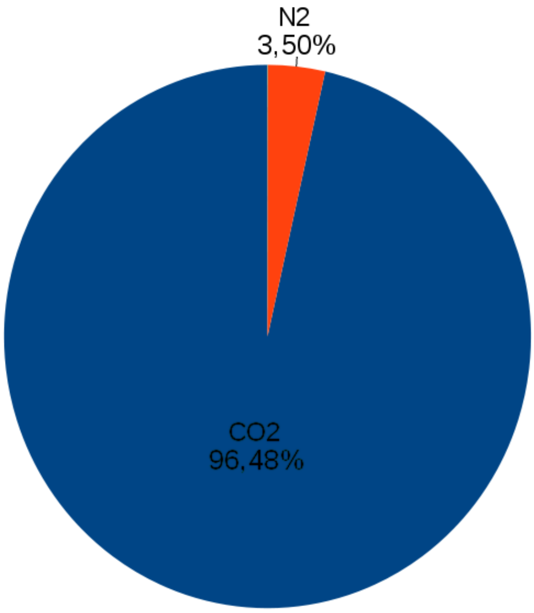
All of this together argues that bulk solar power (not accounting for solar panels on “dead space”, such as walls, flooring, etc) should be located further down in the habitat. There are two main areas for this: in the inner walls of the ballonets, or the outer walls / external envelope.

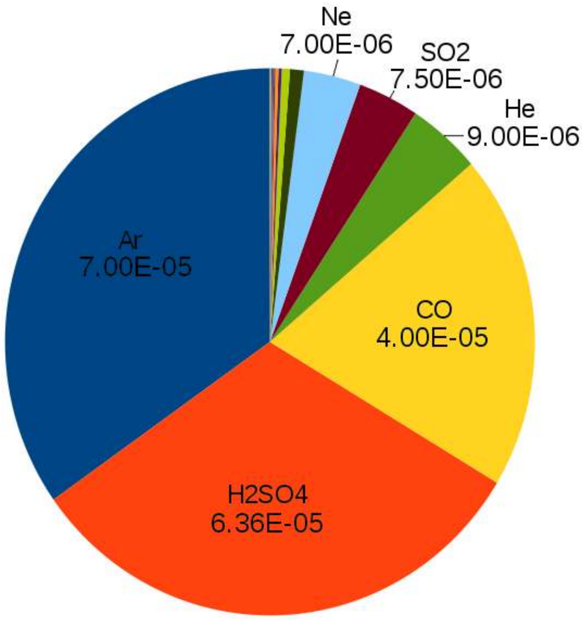
A location on the inner walls of the ballonets means that light from the bottom must pass through two envelope layers before reaching the solar cells, while light from the rest of the habitat moves through only one. The outer location keeps the cells further away from agriculture, particularly when the ballonets are highly inflated (excepting the bottommost extremities of the ballonets). A location on the inner walls of the ballonets has an advantage in that only a single side of the solar cells are exposed to the external chemical environment, and neither side is exposed to weather. It is also much more accessible for maintenance and expansion.

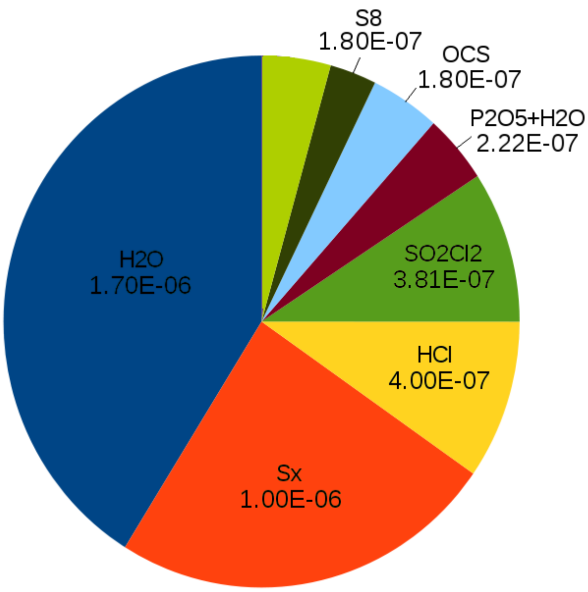
5. Chemical Environment and Resource Considerations

Much about Venus's middle cloud layer can remind one of Earth. Temperatures and pressures are similar. The layer is convective, like Earth's troposphere. Storms that - according to our brief amounts of Vega data - have similar distribution and wind patterns to Earth drift by.[177] However, the chemical environment is famously different and hostile.

Bulk statistics describing Venus's atmosphere are not particularly useful in describing a particular layer of it. Let us begin by describing the atmosphere at flight altitude. The short of it: it's complex, and we've only scratched the surface.

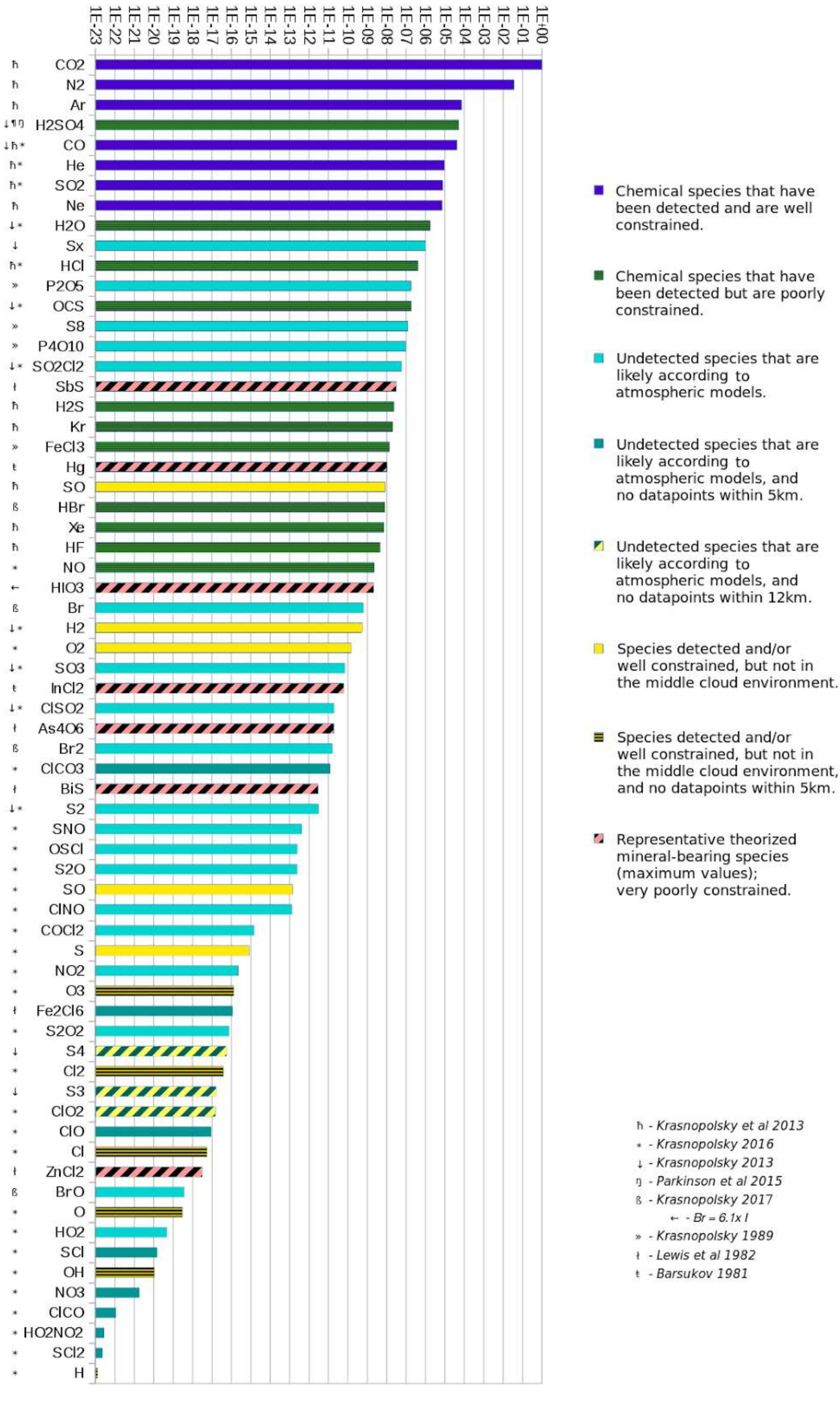






There are many caveats we need to go into concerning this data. However, before we do so, let also include a wider range of species. For simplicity's sake we will present these mixing ratios on a logarithmic scale on the next page.

[177] Dorrington, G. E. (2013). Preliminary evidence for drizzle in the middle cloud layer of Venus. *Advances in Space Research, 52*(3), 505-511. doi:10.1016/j.asr.2013.03.026

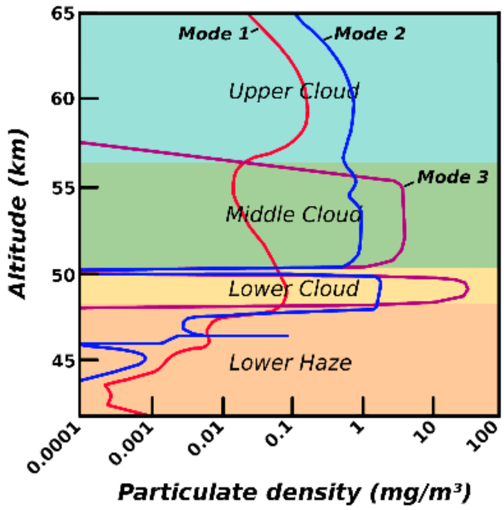


1E-23 1E-22 1E-21 1E-20 1E-19 1E-18 1E-17 1E-16 1E-15 1E-14 1E-13 1E-12 1E-11 1E-10 1E-09 1E-08 1E-07 1E-06 1E-05 1E-04 1E-03 1E-02 1E-01 1E+00
CO2
N2
Ar
H2SO4
CO
He
SO2
Ne
H2O
Sx
HCl
P2O5
OCS
S8
P4O10
SO2Cl2
SbS
H2S
Kr
FeCl3
Hg
SO
HBr
Xe
HF
NO
HIO3
Br
H2
O2
SO3
InCl2
ClSO2
As4O6
Br2
ClCO3
BiS
S2
SNO
OSCl
S2O
SO
ClNO
COCl2
S
NO2
O3
Fe2Cl6
S2O2
S4
Cl2
S3
ClO2
ClO
Cl
ZnCl2
BrO
O
HO2
SCl
OH
NO3
ClCO
HO2NO2
SCl2
H
Chemical species that have been detected and are well constrained.
Chemical species that have been detected but are poorly constrained.
Undetected species that are likely according to atmospheric models.
Undetected species that are likely according to atmospheric models, and no datapoints within 5km.
Undetected species that are likely according to atmospheric models, and no datapoints within 12km.
Species detected and/or well constrained, but not in the middle cloud environment.
Species detected and/or well constrained, but not in the middle cloud environment, and no datapoints within 5km.
Representative theorized mineral-bearing species (maximum values); very poorly constrained.
ħ - Krasnopolsky et al 2013
* - Krasnopolsky 2016
↓ - Krasnopolsky 2013
ŋ - Parkinson et al 2015
ß - Krasnopolsky 2017
← - Br = 6.1x I
» - Krasnopolsky 1989
ł - Lewis et al 1982
ŧ - Barsukov 1981

A few bulk constituents are well quantified and not very altitude-sensitive in the troposphere; nitrogen makes up approximately 3.5%, while the vast majority of the remainder is comprised of carbon dioxide. Noble gases, although known with less precision, are approximately 70 ppm argon, 9 ppm helium, 7ppm neon, 20 ppb krypton and <7 ppb xenon.[178]

Venus has three different cloud decks (upper, middle and lower) containing various populations of three different types of particles (known as modes 1, 2, and 3). Mode 1 particles are aerosols approximately 0.3 microns in diameter (smoke-sized). Mode 2 particles appear to be spheres about 2 microns in diameter (fine fog-sized), believed to be primarily sulfuric acid at approximately 73-98% concentration.[179] There is some dispute over the mode 3 particles; they are most likely high aspect ratio crystals, approximately 7 micron in length, of a species other than sulfuric acid. Theories as to their nature run from perchloric acid to phosphoric acid to polymeric sulfur.

The upper cloud layer is continuous and relatively unchanging in thickness and density all the way around the planet, with the exception of turbulent areas of the polar vortices. The middle cloud layer is somewhat variable, while the lower cloud layer appears highly variable, and may in some cases disappear entirely. Beneath the lower cloud exists the lower haze, a sparse region that may comprise a condensation virga. Beyond the lower haze, the atmosphere becomes optically transparent for the rest of the way to the surface, with the possible exception of surface fogs whose existence is still debated.[180]



Based on Knollenberg and Hunten (1980).[181]

The surface and atmosphere of Venus undergoes complex weathering processes, leading to the creation of a wide variety of gas-phase species (including both detected and hypothesized compounds). These evolve and in some cases precipitate out of the atmosphere at various altitudes. Perhaps the most prominent case is compounds of sulfur, taking part in a complex "sulfur cycle" somewhat reminiscent of Earth's water cycle.

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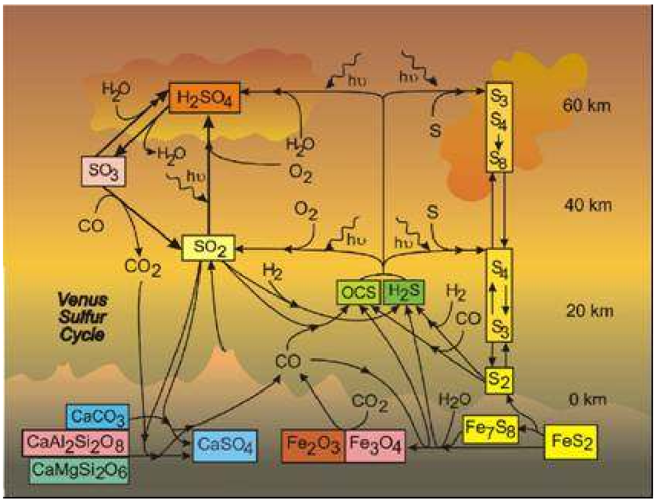
[178] Krasnopolsky, V. A., & Lefèvre, F. (2013). Chemistry of the Atmospheres of Mars, Venus, and Titan. *Comparative Climatology of Terrestrial Planets*. doi:10.2458/azu_uapress_9780816530595-ch011

[179] Krasnopolsky, V. A. (2015). Vertical profiles of H2O, H2SO4, and sulfuric acid concentration at 45–75km on Venus. *Icarus, 252*, 327-333. doi:10.1016/j.icarus.2015.01.024

[180] Grieger, B., Ignatiev, N. I., Hoekzema, N. M., & Keller, H. U. (2004). *Indication of a near surface cloud layer on Venus from reanalysis of Venera 13/14 spectrophotometer data*. Proceedings of the International Workshop Planetary Probe Atmospheric Entry and Descent Trajectory Analysis and Science, 6-9 October 2003, Lisbon, Portugal. ISBN 92-9092-855-7

[181] Knollenberg, R., Hunten, D. (1980) The Microphysics of the Clouds of Venus: Results of the Pioneer Venus Particle Size Spectrometer Experiment. *Journal of Geophysical Research*, 85, 8039-58



Left: Venus's sulfur cycle, reproduced from Fegley et al (1995).[182] *Pyrite is quickly broken down into pyrrhotite, then progressively less sulfur-rich species. The resultant gas-phase sulfur allotropes are progressively oxidized via carbonyl sulfide to sulfur dioxide, which upon further oxidation forms sulfur trioxide / sulfuric acid, or contrarily is sequestered via the formation of anhydrite.*

Middle cloud species of interest

- ***Carbon monoxide***: Approximately 30-60 ppm.[183] [184] [185] At this level, CO_2 represents a greater toxicity / permeation threat.

- ***Water***: Variable, but around two dozen ppm in the middle cloud.[186] [187] Water vapour and sulfuric acid (including water bound therein) would be the primary source of hydrogen (water, hydrocarbons, etc) for a Venus habitat.

- ***Hydrogen chloride***: Approximately 400 ppb, expected to be primarily anhydrous.[188] [189]

- ***Hydrogen fluoride***: Also expected to be primarily anhydrous, it is a relatively rare constituent at around 5ppb.[190]

- ***Sulfuric acid***: Arguably the most notable (and variable) species of Venus's cloud decks. Perhaps surprisingly, while it is among the most familiar chemicals in Venus's atmosphere, models differ greatly on how much is present and at what locations. Sulfuric acid - like water clouds on Earth - appears to vary with respect to altitude, latitude, and time of day.

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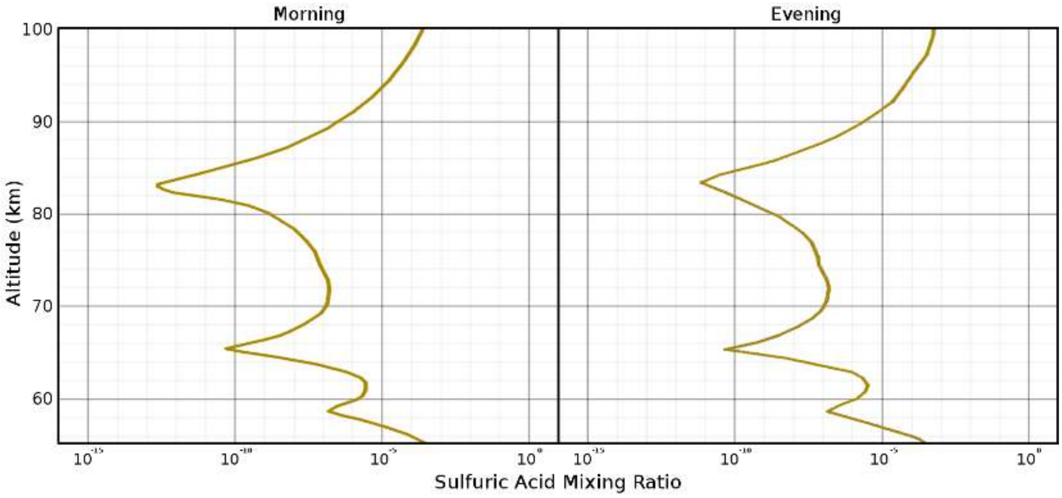
[182] Fegley, B., Lodders, K., Treiman, A. H., & Klingelhöfer, G. (1995). The rate of pyrite decomposition on the surface of Venus. *Icarus*, 115(1), 159-180.
[183] Krasnopolsky, V. A., & Lefèvre, F. (2013). Chemistry of the Atmospheres of Mars, Venus, and Titan. *Comparative Climatology of Terrestrial Planets*. doi:10.2458/azu_uapress_9780816530595-ch011
[184] Krasnopolsky, V. A. (2016). On the iron chloride aerosol in the clouds of Venus. *Icarus*. doi:10.1016/j.icarus.2016.10.003
[185] Krasnopolsky, V. A. (2013). S3 and S4 abundances and improved chemical kinetic model for the lower atmosphere of Venus. *Icarus, 225*(1), 570-580. doi:10.1016/j.icarus.2013.04.026
[186] Krasnopolsky, V. A. (2015). Vertical profiles of H2O, H2SO4, and sulfuric acid concentration at 45–75km on Venus. *Icarus, 252*, 327-333. doi:10.1016/j.icarus.2015.01.024
[187] Krasnopolsky, V. A. (2013). S3 and S4 abundances and improved chemical kinetic model for the lower atmosphere of Venus. *Icarus, 225*(1), 570-580. doi:10.1016/j.icarus.2013.04.026
[188] Krasnopolsky, V. A., & Lefèvre, F. (2013). Chemistry of the Atmospheres of Mars, Venus, and Titan. *Comparative Climatology of Terrestrial Planets*. doi:10.2458/azu_uapress_9780816530595-ch011
[189] Krasnopolsky, V. A. (2016). On the iron chloride aerosol in the clouds of Venus. *Icarus*. doi:10.1016/j.icarus.2016.10.003
[190] Krasnopolsky, V. A. (2016). On the iron chloride aerosol in the clouds of Venus. *Icarus*. doi:10.1016/j.icarus.2016.10.003



Based on Parkinson et al (2015). Calculated estimates of Venus's sulfuric acid mixing ratios are indicated for the morning and evening terminators at 60-70° latitude, varying by orders of magnitude with relatively small altitude differences.

At our particular location of interest - ~55km altitude, ~70° latitude - estimates of density vary over two orders of magnitude, from under 1ppm in Krasnopolsky (2015)[191] to nearly 100ppm in Parkinson et al (2015).[192] While the concentration in the lower cloud deck is disputed, there is little dispute that little sulfuric acid exists below it; at those temperatures, sulfuric acid is unstable and decomposes.

- ***Phosphoric acid** and **phosphorus pentoxide***: Detection by Vega has been suggested but not confirmed. Chemical models strongly suggest that phosphoric acid should be a common if not dominant species in the dense lower cloud deck. Further down, phosphorus pentoxide would be the dominant species. Phosphoric acid likely exists in minor quantities at higher altitudes and as low as 33km.[193]

- ***Ferric chloride** and **ferric sulfate***: Observed by Venera 12 XRF and the Vega landers. Considered a candidate for Venus's "mystery UV absorber" and a potential condensation nucleus for sulfuric acid. Has a latitude dependence. (Bézard et al 2009). Estimated to make up perhaps 1% of the mass of every sulfuric acid droplet. The dramatic variation in sulfuric acid estimates render this value difficult to utilize. We have adopted a low value from Krasnopolsky 2016[194].

  Ferric chloride oxidizes to ferric sulfate in the cloud environment over the course of several weeks. Ferric sulfate has not been the subject of as much research as it is not a candidate UV absorber, and hence, estimates of the resource availability in the middle cloud environment are difficult to come by. It however remains an additional potential iron resource.

[191] Krasnopolsky, V. A. (2015). Vertical profiles of H2O, H2SO4, and sulfuric acid concentration at 45–75km on Venus. *Icarus, 252*, 327-333. doi:10.1016/j.icarus.2015.01.024
[192] Parkinson, C. D., Gao, P., Schulte, R., Bougher, S. W., Yung, Y. L., Bardeen, C. G., . . . Pätzold, M. (2015). Distribution of sulphuric acid aerosols in the clouds and upper haze of Venus using Venus Express VAST and VeRa temperature profiles. *Planetary and Space Science, 113-114*, 205-218. doi:10.1016/j.pss.2015.01.023
[193] Krasnopolsky, V. (1989). Vega mission results and chemical composition of Venusian clouds. *Icarus, 80*(1), 202-210. doi:10.1016/0019-1035(89)90168-1
[194] Krasnopolsky, V. A. (2016). On the iron chloride aerosol in the clouds of Venus. Icarus. doi:10.1016/j.icarus.2016.10.003

- ***Polysulfides***: Unconfirmed, but potentially present in significant quantities. A potential candidate for the mystery UV absorber. In our breakdown, we include both a model of S_x (all polysulfides) and various individual polysulfides, as distributions for both categories are easy to locate.[195] [196]

- ***Higher halides***: Bromine has been detected in minor quantities (<1ppb) in Venus's upper atmosphere from Earth, and is modelled at a maximum of to 20-70 ppb below 60km. A likely fit from Krasnopolsky 2017 places it around 10ppb in the habitable zone, primarily as hydrogen bromide, but also Br and Br_2 in relevant quantities.[197] Iodine has not been as extensively studied; we treat it as being present at a similar relative abundance as in Earth's crust, *Br = 6.1x I*.

- ***Theorized minor metallic compounds***: While many such compounds had been initially suggested as significant cloud-forming compounds, they have since been largely ruled out in this regard. Some, such as SiF_4 and $AlCl_3$, have been determined to likely have too low of a concentration to be meaningful atmospheric constituents.[198] Others, however, still remain likely atmospheric constituents at low levels.

    - **Mercury chlorides, sulfides, metal**: The non-detection of mercury is one of the great mysteries of Venus's atmospheric chemistry, perhaps only second to that of the unknown UV absorber. Models predict 3 ½ orders of magnitude more mercury in the atmosphere than detection constraints indicate (<10ppb).[199] As mercury has a high vapour pressure, the crust should be degassed of it; before the Venera missions it had been theorized that Venus's clouds were dominated by mercury. Future missions with more sensitive equipment will hopefully shed more light on this.

      Mercury would most likely be found as elemental mercury, which should begin to condense out at 62km altitude.

    - **Arsenic oxides, sulfides, chlorides**: Models suggest that arsenic is constrained to under 100ppbv.[200] The leading candidate is As_4O_6, which should begin to crystalize at 42km altitude.[201]

    - **Antimony sulfide, oxides, chloride**: Of undetected metallic compounds, antimony has the most promising model results, with partial pressures as

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[195] Krasnopolsky, V. A. (2015). Vertical profiles of H2O, H2SO4, and sulfuric acid concentration at 45–75km on Venus. *Icarus, 252*, 327-333. doi:10.1016/j.icarus.2015.01.024
[196] Krasnopolsky, V. A. (2013). S3 and S4 abundances and improved chemical kinetic model for the lower atmosphere of Venus. *Icarus, 225*(1), 570-580. doi:10.1016/j.icarus.2013.04.026
[197] Krasnopolsky, V. A., & Belyaev, D. A. (2017). Search for HBr and bromine photochemistry on Venus. *Icarus*, 293, 114-118. doi:10.1016/j.icarus.2017.04.016
[198] Lewis, J. S., & Fegley, B. (1982). Venus: Halide Cloud Condensation and Volatile Element Inventories. *Science, 216*(4551), 1223-1225. doi:10.1126/science.216.4551.1223
[199] Barsukov, V. L., Khodakovskii, I. L., Volkov, V. P., Sidorov, I. I., Dorofeeva, V. A., & Andreeva, N. E. (1982). Metal chloride and elemental sulfur condensates in the Venusian troposphere - Are they possible. Lunar and Planetary Science Conference, 12th, Houston, TX, March 16-20, 1981, Proceedings. Section 2. (A82-31677 15-91) New York and Oxford, *Pergamon Press*, 1517-1532.
[200] Lewis, J. S., & Fegley, B. (1982). Venus: Halide Cloud Condensation and Volatile Element Inventories. *Science, 216*(4551), 1223-1225. doi:10.1126/science.216.4551.1223
[201] Hunten, D. M., Colin, L., Donahue, T. M., Moroz, V. I. (1983). *Venus*. The University of Arizona Press, Tuscon, Arizona.

high as 0.1mb possible.[202] Antimony oxide begins to crystallize out at 42km altitude.[203]

- **Selenium metal, chlorides, oxide**: Models suggest the most likely specie, Se_2, is constrained to under 10 ppm and begins to condense to Se(l) at 18km.[204]

- **Tellurium metal, chlorides, oxychloride, oxides**: Models suggest the most likely specie, Te_2, is constrained to under 100 ppb and begins to crystallize at 18km.[205]

- **Lead chlorides, metal, oxide**: Models suggest the most likely specie, lead chloride, is constrained to under 12 ppb and begins to crystallize at 16 km.[206]

- **Zinc chlorides, metal**: Models suggest the most likely species, $ZnCl_2$, is constrained to under 410 ppt and begins to crystallize at 38km.[207]

- **Indium chloride, metal, oxide**: Models suggest the most likely specie, indium chloride, is constrained to under 1.6 ppb and begins to crystallize at 46km.[208]

- **Bismuth chlorides, metal, oxides**: Models suggest the most likely specie, $BiCl_3$, is constrained to under 410 ppt and begins to crystallize at 50km.[209]

As acidic, hygroscopic compounds, these can be expected to accumulate in the sulfuric acid fraction during atmospheric scrubbing.

Before we address the critical issues of envelope tolerance of the external environment and rates of permeation through it, it's worth considering the effects of the external atmosphere on human health. Clearly one can immediately rule out breathing it - if only for the lack of oxygen. Even absent sulfuric acid, the levels of carbon dioxide and carbon monoxide are hazardous to the eyes; the CO_2 exposure symptoms would be more immediate, including stinging, yellowed vision, and damage from chronic exposure.[210] Immediate hazards to the skin from the atmosphere, however, are not as certain. Middle cloud sulfuric acid levels range from a few to a few dozen mg/m³. The OSHA and NIOSH workplace exposure limits (8h/day) are 1mg/m³ [211] - and this includes breathing and eye

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202 Lewis et al 1982
203 Hunten et al 1983
204 Hunten et al 1983
205 Hunten et al 1983
206 Hunten et al 1983
207 Hunten et al 1983
208 Hunten et al 1983
209 Hunten et al 1983
210 Grant, W.M. (1983) *Toxicology of the Eye. 3rd ed*. Springfield, IL: Charles C. Thomas
211 (2014) Non-Volatile Acids (Sulfuric Acid and Phosphoric Acid). NIOSH Manual of Analytical Methods (NMAM), Fifth Edition. METHOD 7908, Issue 1.

exposure. 2 mg/m³ for five days is considered a risk factor for pulmonary edema, and 2 mg/m³ for one hour a risk factor for bronchoconstriction.[212]

The outside environment, at a few to a few dozen mg/m³ looks at a glance, amazingly, to be tolerable to human skin so long as the individual wears a full face mask. Indeed, the acid mists in the cloud deck are only tenuous, like an urban smog.[213]

A few caveats are of note which temper this, however. First, sulfuric acid mists on Venus at the desired latitude / altitude are around 89% concentration;[214] on Earth they begin at their source concentration but over time self-dilute with atmospheric moisture to as low as 10% concentration.[215] Secondly, there are additionally a wide variety of acidic anhydrous compounds in the atmosphere, as well as a wide range of other chemicals at levels little studied for protracted skin exposure. Lastly, precipitation or condensation could greatly increase the concentration on the skin. While it is difficult to say, without experimentation, what the atmosphere of Venus would do to human skin, it seems plausible that short term, infrequent exposure to the external atmosphere in the absence of precipitation or condensation may not prove highly hazardous. In the medium term or with repeated exposure, or in the case of precipitation or condensation, dermatitis seems likely at a minimum, up to severe burns if highly exposed to concentrated liquid.

Deuterium and power storage issues

A little discussed issue of both risk and benefit to a Venus colony is a particular way in which Venus differs dramatically from Earth: deuterium levels. Most of Venus's light isotope ratios are quite similar to those of Earth,[216] but deuterium is a dramatic exception. Having lost its ancient oceans to space, the concentration of deuterium on Venus has been enriched, to levels which vary with altitude.

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[212] Sulfuric acid [MAK Value Documentation, 2001]. (2012). *The MAK-Collection for Occupational Health and Safety,* 166-222. doi:10.1002/3527600418.mb766493e0015

[213] Hunten, D. M., Colin, L., Donahue, T. M., Moroz, V. I. (1983). *Venus*. The University of Arizona Press, Tuscon, Arizona.

[214] Krasnopolsky, V. A. (2015). Vertical profiles of H2O, H2SO4, and sulfuric acid concentration at 45–75km on Venus. *Icarus, 252*, 327-333. doi:10.1016/j.icarus.2015.01.024

[215] Sulphuric acid mists and occupational health issues. Australian Institute of Occupational Hygienists. AIOH Exposure Standards Committee, July 2015.

[216] Bullock, M. A., Harder, J. W., Simon-Miller, A. A., & Mackwell, S. J. (2014). *Comparative Climatology of Terrestrial Planets*. University of Arizona Press.

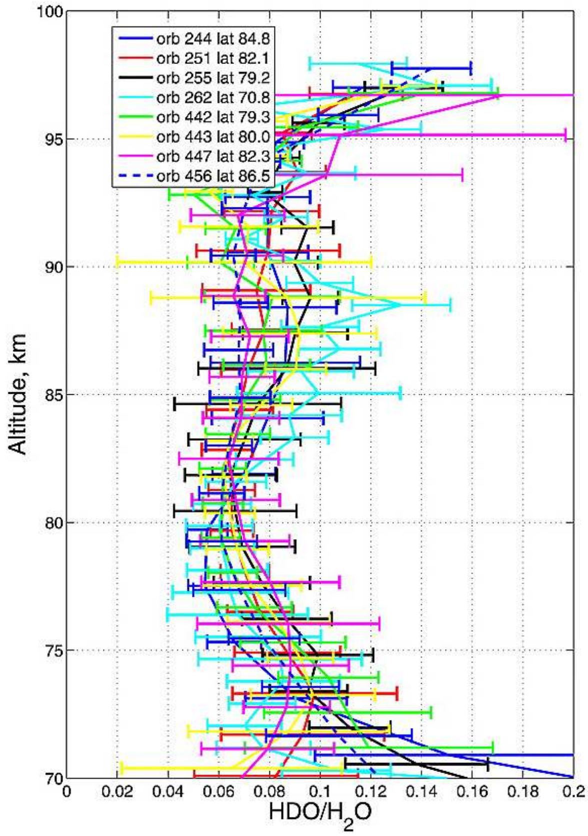

Image from Fedorova et al (2008)[217]

While the Vienna Mean (VSMOW) deuterium levels on Earth are 0.0156%[218], earlier estimates from Pioneer Venus estimated Venus's ratio to be 1.6%, via mass spectrometry measurements in the lower atmosphere.[219] More recently Venus Express measured an average deuterium concentration 240 times that of Earth in the upper atmosphere (3.7%), varying with latitude and altitude.[220]

What practical impact does this large difference represent?

- ***Chemistry***

Deuterium and protium are surprisingly different, and thus their compounds are as well. Consider heavy vs. light water. Heavy water is 11% denser and 20% more viscous. It freezes at 3.8°C and boils at 101.6°C. Its maximum density is at 11.6°C, versus 4°C in light water. Heavy water has a dissociation rate 16 orders of magnitude higher than light water, and salts are often significantly less soluble in it.[221]

A new research field has been built around deuterated drugs, which tend to have much longer lifespans in the body than their non-deuterated counterparts.[222] The first commercial deuterated drug, a treatment for Huntington's disease, is currently awaiting FDA approval; it is expected to pave the way for many others, representing a market worth tens of billions of dollars.[223] Deuteration can provide a severalfold increase in resistance to thermoxidative breakdown, making it of interest for lubrication in extreme conditions.[224] Deuterated PMMA, polyfluoromethacrylate, and other polymers have has been researched

[217] Fedorova, A., Korablev, O., Vandaele, A., Bertaux, J., Belyaev, D., Mahieux, A., . . . Villard, E. (2008). HDO and H2O vertical distributions and isotopic ratio in the Venus mesosphere by Solar Occultation at Infrared spectrometer on board Venus Express. *Journal of Geophysical Research, 113*. doi:10.1029/2008je003146
[218] National Institute of Standards & Technology Report of Investigation Reference Materials 8535, 8536, 8537
[219] Donahue, T. M., Hoffman, J. H., Hodges, R. R., & Watson, A. J. (1982). Venus Was Wet: A Measurement of the Ratio of Deuterium to Hydrogen. *Science, 216*(4546), 630-633. doi:10.1126/science.216.4546.630
[220] Fedorova et al 2008
[221] Chaplin, M. (2000, 2017). *Water Properties (including isotopologues*. Retrieved from http://www1.lsbu.ac.uk/water/water_properties.html
[222] Katsnelson, A. (2013). Heavy drugs draw heavy interest from pharma backers. *Nature Medicine, 19*(6), 656-656. doi:10.1038/nm0613-656
[223] Benmeleh, Y., & Cortez, M. (2016, September 16). A Decades-Old Drug Technology Finally Nears Its Big Breakthrough. *Bloomberg*.
[224] Campana, J. E. (1983). *High-Temperature Deuterated Lubricants: Additives, Mechanisms, and Methods.* (Tech. No. ADA138114). Washington DC: Naval Research Lab.

for use in fibre optics, as the substitution of deuterium for hydrogen dramatically lowers light attenuation.[225] [226] Deuterated plastics tend to be more resistant to ionizing radiation.[227]

Of particular interest for local production, a curious effect can occur in deuterated thermoplastics: while thermoplastics such as polyethylene may be transparent in both low-deuterium and highly-deuterated versions, mixtures of them tend to be highly opaque. This is a result of the differing melting points between deuterated and non-deuterated compounds, causing the lower-melting-point low-deuterium polymer to crystallize first. The droplets of highly deuterated plastic left behind then crystalize. Having a significantly higher refractive index and a particle size much larger than the wavelength of visible light, the crystals heavily scatter the light and leave the polymer opaque.[228]

- ***Health***

Deuterium is acutely toxic to mammals at high doses, with lethality beginning at around 20-25%. Studies on humans have been limited, generally only involving the short-term elevation of body deuterium levels to 0.2-0.5%; the most common side effect was vertigo, likely to the change of density of fluid in the vestibular system. One subject was maintained at 0.5% for 130 days, without acute toxicity symptoms.[229]

Relatively few studies have been done to search for chronic low-level impacts of elevated deuterium on humans, and even fewer in recent years. Perhaps the most notable was Strekalova et al 2015, a multi-institutional and multidisciplinary study which found a significant positive correlation deuterium exposure and depression over the ranges normally found on Earth. As the Earth range is dramatically lower than that of Venus, this raises a significant concern for the long-term habitation on Venus.[230]

Many algae and bacteria can grow and reproduce in up to 100% deuterium, although generally at a slower rate. Many show a preference for deuterium and enrich it, such as Chlorella (2.5x) and E. coli (3.9x).[231] Since the whole-cell enrichment factors are so large, it's expected that various chemical processes within them that lead to the enrichment can themselves have much higher enrichment factors. For higher animals such as fruit flies, high deuterium levels (peaking at 7.5%) prolong lifespan but reduce growth rate.[232] Biological effects at the molecular level have been studied; for example, Lobyshev et al 1989 and 1992

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[225] Kaino, T. (1987). Preparation of plastic optical fibres for near-IR region transmission. *Journal of Polymer Science Part A: Polymer Chemistry, 25*(1), 37-46. doi:10.1002/pola.1987.080250105
[226] Yoshimura, R., Hikita, M., Tomaru, S., & Imamura, S. (1998). Low-loss polymeric optical waveguides fabricated with deuterated polyfluoromethacrylate. *Journal of Lightwave Technology, 16*(6), 1030-1037. doi:10.1109/50.681460
[227] Milinchuk, V. K., Klinshpont, E. R., & Vasilenko, V. V. (1976). Effect of isotopic composition on free-radical reactions in polyolefins. *Journal of Polymer Science: Polymer Chemistry Edition, 14*(6), 1419-1427. doi:10.1002/pol.1976.170140610
[228] Tanaka, T. (2000). *Experimental methods in polymer science: modern methods in polymer research and technology*. San Diego: Academic Press.
[229] Jones, P. J., & Leatherdale, S. T. (1991). Stable isotopes in clinical research: safety reaffirmed. *Clinical Science, 80*(4), 277-280. doi:10.1042/cs0800277
[230] Strekalova, T., Evans, M., Chernopiatko, A., Couch, Y., Costa-Nunes, J., Cespuglio, R., . . . Lesch, K. (2015). Deuterium content of water increases depression susceptibility: The potential role of a serotonin-related mechanism. *Behavioural Brain Research, 277*, 237-244. doi:10.1016/j.bbr.2014.07.039
[231] Choppin, G. R., Choppin, G. R., Liljenzin, J., & Rydberg, J. (2002). *Radiochemistry and nuclear chemistry*. Woburn, MA: Butterworth-Heinemann.
[232] Hammel, S. C., East, K., Shaka, A., Rose, M. R., & Shahrestani, P. (2013). Brief Early-Life Non-Specific Incorporation of Deuterium Extends Mean Life Span in Drosophila melanogaster Without Affecting Fecundity. *Rejuvenation Research,16*(2), 98-104. doi:10.1089/rej.2012.1368

determined that Na,K-ATPase activity increases by 50% at deuterium levels of only 0.03-0.04%[233] [234]

With specific focus on the effects of human life on Mars and Venus, Xie and Zubarev 2017 reviewed existing studies, on topics ranging from bacterial growth to cancer, and conducted two additional experiments: E. coli grew slower under Mars conditions, and even slower under Venus conditions; while brine shrimp grown under such elevated conditions had lower year-long survival rates. As per the study: “It is far from certain that terrestrial life will thrive in these isotopic conditions … the biological impact of varying stable isotope compositions needs to be taken into account when planning interplanetary missions.”[235]

- ***Export***

While many potential local uses of deuterium are tangential, there is a very important issue of note: its potential for export. Deuterium is valuable. Reactor grade heavy water sells for roughly $300/kg.[236] [237] As deuterium makes up 1/3rd of the mass of heavy water, its mass value fraction is $900/kg. This raises an interesting prospect: a Venus economy based on deuterium exports.

A few issues of note:

- Hydrogen gas tankage is usually significantly heavier than the hydrogen itself - often 10-20 times heavier. [238] Hydrogen absorbers eliminate the high tankage masses but replace them with absorbent masses. The highest densities / lowest tankage masses can be achieved by direct bonding of deuterium into other compounds, such as heavy water (20%), methane (40%), ammonia (30%), hydrazine (22%), lithium hydride (25%), tetraborane (38%), lithium aluminum hydride (21%), silane (25%), beryllium hydride (36%), and others.

- As an alternative, liquid hydrogen, commonly used in rocketry, provides low tankage masses compared to the mass of the hydrogen stored; bulk storage of such deep cryogens in space is an active topic of research.

- The mass of deuterium can be worked around to some extent. Wherein there are materials that that will be be sent back to Earth regardless, such as containers or liquids (for example, ammonia coolant), one can return deuterated variants instead. This effectively allows you to halve the mass of the deuterium, since one would have had to export hydrogen (half its mass) regardless.

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[233] Lobyshev VI, Tverdislov VA, Vogel J, Iakovenko L V. (1978) Activation of Na,K-ATPase by small concentrations of D2O, inhibition by high concentrations. *Biofizika*. pmid:148298
[234] Lobyshev VI, Fogel' Iu , Iakovenko L V., Rezaeva MN, Tverdislov VA. (1982) D2O as a modifier of ionic specificity of Na, K-ATPase. *Biofizika*. pmid:6289916
[235] Xie, X., & Zubarev, R. A. (2017). On the Effect of Planetary Stable Isotope Compositions on Growth and Survival of Terrestrial Organisms. *Plos One, 12*(1). doi:10.1371/journal.pone.0169296
[236] Miller, A. I. (2001). Heavy Water: A Manufacturers' Guide for the Hydrogen Century. *Canadian Nuclear Society Bulletin*, vol.22, no.1, 2001 February
[237] Europeans Interested in Purchasing Heavy Water. (2016, December 28). *Financial Tribune*.
[238] See *Mass Budget* for details on estimations of tankage mass.

- By enriching to higher levels, one shrinks the size of the market but greatly increases the value of the deuterium. While reactor-grade heavy water is 99.75% and $300/kg, it can be enriched significantly beyond this for laboratory purposes, such as NMR spectroscopy. Comparing retail prices in the largest bulk quantities available:[239] [240]

Seller	Item #	Price	Quantity (kg)	Enrichment	Price per kg
Cambridge Isotopes	DLM-2259-1	$793.00	1.107	99.8%	$716.35
Cambridge Isotopes	DLM-4-1000	$888.00	1	99.9%	$888.00
Sigma-Aldrich	151882-4KG	$3880.00	4	99.9%	$970.00
Cambridge Isotopes	DLM-6-1000	$1015.00	1.0	99.96%	$1015.00
Sigma-Aldrich	364312-10G	$68.90	0.01	99.98%	$6890.00
Sigma-Aldrich	191701-10G	$121.00	0.01	99.990%	$12100.00
Sigma-Aldrich	613398-50G	$472.50	0.05	99.994%	$9450.00

In short, if material return costs for deuterium can be gotten low enough - thousands of dollars per kilogram for a small market, hundreds of dollars per kilogram for a large market - an entire economy can be built on the export of deuterium, based around Venus's significant natural advantage in this regard. While costs of return cargo on the order several hundred or even a thousand dollars per kilogram are unlikely to be achieved in the near term, there is the potential for a large industry in the long term. In the short to medium term, exports in the $5-10k/kg range are much more plausible - and while the market is greatly reduced, it should prove more than enough compared to the needs of a small colony.

Deuterium is a very high demand product on Earth relative to its price, used in some nuclear reactors (such as CANDU), nuclear weapons production, research (NMR, tracing, etc), and a variety of other applications. Should fusion power take off in the future, very large amounts of deuterium will be needed, as the feedstocks are deuterium and lithium (the latter, used for tritium breeding, is available in virtually unlimited quantities from seawater at under $25/kg carbonate - far cheaper than the deuterium)[241]

This raises the question: how could enrichment on Venus proceed? Enrichment plants tend to be huge, energy-hungry systems. So we must investigate the various processes, which vary significantly:[242]

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239 Sigma-Aldrich, deuterium oxide prices. Retrieved on 11 February 2017 from http://www.sigmaaldrich.com/catalog/search?term=deuterium+oxide&interface=All&N=0&mode=match%20partialmax&lang=en&region=IS&focus=product

240 Cambridge isotopes, deuterium oxide prices. Retrieved on 11 February 2017 from http://shop.isotope.com/advancedsearchresults.aspx?id=0&keyword2=deuterium+oxide&searchType=ALL%20Keywords&SearchSpecificField=0&SearchContent=0

241 Ciez, R. E., & Whitacre, J. (2016). The cost of lithium is unlikely to upend the price of Li-ion storage systems. *Journal of Power Sources, 320*, 310-313. doi:10.1016/j.jpowsour.2016.04.073

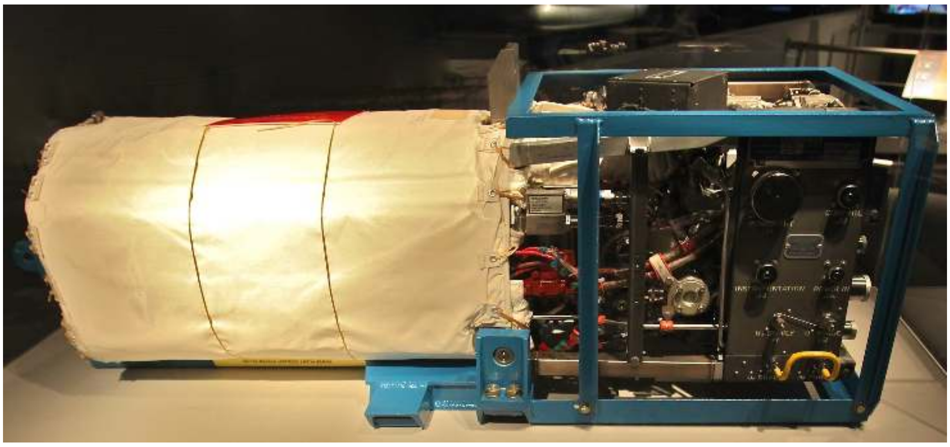
242 Miller, A. I. (2001). Heavy Water: A Manufacturers' Guide for the Hydrogen Century. *Canadian Nuclear Society Bulletin*, vol.22, no.1, 2001 February

Enrichment Process	Separation Factor	Energy Needed	Natural Exchange Rate	Counter-current Flows	Feed Distillation of H_2O
Distillation of H_2O	1.015 to 1.055	Very high	Moderate	Yes	Water
Distillation of liquid H_2	~1.5	Moderate	Slow	Yes	Very pure H_2
Water electrolysis	5 to 10	Very high	Fast	No	Water
Hydrogen sulfite exchange	1.8 to 2.3	High	Fast	Yes	Water
Ammonia - hydrogen exchange	2 to 6	Moderate	Slow - catalyst needed	Yes	H_2
Aminomethane - hydrogen exchange	3.5 to 7	Moderate	Slow - catalyst needed	Yes	H_2
Water-hydrogen	2 to 3.8	Moderate	Almost nonexistent - catalyst needed	Yes	Water

The enrichment factor and exchange rate largely determine the size of the enrichment system, while the power consumption determines the size of the power supply needed to power it. Standing out in both regards is electrolysis. Useful with most hydrogen compounds, although most studied for water, a high rate of separation can be achieved using a compact system. However, it is rarely used today in bulk; electrolysis consumes great amounts of electricity in the process of splitting its feedstock. The resultant hydrogen gas can be reversed in a fuel cell, but the losses in the reversal process alone mean that enrichment from this method is uncompetitive on Earth versus other processes (such as Girdler-Sulfide). There are hopes in the future that with a large market for electrolysis hydrogen, such as from hydrogen fuel cell vehicles, it could become a competitive means for enrichment; however, hydrogen today comes primarily (95%) from natural gas reformation, which is much cheaper.[243]

On Venus, though, an interesting opportunity arises. The large nighttime power storage needs mandate a storage system, and fuel cells tend to provide greater mass density than batteries,[244] as well as offering the ability for their working fluids to be produced by ISRU. In galvanic (discharge) mode, hydrogen-oxygen fuel cell combines hydrogen and oxygen to produce power, while in in electrolytic (charge) mode hydrogen and oxygen are regenerated. Alternative fuel cells operate similarly - for example, in HCl fuel cells, hydrogen and chlorine are combined to hydrogen chloride in galvanic mode, while they are split in galvanic mode. In short, extensive electrolysis needs to be conducted every day independent of enrichment / depletion needs.

[243] *Hydrogen Production: Natural Gas Reforming*. United States Department of Energy. Retrieved from https://energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming
[244] See calculations and discussion in *Mass budget*.



Fuel cells have a significant history in spaceflight due to their mass advantages. The above alkaline hydrogen-oxygen fuel cell was taken from the Space Shuttle Endeavour. Photo: Steve Jurvetson

In short, a fuel cell stack (which is comprised of many individual cells), plumbed into a cascade, can enrich hydrogen at the same time it provides nighttime backup power. The primary expense over a basic fuel cell stack is greater system complexity, particularly a greater number of storage envelopes and pumps. At the same time it produces deuterium it also produces depleted water for local consumption. As an example, enrichment in an 11-stage cascade can proceed (assumed enrichment factor = 6):

Stage	% of system hydrogen depleted	% of system hydrogen enriched	Total % of system hydrogen	Deuterium molar % depleted	Deuterium molar % enriched
1	0.17%	**0.04%**	0.21%	98.80%	***99.75%***
2	0.21%	0.07%	0.28%	95.70%	98.80%
3	0.24%	0.10%	0.33%	86.61%	95.70%
4	0.26%	0.19%	0.45%	64.70%	86.61%
5	0.35%	0.50%	0.85%	34.38%	64.70%
6	0.67%	1.60%	2.27%	12.99%	34.38%
7	1.77%	5.46%	7.22%	4.09%	12.99%
8	5.62%	18.97%	24.60%	1.20%	4.09%
9	5.37%	18.62%	23.98%	0.35%	1.20%
10	5.01%	17.50%	22.50%	0.099%	0.35%
11	**3.89%**	13.61%	17.50%	***0.028%***	0.099%

Thus on every cycle, 0.04% of the mass of hydrogen in the system is output as deuterium at reactor grade (99.75%), while 3.89% of the hydrogen mass in the system is output depleted for drinking, agriculture and manufacture (~280ppm). The removal of these from the system is compensated for by the injection of new unprocessed hydrogen into stage 8. For a nighttime storage of 23GJ (small initial habitat), 204.5kg of hydrogen would pass through the system per day; this would yield 82 grams of D_2 and 7.95kg of H_2 per day.

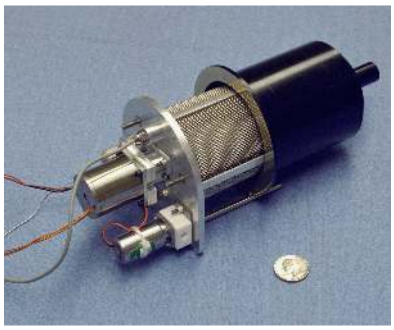
For a stack designed for the common nominal DC voltage of 380V and a fuel cell voltage of 1.31V, the number of stacks per layer would be: 1, 1, 1, 2, 2, 6, 21, 71, 69, 65, and 51, respectively, yielding slightly poorer results than optimal due to rounding errors. The enrichment levels and/or throughput can be increased by increasing the number of stages, at the cost of system mass and complexity.

A few factors need to be discussed - most of these favorable to a Venus habitat. The above fuel cell stack assumes only enrichment during electrolysis, with no consideration towards galvanic enrichment. Likewise, while the most researched electrolysis enrichment system is water, other hydrogen compounds such as hydrogen chloride also provide strong enrichment factors. Compared to water PEMs, hydrogen chloride PEMs are higher power density (smaller), much more efficient, much more readily reversible (aka, using a single system for galvanic and electrolysis mode).[245] [246]

A negative aspect of fuel cell usage for enrichment is that optimal stack efficiency involves operating at as low of an overpotential as possible; however, enrichment is maximized at around 0.4V overpotential.[247] Thus, the more a colony is experiencing excess power, the greater that hydrogen can be enriched, while when power is more in short supply, the enrichment factor can be decreased.

An issue arises as to how to perform pumping in a manner that ensures reliability. While chlorine and hydrogen chloride compression are easy to achieve via phase change, hydrogen distinctly is not.

A relatively simple approach to H_2 compression allows us to avoid all moving parts except for one-way check valves: metal hydride compression. Utilized on NASA's Planck satellite,[248] hydrogen is adsorbed into a substrate at lower temperatures and pressures, then heated to release it at high pressures. Lifecycles are on the order of tens of thousands of cycles, and the absorbant be almost entirely renewed by vacuum heating.[249] The 40kg system on Planck pumped over a kilogram per second; our needs are on the order of two grams per second, and thus the "pumps"



Absorption compressor designed for Mars ISRU. Photo: NASA / ARC

[245] Anderson, E. B., Taylor, E., Wilemski, G., & Gelb, A. (1994). A high performance hydrogen/chlorine fuel cell for space power applications. *Journal of Power Sources, 47*(3), 321-328. doi:10.1016/0378-7753(94)87011-x
[246] Liu, S., Zhou, L., Wang, P., Zhang, F., Yu, S., Shao, Z., & Yi, B. (2014). Ionic-Liquid-Based Proton Conducting Membranes for Anhydrous H2/Cl2Fuel-Cell Applications. *ACS Applied Materials & Interfaces, 6*(5), 3195-3200. doi:10.1021/am404645c
[247] Hammerli, M., Mislan, J. P., & Olmstead, W. J. (1969). The Effect of Overpotential on the Electrolytic Hydrogen-Deuterium Separation Factor on Bright Platinum Electrodes in 1.2N HCl-10% D_2O. *Journal of The Electrochemical Society,116*(6), 779. doi:10.1149/1.2412051
[248] Wade, L. A., Bhandari, P., Bowman, R. C., Paine, C., Morgante, G., Lindensmith, C. A., . . . Rapp, D. *Hydrogen sorption cryocoolers for the Planck mission*. Presented at CEC-Montreal July, 1999, Submitted to Adv. Cryogenic Engineering Vol. 45
[249] Lototskyy, M., Yartys, V., Pollet, B., & Bowman, R. (2014). Metal hydride hydrogen compressors: A review. *International Journal of Hydrogen Energy, 39*(11), 5818-5851. doi:10.1016/j.ijhydene.2014.01.158

would be nothing more than specialized plumbing fittings, pumping from inflated bags of hydrogen that contribute to lift.

As noted previously, for chlorine pumping, phase-change compression suffices. At ideal HCl fuel cell pressures and temperatures, (~5 MPa, ~50°C)[250], chlorine condenses at around 10°C [251] - a quite small temperature difference. Consequently, a small peltier cooler could liquefy the 66 grams per second without difficulty - a system that is once again small enough to be little more than pipe fittings. See *Mass budget* for more details on flow rates.

Other issues related to the enrichment of isotopes will be discussed under *Indirect export of energy*.

In-Situ Resource Utilization

Due to the very high shipping costs from Earth, and the desire to ultimately achieve local resource independence, as well as to reduce the launch mass of an initial habitat, producing local resources via ISRU is essential. IRSU shares many similarities as well as many significant differences with the more researched topic of IRSU on Mars.[252]

Let us begin with the key difference, the primary category where Mars has an advantage over Venus: cation availability. With the exception of iron, most metallic cations are rare or absent from Venus's atmosphere, including many that are essential to life (calcium, potassium, sodium, magnesium, zinc, silicon, minor nutrients) and industry (copper, aluminum, tin, nickel, cobalt, molybdenum, and numerous others to increasingly lesser extents).

There are three primary means to acquire these elements: the surface (see *Surface access*), shipment from Earth (which is quite acceptable in the early stages of habitation, but must be minimized due to costs), and recycling.

Cation recycling, thankfully, turns out not to be as difficult as might be expected. Examples have been researched for hydroponics. The general process is high temperature incineration of all waste in the presence of oxygen and optionally steam, to produce a mixture of oxides and hydroxides. The temperature can be boosted by the injection of manufactured hydrocarbons or plasma arc incineration. The resultant oxides and hydroxides are then dissolved in strong acids; as the main needs for hydroponics are nitrates and nitrate salts tend to be highly soluble, nitric acid is the most useful for this purpose. Simple addition of these salts to hydroponic nutrient solutions are, however, insufficient to sustain proper nutrient balances; the salts must be separated first, such as with fractional crystallization

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[250] Huskinson, B., Rugolo, J., Mondal, S. K., & Aziz, M. J. (2012). A high power density, high efficiency hydrogen–chlorine regenerative fuel cell with a low precious metal content catalyst. *Energy & Environmental Science, 5*(9), 8690. doi:10.1039/c2ee22274d

[251] Kapoor, R., Martin , J. J. (1957). *Thermodynamic Properties of Chlorine*. Eng. Res. Inst. Univ. of Michigan, 1957.

[252] Watson, R. D. (1999) *A survey of resource utilization processes for Mars and its moons*. Space Studies Institute.

(DTB), and then those added to solution as needed. This also makes individual salts available for other industrial processes.[253]

Thankfully, most of the mass needed on a Venus habitat has nothing to do with metallic cations - and in regards of what the habitat needs, Venus's environment shines. First, we shall look at the types of primary feedstocks (discussed briefly under *Habitat propulsion*).

- **Condensation / precipitation**: Fluids gathered from condensation and precipitation would be expected to be primarily sulfuric acid with additional minor constituents, such as iron chloride.

- **Absorption**: Absorption into a liquid (such as water or similar) would collect Venus's diverse anhydrous, hygroscopic species as well as its sulfuric acid mists.

- **Tail gases**: Tail gases left over after any absorption processes are predominantly carbon dioxide, followed by nitrogen, argon, carbon monoxide, and then increasingly minor noble gases.

Two key aspects of establishing an industrial manufacturing infrastructure are the creation of streams of the major industrial acids, and the establishment of a petrochemical industry. Likewise, key habitat consumables like oxygen, propellant(s), ammonia and water must be produced in significant quantities. We shall investigate the processes involved in doing so.

Atmospheric scrubbing

In designing a scrubbing system, we face the following primary challenges:

- **Capture efficiency**. It is important to capture as broad of a spectrum of minor gases moving through the scrubber as possible, not just specific common species. It is also important to capture as high of a percentage as possible to maximize production.

- **Longevity**. Beyond ensuring that materials used are chemically compatible with Venus's atmosphere, it must be ensured that any solid particulates (if present) do not erode the scrubber. Additionally, moving parts should be minimized.

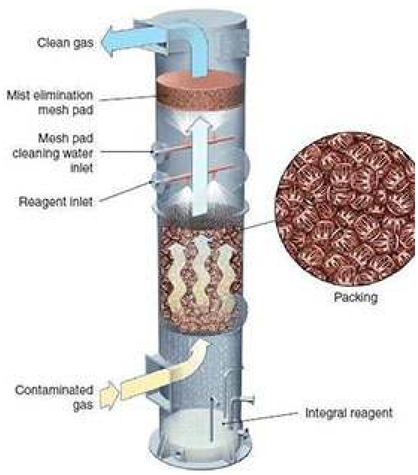
- **Water loss**. The easiest way to capture most of the hygroscopic gases of interest, as well as liquids like sulfuric acid, is a wet scrubber. However, the very dry atmosphere of Venus means a significant loss of water to the exhaust stream. Increased pressure can densify the air such that the scrubbing water's vapour pressure is lower than the vapour pressure of the outside air, but this requires very high (>100 bar) pressures.

[253] Bubenheim, D., & Wignarajah, K. (1997). Recycling of inorganic nutrients for hydroponic crop production following incineration of inedible biomass. *Advances in Space Research, 20*(10), 2029-2035. doi:10.1016/s0273-1177(97)00937-x

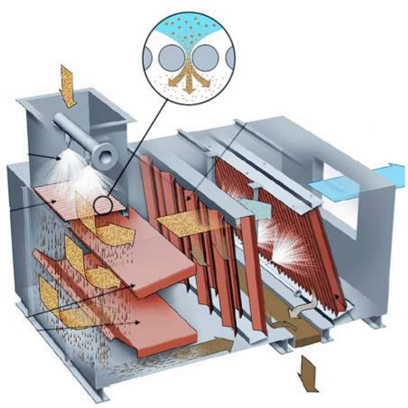
- **Pressure drop**. In order to minimize mass and power consumptions, air moving through the system should experience as small of a pressure drop as possible.

- **Lightweight and transportable**. A system is of no use if it can't be stowed inside a fairing without requiring unreasonable amounts of mass or volume.

In short, we need a lightweight, collapsible scrubber with very efficient water scavenging and minimal obstruction to airflow, in order to capture mists for recovery. With this in mind, let us examine a variety of options used in conventional industrial scrubbers on Earth:[254]



Countercurrent packed tower scrubber. (© Nederman MikroPul)



Horizontal multi-venturi scrubber with demist vanes (© Nederman MikroPul)

- **Orientation:**
  - **Vertical**: Gas enters a vertical chamber and flows to the opposite end. Falling / blowing liquid can spend long periods of time in contact with the air before reaching collection at the base.
  - **Horizontal**: Gas enters the scrubber from the side and flows to the opposite side. Liquid gets cycled through more frequently, constantly being replaced by fresh. Generally less susceptible to fouling.
- **Flow:**
  - **Countercurrent scrubber**: Liquid and gas move in opposite directions. This generally involves a vertical orientation.
  - **Co-current scrubber**: Liquid and gas move together in the same stream.
  - **Crossflow scrubber**: Liquid interacts with the gas stream at a 90 degree angle to the flow of the stream. This is common in horizontal systems, with the liquid entering from the top.
- **Liquid distribution**:
  - **Weir**: Full troughs constantly overflow along their length. Weirs are largely immune to

[254] Joseph, G. T., Beachler, D. S. (1998) [Scrubber Systems Operation Review.](#) Industrial Extension Service College of Engineering North Carolina State University

liquid distribution methods, top to bottom: extraction (weir), bottom hole (weir / drip), slotted (weir / drip), tube (drip), spray, and radial (spray). (© Sulzer Chemtech Ltd.)

clogging and allow for high flow rates for minimal power, but require a very level alignment.

- **Nozzles**: Spray nozzles atomize the liquid as it enters the scrubber. They provide excellent fluid distribution without sensitivity to alignment, but are intolerant of solid contamination in the liquid and require higher pressure pumps.
- **Drip line**: Tubes with holes drip liquid into the scrubber. Their properties with respect to flow and clogging lie in-between those of nozzles and weirs.
- **Venturi** or **orifice**: The airflow is constricted to accelerate flow and reduce pressure, creating a venturi valve. Liquid is injected, either at the nozzle, or in the case of erosive environments, above it; the airstream atomizes the inflowing liquid.
- **Mechanical**: Liquid flows onto a moving element, typically a fan, which atomizes and distributes it.

- **Bed**:
  - **Packed bed**: Liquid flows across a stationary packing material (structured or random, generally metal, ceramic or plastic), designed to spread out the liquid and maximize its surface area for gas exchange..
  - **Fluidized bed**: Similar to a packed bed, the flow is maintained at high enough pressure and rate to loft the packing material, causing it to circulate like a fluid. This offers better mixing, at the cost of greater inflow requirements.
  - **Impingement plate**: Liquid is forced along a circuitous route as it falls along nearly horizontal plates or tray columns with perforations. Air flows up from underneath

through the perforations, preventing the liquid from dripping through them and mixing with the sheet of liquid.

- **Fibre bed**: Beds of fibrous material block the airflow, leading to the interaction of particulate and liquid on the fibres. The beds are designed for maximal surface area, such as a corrugated folding or long bags.

NeXRing^{TM} random packing (© Sulzer Chemtech Ltd.)

Tray columns (© Sulzer Chemtech Ltd.)

Mist eliminators. Top: vane; bottom: knitted wire. (© Amacs Process Tower Internals)

High Efficiency fibre Bed Mist Eliminator

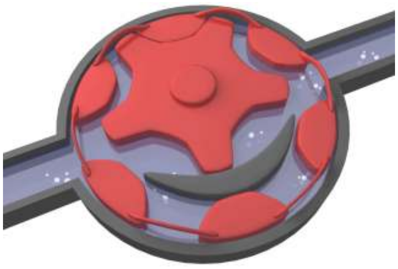
- **Liquid / particulate recovery:**
    - **Simple drainage**: An inherent part of most wet scrubbers; liquid reaches the bottom via gravity and is pumped for processing and reuse.
    - **Cyclonic**: A cyclonic flow is maintained within the scrubber, causing liquid droplets to be pushed to the sides to drain off.
    - **Mist eliminators**: Knitted wire, vane or fibre systems for collecting mist from the air as it passes through; entrained droplets impinge or absorb onto the substrate.
    - **Condensation scrubbing**: The gas is brought to saturation, followed by steam injection. This causes moisture in the gas to condense, with any particulate in the gas stream acting as condensation nuclei.
    - **Electrostatic precipitation**: Similar to “ionic wind” home air filters as well as electrohydrodynamic propulsion, the air stream passes over high voltage negative wires, followed by positive collection plates. Ionized particulate is attracted to the plates and is removed from the stream.[255]

- **Pumping:**[256] [257]

[255] Parker, K. R. (2012). *Applied electrostatic precipitation*. Blackie Academic and Professional.
[256] Kerri, K. D. (2008). *Operation of wastewater treatment plants: a field study training program*. Sacramento: California State University. ISBN 978-1-59371-038-5
[257] (2017) *When to use a positive displacement pump*. Pump School / Viking Pump. Retrieved from http://www.pumpschool.com/intro/pd%20vs%20centrif.pdf

Reciprocating pump

- **Reciprocating**: Reciprocating pumps come in a variety of forms, all having the property that a piston, plunger or diaphragm reciprocates, alternately pushing liquid through the outlet and sucking it through the inlet. Such pumps tend to deliver low volumes with excellent head and efficiency.



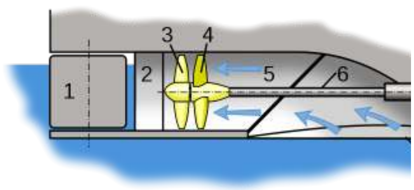
Internal gear pump. Image: Staffan Lincoln

- **Positive displacement rotary**: Two counter-rotating, interlocking shapes (lobes, gears, etc) intermesh to push fluid through moving cavities. They offer excellent efficiency, good head, and moderate flow rates. They also deal well with solids, can often run in reverse as generators, and some can run dry for periods of time.

  The above types have poor to moderate wear and are sensitive to pressure buildup.

Chopper (centrifugal) pump.
Image: Bogelund.

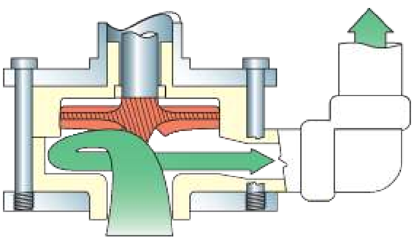
- **Centrifugal**: The inverse of a water turbine, a rotating impeller accelerates liquid outwards, providing for low/moderate head and high flow. Most varieties are intolerant of air ingestion, excepting froth pumps.



Axial jet pump. Image: Ladar

- **Rotary (axial)**: Axial-flow pumps drive liquid by means of an impeller - a propeller inside a tube. Often used for very high flow rate pumping applications; flow rate vs. head can be adjusted by blade pitch changes.

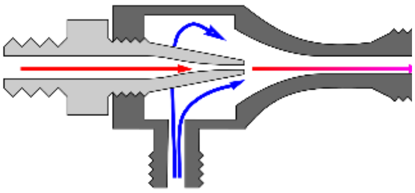
  The above types experience low to moderate wear and moderate to good efficiency.



Recessed vortex impeller.
Image: Vanton

- **Vortex pump**: Otherwise similar to traditional centrifugal and axial pumps, vortex pumps differ by relying on induced vorticity to drive fluids, eliminating the need for tight wall tolerances. This renders them resistant to erosion and fouling, at a small efficiency cost.[258]

[258] Evans, J. *How Lower Efficiency Can Reduce Overall Costs - Vortex Action*. Pump Ed 101.



Eductor pump. Image:Egmason

- **Jet pump (eductor / injector)**: In a jet pump, a high pressure jet, ideally of a condensable gas such as steam, is injected through a venturi nozzle. Steam condenses, creating more suction. The stream is moved through an expander, lowering velocity and increasing pressure. Compared to other pumps, eductors are low efficiency, but by operating on heat they avoid the losses inherent in thermal electricity generation. With no moving parts (excepting any check valves to prevent backflow), they can be made extremely reliable, and are very tolerant of solid intrusion. However, suction drops if the inflow water temperature rises too much.[259]

As propulsion is directing air horizontally, we will begin with consideration of a horizontal scrubbing layout. To ease collapsibility, we will baseline a flexible material for the scrubber body, held rigid by internal overpressure and/or rollable trusses. Prop wake speeds (12-25 m/s) are normal for cocurrent scrubbers;[260] however, such high velocities require long scrubber lengths. Pressure drop in a fluid due to friction is proportional to the velocity squared,[261] and we wish to keep the pressure drop under 800Pa (aka, "low energy"),[262] so for a wet scrubbing design it is preferable to take advantage of our long airship length to maximize liquid contact time rather than using thick, dense beds.

Can wet scrubbing be utilized?

Let us first investigate whether we can, in fact, utilize wet scrubbing.

A common problem with wet packed bed scrubbers is that hygroscopic acid gases form submicron mists that zigzag past the packing.[263] In our case, those are exactly what we want to scrub, and the standard solution to the problem - mist collectors - is what we need to utilize. Diffusion time requirements in turn require a long duct; we will target at least 1 second for mixing and saturation.[264] This means a leading duct of at least 12-25m.

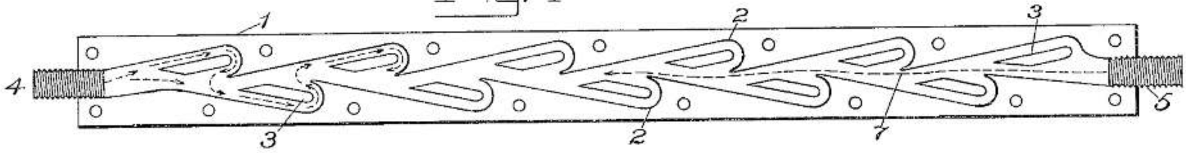
As we do not have the sort of high flow velocity needed for an effective venturi nozzle and do not want the associated pressure drop (venturi scrubbers are high energy[265]), we will look at other options - a diverse topic on its own.[266] Weirs are easily ruled out due to the levelness requirement. Clogging should not be an issue as the incoming water is condensed steam, so sprayers and drip tubes are options. Normally mechanical spraying would seem

[259] Power, R. B. (1994). *Steam jet ejectors for the process industries.* New York: McGraw-Hill, inc.
[260] Kohl, A. L., & Riesenfeld, F. C. (1997). *Gas purification* (5th ed.). Abington Publ.
[261] Darcy–Weisbach equation: $\Delta P / L = 0.5 f_D \rho v^2 / D$
[262] Reddy, A. (2016) Scrubbing Systems. Retrieved from http://www.slideshare.net/reddyas/scrubbing-systems
[263] Eldridge, J. (2008) *Cross-flow scrubber design*. AIChE Annual International Phosphate Fertilizer & Sulfuric Acid Technology Conference.
[264] Typical is 0.4 -0.8 seconds (Manuzun et al 2011)
[265] Identification of point source emission controls and determination of their efficiencies and costs (1998), Appendix B. California Air Resources Board. Penchan Report No. 98.01.001/548.
[266] Column Internals. RVT Process Equipment GmbH. Retrieved from http://www.rvtpe.com/wp-content/uploads/prospekte/RVT_Column_Internals_120601.pdf

an undesirable choice, as it implies the addition of another moving part. However, in this case the water could be dripped / sprayed on the propeller itself, so long as this does not shorten its lifespan or significantly interfere with its operation. For droplet evaporation with time for mixing, we target a size of 10-30 micron,[267] a wet fog or mist. This will saturate to effectively 100% humidity.

For feeding the boiler to remove captured compounds from the scrubbing water, a eductor pump is a natural fit, requiring no moving parts with the potential exception of check valves to prevent backflow. Indeed, if any check valves are required that do not mandate a near-zero reverse flow rate, these too can come in variants with no moving parts - for example, the Tesla valve, which experiences 1-2 orders of magnitude higher resistance in one direction than the other.[268]

Fig. 1



Due to the very high energy requirements of heating the water, a heat exchanger must be paired with the boiler to recapture as much heat as possible. In cases where boiler flow rates would be too low to provide a steam source for meeting scrubber pumping demands, a vortex pump would be desirable.

After expansion and condensation, the water must be removed. The need for the scrubber to be collapsible strongly favours fibre mist collection, particularly corrugated / accordion foldings. As electrostatic scrubbing presents foldable, low mass requirements and can even add to thrust, a electrostatic scrubber after the fibre scrubber would be desirable to catch finer particulate. If sulfur particulate is present and poses a fouling risk to fibre matting, carbon disulfide (an effective solvent of sulfur[269] with simple synthesis routes) can be used to periodically flush the mist collectors. This would require all pumps and scrubber components be chemically compatible with it. Contrarily, the mist collectors could be designed to be removed and cleaned.

At this point, there should be little to no particulate left in the stream - however, the stream is now fully saturated with water vapour at around 2.3 kilopascals[270], versus around 0.1 pascal of water in the ambient air. The water vapour level in the exhaust does not need to be below ambient - we're also recovering significant amounts of sulfuric acid, from which water can be recovered. However, we need the outflowing water vapor to be maintained at as low of a level as possible, as it is a valuable resource.

Since we're going from such a high partial pressure to such a low one, an ideal approach is multistage moisture removal, progressing from most to least. The air passes through desiccant blankets - the first stages being silica gel or zeolites / molecular sieves

[267] Holterman, H.J. (2003) *Kinetics and evaporation of water drops in air*. IMAG report 2003 – 12
[268] West, N (2003). Tesla's Valvular Conduit. Fluid Power Journal.
[269] *Carbon Disulfide: Properties and Uses / Methods of Production.* Sevas Educational Society.
[270] Buck equation, $P = 0.61121\ e^{(18.678 - T / 234.5) * (T / (257.14 + T))}$, *where P is pressure in kPa and T is temperature in celsius.*

tuned for easy reversibility at particular temperatures and levels of saturation.[271] Finally the air passes through blankets containing phosphorus pentoxide, a highly aggressive absorbent (capable of even desiccating sulfuric acid to sulfur trioxide[272]), but with limited capacity and requiring significant heating to drive off captured moisture.

Here lies the challenge for a wet scrubber. If we are scrubbing around 300 cubic meters per second, and we need several seconds in close contact with our desiccants, then we're needing around a thousand cubic meters of pore space in the dessicant. This represents, needless to say, a problematically large amount of dessicant. In short, we should examine alternatives that might improve the scenario.

Improving the process

- **Partial saturation**:

While the saturation vapour pressure inside the scrubber is several kilopascals, various anhydrous compounds will condense out at lower vapour pressures. Sulfuric acid tends to already be condensed. At 20°C, the vapour pressure over 42% hydrochloric acid is 208 pascals;[273] 50% hydrofluoric is 1640 pascals;[274] and phosphoric acid (25°C) is 5.3 pascals.[275] In short, full saturation is not required, but unless we wish to reject our primary source of fluorine, saturation still must be significant.

- **Hydrogen-free solvents**:

The problem with allowing water to leave the scrubber is that hydrogen is rare; hence, any solvent which does not reject hydrogen (or rarer elements such as fluorine) is worth investigating. Indeed, of what we collect, sulfur ends up naturally in significant excess and must be discarded. Carbon and oxygen are available in unlimited quantities, and with somewhat greater effort, nitrogen.

Concerning room-temperature liquids comprised of these elements, only one combines stability, simple synthesis and solvency properties of note: carbon disulfide (discussed previously).

Unfortunately, while an excellent solvent solvent for sulfur, phosphorus, bromine, and a number of other substances, it is not a particularly good solvent for acid gases. As a more serious problem, with a vapour pressure at 25°C of 48.1 kPa,[276] the loss rate would vastly exceed our sulfur intake.

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[271] Goldsworthy, M. (2014). Measurements of water vapour sorption isotherms for RD silica gel, AQSOA-Z01, AQSOA-Z02, AQSOA-Z05 and CECA zeolite 3A. *Microporous and Mesoporous Materials, 196*, 59-67. doi:10.1016/j.micromeso.2014.04.046

[272] *Phosphorus pentoxide*. (2016) Chemical Book.

[273] Liley, P. E., Thomson, George H., Friend, D. G., Daubert, T. E., Buck, E. (1999) *Perry Chemical Engineers Handbook 7th Edition.* Section 2: Physical and Chemical Data. McGraw-Hill.

[274] (2011) *Material Safety Data Sheet: Hydrofluoric Acid*. Seastar Chemicals Inc.

[275] (2012) Purified Phosphoric Acid Technical Information Bulletin. Potash Corp.

[276] Linstrom, P.J.; Mallard, W.G. (2016) *NIST Chemistry WebBook. NIST Standard Reference Database Number 69*. National Institute of Standards and Technology

- **Gas injection**:

Rather than attempting to absorb water vapour (whether normal atmospheric water vapour or recapture of scrubbing water), we can instead attempt to nucleate it to particles that we can capture. There is one obvious choice for this: sulfur trioxide, which forms sulfuric acid upon absorption of water.

Sulfur dioxide from volcanic eruptions slowly oxidizes to sulfur trioxide, which forms a blue mist of sub-micron sulfuric acid particles via absorption of atmospheric moisture. Photo: Brocken Inaglory

Injection of sulfur trioxide is used for this purpose as a “conditioning agent” in some scrubbers.[277] At 98% concentration and 20°C, the water vapour partial pressure over sulfuric acid is 0.01 pascals[278] - hence virtually any water vapour will condense out with a sufficient supply of SO_3.

Unlike with direct water absorption, sulfur trioxide can flow with the gas stream and thoroughly mix with. A few caveats must be mentioned. First, existing sulfuric acid mists need to be scrubbed to avoid SO_3 wastage toward concentrating existing sulfuric acid. Secondly, our rate of SO_3 injection cannot utilize more sulfur than we collect (the two primary sources being sulfuric acid and sulfur dioxide). Hence it can only function as a minor additive.

- **Ionic solvents**:

1-ethyl-3-methylimidazolium tetrafluoroborate, an ionic liquid, on polyethylene. Photo: Indrek Must

Room-temperature ionic liquids (RTIL) represent a rapidly expanding research topic touching on numerous scientific fields. RTILs are semi- or completely organic equivalents of molten salts, but existing in a liquid state at moderate temperatures (<100°C) with essentially no vapour pressure of relevance. With over 150000 different ionic liquids investigated, they are eminently tuneable and have been referred to as “almost universal solvents”.[279] While gas solubility in RTILs is broadly similar to solubility in water (in decreasing order of solubility: $SO_2 \rightarrow CO_2 \rightarrow Ar \rightarrow O_2 \rightarrow N_2$, CO, H_2[280]), the flexibility of the the organic scaffolding allows a great degree of enhancement / suppression of gas absorption. For

[277] Cook, R. E. (1975) Sulfur Trioxide Conditioning. *Journal of the Air Pollution Control Association*, 25:2, 156-158, DOI: 10.1080/00022470.1975.10470065

[278] Liley, P. E., Thomson, George H., Friend, D. G., Daubert, T. E., Buck, E. (1999) *Perry Chemical Engineers Handbook 7th Edition.* Section 2: Physical and Chemical Data. McGraw-Hill.

[279] Fedorov, M. V., & Kornyshev, A. A. (2014). Ionic Liquids at Electrified Interfaces. *Chemical Reviews*, 114(5), 2978-3036. doi:10.1021/cr400374x

[280] Lei, Z., Dai, C., & Chen, B. (2014). Gas Solubility in Ionic Liquids. *Chemical Reviews*, 114(2), 1289-1326. doi:10.1021/cr300497a

example, of our greatest concern (hydrogen fluoride), using acetate and oxalate anions significantly enhances absorption.[281] Absorption capacity varies with temperature, and the peculiar properties of RTILs allow for unusual separation methods. For example, water dissolved in many RTILs exists as solitary water clusters; heating by relatively small amounts can cause it to separate out as a separate layer.[282]

While ionic liquids are in many ways ideal for our scrubbing needs, there are a few caveats. While the anions are frequently simple to produce, cation synthesis is often highly complex and beyond the means of an early-stage habitat (with the possible exception of laboratory-scale batch production). This means both that quantities must be kept down to readily-deliverable scales, and that leakage from the system must be kept to an absolute minimum.

An additional issue is that ionic liquids are usually fairly viscous - commonly 40-800 mPa-s at room temperature[283] (ranging from the viscosity of motor oil to syrup). A high viscosity increases the difficulty of atomizing liquids; however, viscosity is itself another tunable parameter. Even small amounts of low-viscosity solvents dissolved in an ionic liquid can dramatically decrease its viscosity.[284] Water is well studied for this role; contrarily, carbon disulfide, having a viscosity lower than water[285] and containing no hydrogen, is certainly worth consideration.

A final issue of note is the long-term stability of the liquid. Most ionic liquids have no problems with the operating temperatures on hand.[286] RTILs are frequently very acid-tolerant - indeed, some are superacids,[287] and RTILs are now employed in the production of sulfuric acid.[288] Nonetheless, proper long-term compatibility with the external environment must be ensured.

- **Electrostatic precipitation**:

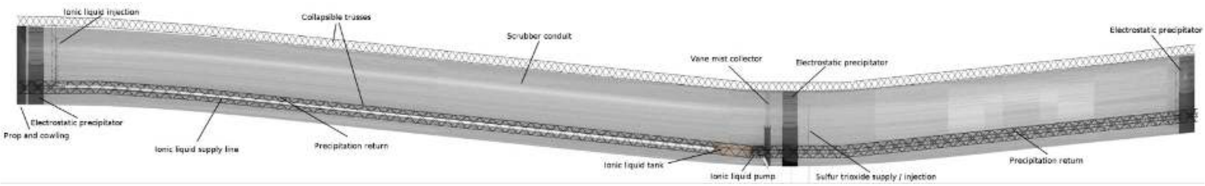
As discussed previously, electrostatic precipitation (ESP) is an excellent means for removing fine particulate from a gas stream. Hence, on its own it can collect the sulfuric acid mists already present on Venus, but its impact on the desired anhydrous gaseous components is limited. Limited, but not nonexistent - ESPs have been shown to remove gaseous metallic trace elements like mercury even at low concentrations.[289] ESPs not only

[281] Chaban, V. (2015). Hydrogen fluoride capture by imidazolium acetate ionic liquid. *Chemical Physics Letters*, 625, 110-115. doi:10.1016/j.cplett.2015.02.041
[282] Chaban, V. V., & Prezhdo, O. V. (2013). Ionic and Molecular Liquids: Working Together for Robust Engineering. *The Journal of Physical Chemistry Letters*, 4(9), 1423-1431. doi:10.1021/jz400113y
[283] Fedorov, M. V., & Kornyshev, A. A. (2014). Ionic Liquids at Electrified Interfaces. *Chemical Reviews*, 114(5), 2978-3036. doi:10.1021/cr400374x
[284] Chaban et al 2013
[285] Haynes, W. M. (2016) *CRC Handbook of Chemistry and Physics*, 97th ed. CRC Press.
[286] Maton, C., Vos, N. D., & Stevens, C. V. (2013). Ionic liquid thermal stabilities: decomposition mechanisms and analysis tools. *Chemical Society Reviews*, 42(13), 5963. doi:10.1039/c3cs60071h
[287] Thomazeau, C., Olivier-Bourbigou, H., Magna, L., Luts, S., & Gilbert, B. (2003). Determination of an Acidic Scale in Room Temperature Ionic Liquids. *Journal of the American Chemical Society, 125*(18), 5264-5265. doi:10.1021/ja0297382
[288] Rogers, R. D., Seddon, K. R., & Volkov, S. V. (2003). *Green industrial applications of ionic liquids: proceedings of the NATO Advanced Research Workshop held in Heraklion, Greece, 12-16 April 2000.* Dordrecht: Kluwer Academic.
[289] Liang, X., Looy, P., Jayaram, S., Berezin, A., Mozes, M., & Chang, J. (2002). Mercury and other trace elements removal characteristics of DC and pulse-energized electrostatic precipitator. *IEEE Transactions on Industry Applications, 38*(1), 69-76. doi:10.1109/28.980355

create a charge gradient to ionize and attract particulate, but also generate carbon monoxide and ozone, which can subsequently react with other components in the gas stream. This can further oxidize SO_2 to SO_3, which in turn can absorb moisture to form ultrafine sulfuric acid particulate.[290]

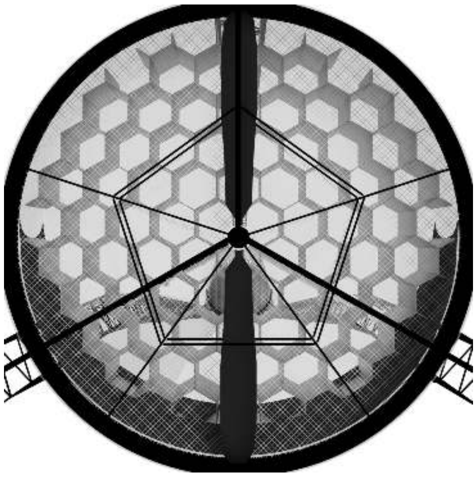
If solid particulate condensation (e.g. sulfur) turns out to be a fouling issues for electrodes, cleaning can either be mechanical (brushes, rotary electrodes, etc) or thermal (microwave heating, resistive heating wires). The latter approach would be favored.

All taken together, a variety of scrubbing designs can be acceptable, but we shall consider an example system that provides a minimal yield for a self-sustaining habitat (a 4.3m ID duct, a single 4.2m prop, and daytime airflows of 275 m^3/s at 20m/s). Sulfuric acid mist collection rates per ESP are assumed at 75%.



Collapsible truss (3x) structure picture, without radial reinforcements; highly reinforced or purely pressure-supported designs are also possible.

1) A propeller (premised on the assumption that pure electrohydrodynamic thrust proves insufficient / immature) drives the primary airflow.



2) The air immediately passes through a fine high voltage DC negative grid operating at a safe margin below breakdown voltage, ionizing the stream through coronal discharge.

3) Shortly downstream, the air passes through a HV DC positive grid (hole-type hex grid, dozens of centimeters long) and collects nearly 2 g/s H_2SO_4. Both the anode and cathode grids must be overbuilt to be robust enough for long-term operation, and allow cleaning.

4) One meter downstream, ionic liquid injection begins. We will operate on the following assumptions: contact time 2 seconds, circulating volume 1000kg, total stored mass 3000kg, density 1.25g/cc. This co-current scrubbing section is thus 40 meters long with a liquid flow rate of 500kg/s, and 3.8kg of liquid per cubic meter of air. Without being able to narrow down the viscosity of the liquid at this point, we will not focus on

[290] Mertens, J., Anderlohr, C., Rogiers, P., Brachert, L., Khakharia, P., Goetheer, E., & Schaber, K. (2014). [A wet electrostatic precipitator (WESP) as countermeasure to mist formation in amine based carbon capture](). *International Journal of Greenhouse Gas Control, 31*, 175-181. doi:10.1016/j.ijggc.2014.10.012

determining specific injection or pumping methods in order to achieve a fine mist and even mixing.

We operate on the premise of nearly-horizontal operation but a slight downward slope to assist drainage of unintentionally precipitated liquid. Should precipitation prove too excessive, though, this segment could be oriented vertically.

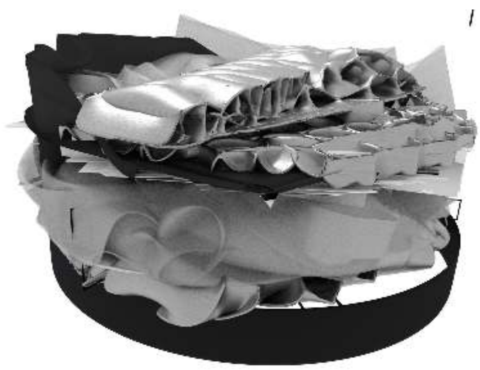
5) Bulk liquid is removed via a low-drag means, such a vane mist collector and diverted for distillation.

6) Steps #2 and #3 are repeated to scrub the fines and help overcome pressure drop. This is conducted after #5 in order to minimize the risk of decomposition of the ionic liquid by the ESP.

7) Half a meter downstream, waste sulfur is injected in the form of sulfur trioxide (around three grams per second) to attempt to nucleate any remaining moisture, whether from the original airstream or from the scrubbing stage. One second of contact time (20 meters) is provided, yielding a SO_3 concentration of 20 ppm (far higher than the minimum needed for nucleation, and potentially aided by the air ionization)[291]. This step is conducted after ionic liquid scrubbing to avoid wasting the SO_3 via absorption into the liquid droplets. This section is angled slightly upwards, to allow for gravity drainage of return liquids.

8) Steps #2 and #3 are repeated at the outlet, proving a final opportunity to catch lost scrubbing liquid, as well as any newly nucleated mists.

   Step 7 may be shortened or eliminated if the recovery rates do not justify the mass.



The folded up size is quite small so long as the precipitators and mist collectors are collapsible. The image on the right is a soft-body simulation of the collapse of the above scrubbing duct. For a sense of size, the prop cowling on the bottom is 4.3 meters in diameter, versus the 4.6m wide / 11 meter high inner dimensions of a Falcon Heavy standard fairing.

As with many systems developed for a Venus habitat, the development of scrubber systems for Venus resource harvesting has direct applicability to pollution control systems on Earth, where the goal - removing acidic particulates and gases from CO_2-rich streams - is a common task.

[291] Duplissy, J., Merikanto, J., Franchin, A., Tsagkogeorgas, G., Kangasluoma, J., Wimmer, D., . . . Kulmala, M. (2016). Effect of ions on sulfuric acid-water binary particle formation: 2. Experimental data and comparison with QC-normalized classical nucleation theory. *Journal of Geophysical Research: Atmospheres*, 121(4), 1752-1775. doi:10.1002/2015jd023539

Scrubber-free scrubbing?

While the above presents a workable scrubbing approach, the introduction of ionic liquids and heavier use of electrostatic precipitators invites consideration of some radically different approaches.

First among them is the concept of eliminating the propeller and relying entirely on electrohydrodynamic thrust with simultaneous scrubbing. This certainly could be done within a scrubber duct, but is much more effective if spread this out across the skin of the envelope on all sides. With such a vast collection area, we can now optimize our process for thrust and mass efficiency rather than precipitation efficiency; if one EHD thrust element does not catch a given amount of particulate, there will be many more to come. As for collection, condensed droplets need to be focused into channels for drainage, merging together and ultimately being collected into tubing to bring to the industrial section. The main concern, as discussed under *Habitat propulsion*, is electrode longevity; should it prove achievable, this could be an appealing option.

By contrast, the near-zero vapour pressure of ionic liquids allows for a collection method that could never be considered with volatile fluids: spreading them across the top surface of the habitat, or even spraying them into the air to be collected on the top surface. In this case, the high viscosity of ionic fluids works to their advantage, decreasing the odds of them being entrained into winds and lost (the primary limiting factor to top-spraying). For fluids flowing across the surface, a fine mesh over the surface could help prevent entrainment if necessary.

If we assume a fluid density of 1.3 g/cm^3 and an average 1mm of liquid per square meter, the force of 1.3 kg/m^2 under 8.7 m/s^2 gravity is 11.3 pascals, an amount that can easily be overcome by the several hundred pascals overpressure inside. With many thousands or even tens of thousands of square meters of surface area that could be utilized, the only practical limitation is ionic liquid availability and processing.

In this scenario, the ionic liquid must be compatible with the outer coating of the envelope; however, with the envelope already requiring a highly inert coating, this is unlikely to be prohibitive. Additionally, with typically high refractive indices, usage of ionic liquids on the top of the habitat would be expected to somewhat decrease light penetration beneath them due to specular reflection; consequently, locating it near inhabited areas could allow it to function as a source of a limited degree of overhead shade.

In either the EHD or ionic liquid cases, multi-lobed habitat designs (such as hybrid lifting bodies) can make drainage simpler, by focusing flowing fluids inwards to creases between lobes.

Collection rates

Since we now have multiple collection methods, we need to look at how our collection rates compare to our habitat's needs. We will begin with a prop-driven duct with a daytime airflow of 275 kg/s. Our scrubber model will be based on the following assumptions:

- 50°C warming required to release 60% of all absorbed compounds from the ionic liquid, with a specific heat of 1400 J/kg and a 95% efficient heat exchanger.

- 500 kg/s ionic liquid flow rate with 2 seconds exposure and evenly spaced droplets with diameters of 40 microns.

- Henry's Law (equilibrium absorption) constants taken from median figures for ionic liquids where available, figures for water used otherwise. Liquid diffusion rate figures taken from water.

- Absorption coefficients that were not available for species for ionic liquids or water are estimated based on similar species.

- Absorption rates for hydrogen chloride take into account increasing Henry's Law constants at low gas concentrations;[292] other species do not, and thus can be considered to be pessimistic.

- Based on Liang et al (2002),[293] we will assume that combined our ESPs strip 50% of mercury and extrapolate to 50% of tellurium and selenium and 25% of compounds containing lead, bismuth, indium, iodine, bromine, zinc, arsenic and iron. Sulfur particulate is assumed recovered at 80%. These figures (beyond mercury) have in no way been validated and will be denoted separately in the below graphs due to their speculative nature.

- Beyond direct scrubber capture, we will also be diverting a small fraction of the post-scrubber exhaust (for our calculations, an average of 0.1%) for direct distillation. Acid gas stripping (ethanolamine or ionic liquid) removes 99.8% of CO_2 and other bulk acid gases (4% of other species). Then 99.8% of remaining CO_2 is removed via freezing with an unintentional loss of 2% of all compounds with lower freezing/boiling points than CO_2 and 99.8% of those which would co-freeze with carbon dioxide.

- Interactions between dissolved species are not considered.

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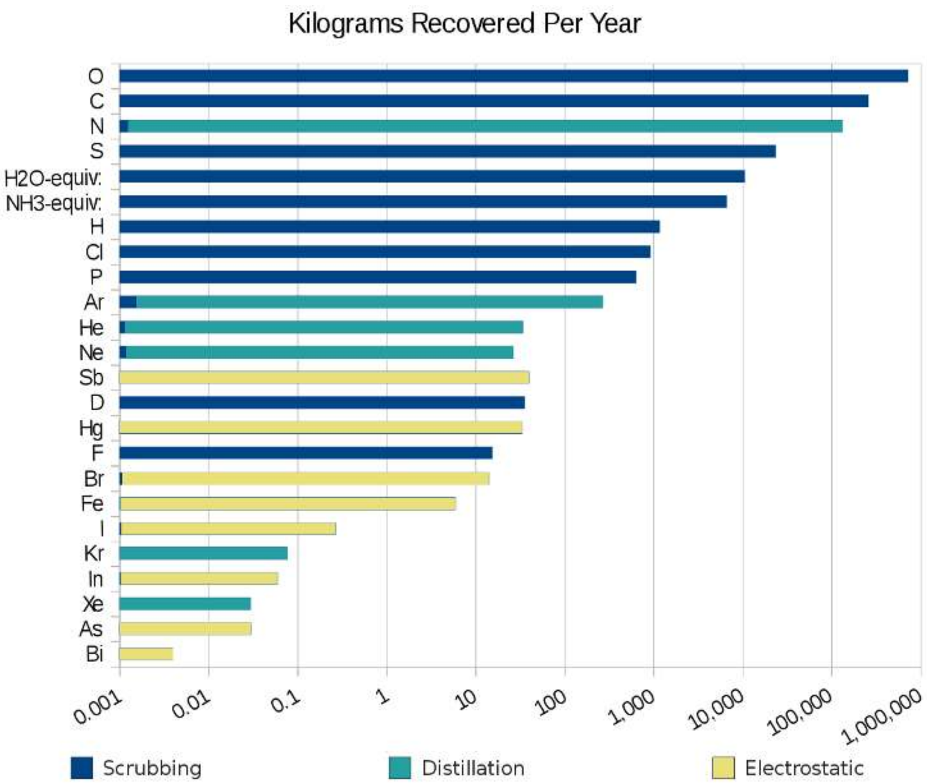
[292] He, R., Long, B., Lu, Y., Meng, H., & Li, C. (2012). Solubility of Hydrogen Chloride in Three 1-Alkyl-3-methylimidazolium Chloride Ionic Liquids in the Pressure Range (0 to 100) kPa and Temperature Range (298.15 to 363.15) K. *Journal of Chemical & Engineering Data, 57*(11), 2936-2941. doi:10.1021/je3003783

[293] Liang, X., Looy, P., Jayaram, S., Berezin, A., Mozes, M., & Chang, J. (2002). Mercury and other trace elements removal characteristics of DC and pulse-energized electrostatic precipitator. *IEEE Transactions on Industry Applications, 38*(1), 69-76. doi:10.1109/28.980355

- Nighttime propulsion power is cut to 1/9th and air density increased to 1 kg/m³ due to a lower flight altitude, yielding nighttime flight speeds 45% of those during the day and a reduction of gas flow rate to around 150kg/s. Nighttime liquid pumping is cut to 25kg/s, and distillation is postponed to daytime.

- Particulate (droplets) are assumed to be pure H_2SO_4; dissolved species in droplets (such as ferric chloride) would increase the latter's recovery rate.

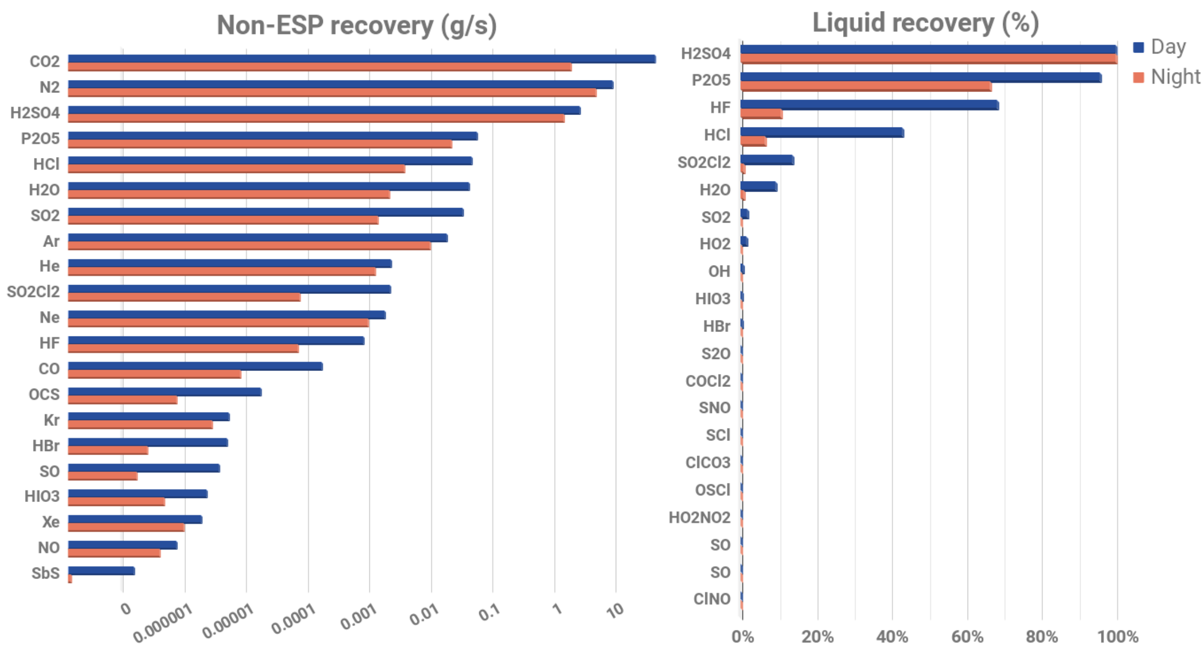


In the above graph, each element's annual recovery is plotted versus the means through which it is recovered. Recovery figures are on a logarithmic scale, while the percentage of each source (blue, teal or yellow) are on a linear scale. Hydrogen is presented in three forms: raw hydrogen quantity as well as the water and ammonia equivalences for that amount of hydrogen (e.g. if all hydrogen was converted into one of those products).

Assuming no elements lost during manufacturing, the below table shows how much of each element and long it would take to produce the propellant for a MON/CyMet-15 rocket as laid out in *Staging options*:

Element	MON (kg)	C_2N_2 85% / CH_4 15% (kg)	Total (kg)	Days
C	0	21839	21839	31
N	26332	19190	45522	115
O	57941	0	57941	29
H	0	898	898	279
Total	*84273*	*41927*	*126200*	

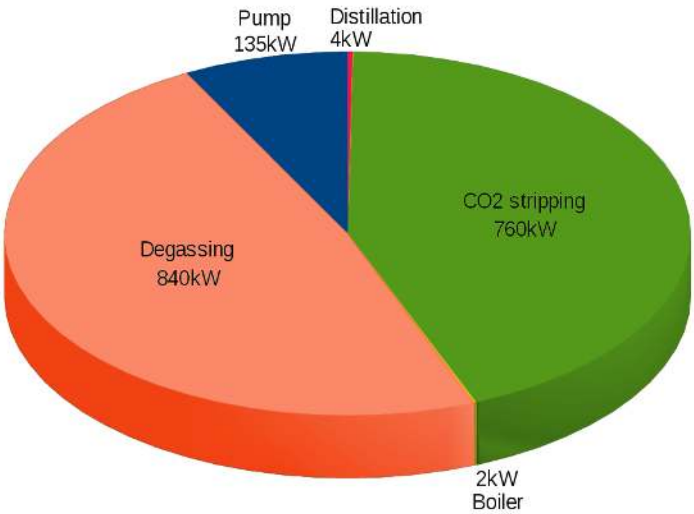
Recovery rates of compounds of relevance are:



As an example of limiting elements, if we dedicate all of the 16kg/yr of fluorine to envelope production without losses, with the assumption of a 200g/m² fabric that is comprised of 10% fluoropolymer coating that is in turn 25% fluorine, then 3200m² of fabric could be produced per year - enough to replace the entire ~54k m² external envelope in 17 years.

For energy consumption we assume a 95% heat exchanger efficiency on ionic liquid degassing; 80% on boiler heat recovery; 3 GJ/tonne on acid gas stripping of diversion gas;[294] and 0.5kWh/kg for distillation cooling (treating the whole stream processing as equivalent to generating liquid nitrogen)[295] with 80% heat recovery. For pumping, a nozzle generating a 40 micron mist at a viscosity of ~150 mPa-s is equivalent to one generating a water fog at 14 micron;[296] we will consider a nozzle array of 70x 5cm, 5-bar, 357 l/min nozzles,[297] with a 60% efficiency vortex pump, 15m/s liquid speed and 1 bar line pressure drop. The energy involved in the process breaks down as follows:

[294] Yang, Y., Zhai, R. (2010). *MEA-Based CO2 Capture Technology and its Application in Power Plants*. Paths to sustainable energy, Dr Artie Ng (Ed.), ISBN: 978-953-307-401-6, InTech
[295] Pusavec, F., Krajnik, P., & Kopac, J. (2010). Transitioning to sustainable production – Part I: application on machining technologies. *Journal of Cleaner Production,18*(2), 174-184. doi:10.1016/j.jclepro.2009.08.010
[296] *Guide to spray properties - 4. Droplet size*. BETE. Retrieved from http://www.spray-nozzle.co.uk/resources/engineering-resources/guide-to-spray-properties/4--droplet-size
[297] Dense fog misting nozzle. BETE. Retrieved from http://www.spray-nozzle.co.uk/docs/default-source/spec-sheet-pdf's/ss-dense-fog-misting-nozzle.pdf?sfvrsn=0



It can be noted that boiler and distillation energy levels are almost irrelevant; this is because, as they work on scrubber *products*, they deal with only small quantities of material.

The overall process is very sensitive to the chosen parameters. In particular:

- Equilibrium can be reached with a shorter duct, but this requires a finer spray and thus a higher pressure drop or lower viscosity fluid. On the other hand, a shorter duct allows for a reduction in pump flow velocity and/or ionic liquid mass. No attempt has been made to solve for the optimum.

- Higher liquid flow rates through the scrubber allow for higher recoveries, but are strongly correlated with power demand (heating for the separation of captured species, pumping power), as well as involving higher shipping mass (fluids, tankage, plumbing, pumping).

- Higher dissolved gas equilibrium levels via ionic liquid selection / tuning present a promising avenue for significant reductions in power consumption and improved capture rates. This remains a research topic beyond the scope of this work.

- Higher heat exchanger efficiencies correspond directly with reduced power consumption, but likewise represent increased mass.

- CO_2 stripping efficiencies (for distillation) are an active topic of research at present, and our energy cost estimate may be significantly overstated from the state of the art by the time of construction. Additionally, most industrial CO_2 stripping is based around leaving the carbon dioxide in a capturable format (such as compressed), while we simply exhaust it.

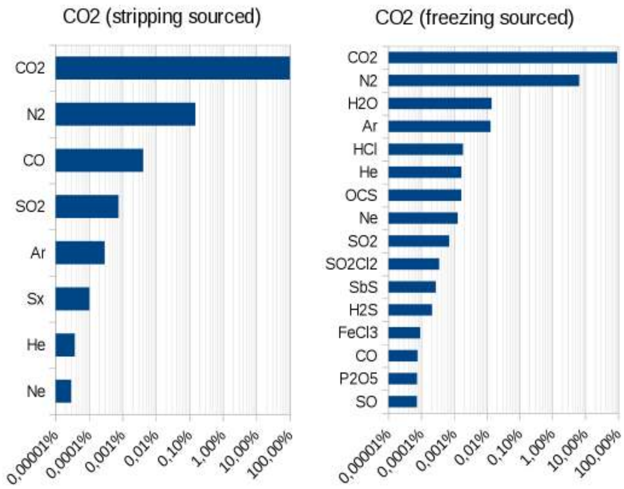
- Increased scrubber flow rates, such via from larger propellers, increase recovery of well-absorbed species but do not help with recovery of species which are already limited by absorption; the latter requires more scrubbing liquid.

Concerning specific recovery targets:

- **Oxygen**: Inherently recovered in excess regardless of the parameters chosen. Recoverable via SO_3 decomposition with a vanadium oxide catalyst in the boiler or solid oxide fuel cell fed by CO_2, but most commonly via water electrolysis.

- **Carbon**: Recovered as CO_2 by pre-freezing of distillation feedstocks in a dual-chamber process, with one chamber regenerating while the other freezes. The acid gas removal stream can also be used as a CO_2 source.

  Contaminants in the carbon dioxide with our above figures are pictured to the right.



- **Nitrogen**: recovery can only be realistically increased by increasing the diversion stream volume, and thus increasing CO_2 removal costs.

- **Hydrogen**: the fact that hydrogen is commonly found in the form of sulfuric acid makes easy to capture, both due to its high solubility and its existence as aerosols. However, it is limited by low total quantities in the atmosphere - hence increasing production implies increasing mass flow rates.

- **Sulfur**: As discussed previously, sulfur is harvested in excess relative to hydrogen, and is best disposed of as sulfur trioxide to aid in water vapour recovery. This however runs counter to the ability to use it to produce oxygen by catalytic decomposition. The best option involves having both options available as needed.

- **Chlorine**: Chlorine absorption is highly dependent on liquid recovery, both in terms of liquid equilibrium concentrations and liquid flow rates.

- **Fluorine**: Some limited additional increase in absorption can be attained through improved recovery techniques, such as better absorbing liquids and higher liquid flow rates. However this can only add so much; further improvements require higher gas flow rates as well.

- **Iron**: Data is lacking on ferric chloride absorption. Our assumption of equilibrium concentrations being similar to sulfur dioxide results in low capture rates; however, this may be pessimistic. On the other hand, in the above data we are assuming a 25% ESP collection figure; there is little confidence in this number. Lastly, we are assuming that there is little material (such as iron chloride) dissolved in H_2SO_4 particulate or in other forms of particulate. In short, total iron recovery figures could be greatly varied.

- **Minor species**: Like with iron, data on minor and theorized species - antimony, mercury, zinc, iodine, bromine, indium, tellurium, selenium, lead and bismuth is lacking. Many of them present in low quantities in our model are due to the habitat being at higher altitude than the altitude in which they would tend to precipitate out, and thus would be better harvested by lower altitude craft (not investigated here).

  How would alternative, advanced capture approaches compare?

- **High diameter prop(s)**: If we consider a large propeller (collapsible or stored in a large fairing), gas mass flow rates increase significantly while flow speeds drop. This shortens the duct, reducing the pumping velocity and thus power consumption. Well captured species like sulfuric acid are gained in much greater quantity, as are those otherwise captured by electrostatic precipitation; others are little affected.

- **EHD propulsion**: If electrohydrodynamic propulsion designed to simultaneously capture resources is utilized, hydrogen and minor species recovery would dramatically increase. However, unless an additional liquid scrubber is used, species not present as particulate or otherwise well recovered by ESPs would fall significantly.

- **Scrubber-free liquid scrubbing**: Concerning the concept of having liquid films or sprays on the top of the habitat, airflow speeds are reduced (flight speeds rather than prop wake), but a vastly greater amount of gas mass is exposed. However, this does not work around limitations imposed by equilibrium solubility levels for dissolved species in the fluid; total fluid flow rates remain key. However, well-absorbed species such as sulfuric acid (and thus hydrogen recovery) would significantly increase. Furthermore, depending on the design, a much greater fraction of the liquid could be actively absorbing at any given point in time (rather than being in pipes being circulated back to a duct entrance).

- **Lower altitude scrubbing**: As noted, some species are likely to precipitate out at significantly lower altitudes and only be present at high altitudes in vanishingly small quantities. This raises the prospect of lower altitude scrubbing. While this can be done with independent aerobots, perhaps the most promising approach is to combine scrubbing with wind power generation, with flow through the duct being driven by zonal wind differences. Power would be generated right where it is needed to power the scrubbing process. In order to avoiding the need for prohibitively long and heavy plumbing connections to the main habitat, it would need to be periodically serviced or raised for resource collection. A beneficial side effect of lower altitude scrubbing is that higher gas partial pressures yield higher equilibrium gas solubilities and thus more scrubbing per kilogram of liquid. However, all components - most notably, the liquids themselves - must be able to withstand the higher temperature environment.

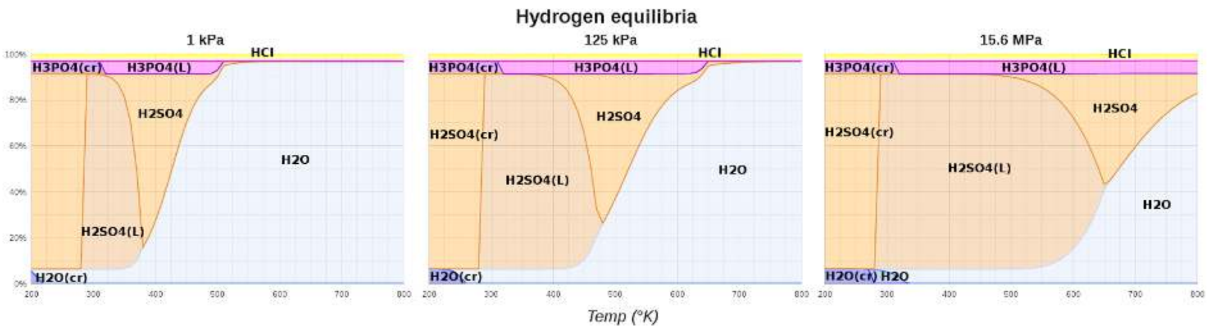
- **Precipitation / condensation**: As noted previously, if precipitation or condensation occurs on the envelope, this would yield large amounts of liquid (mainly H_2SO_4).

Boiling and distillation

As covered previously, sulfuric acid, generally thought of as a hazard to the habitation of Venus, is a resource blessing. Highly hygroscopic and easily absorbed, the heating of H_2SO_4 in a boiler first drives off the existing water (~11% of the acid's mass),[298] which can be separated by a molecular sieve or selective membrane. Further heating decomposes H_2SO_4 to SO_3 plus more H_2O (18% of the remaining mass). Still further heating, in the presence of a catalyst such as vanadium pentoxide, converts SO_3 to SO_2 and O_2, which can be likewise stripped off;[299] otherwise, it can be retained as SO_3, either for onboard regeneration of sulfuric acid for industry, or for exhaustion to aid in scrubbing. This one single, simple process can yield two critical compounds: water and oxygen.

The input fluids are, however, not purely sulfuric acid. Consequently, fractional distillation needs to be used to separate out the individual species. It is a question of importance what species will be sent from the boiler to distillation, as this determines the condensation points. To that end, we will examine chemical equilibria (as calculated by CEA2) for the mixture being fed into the boiler. This represents the case where - if every possible reaction were catalyzed - the chemical mixture would reach a state where it ceases to change. In practice, reaction rates (controllable to varying degrees by catalysts) yield results that differ from the equilibrium case.

To illustrate the typical effect of pressure on chemical equilibria, the following graph plots the allocation of hydrogen between different chemical species at different pressures:



While pressure affects the ratios between different species, the most notable effect is that low pressures narrow the temperature range for a given effect, while high pressures increase the range.

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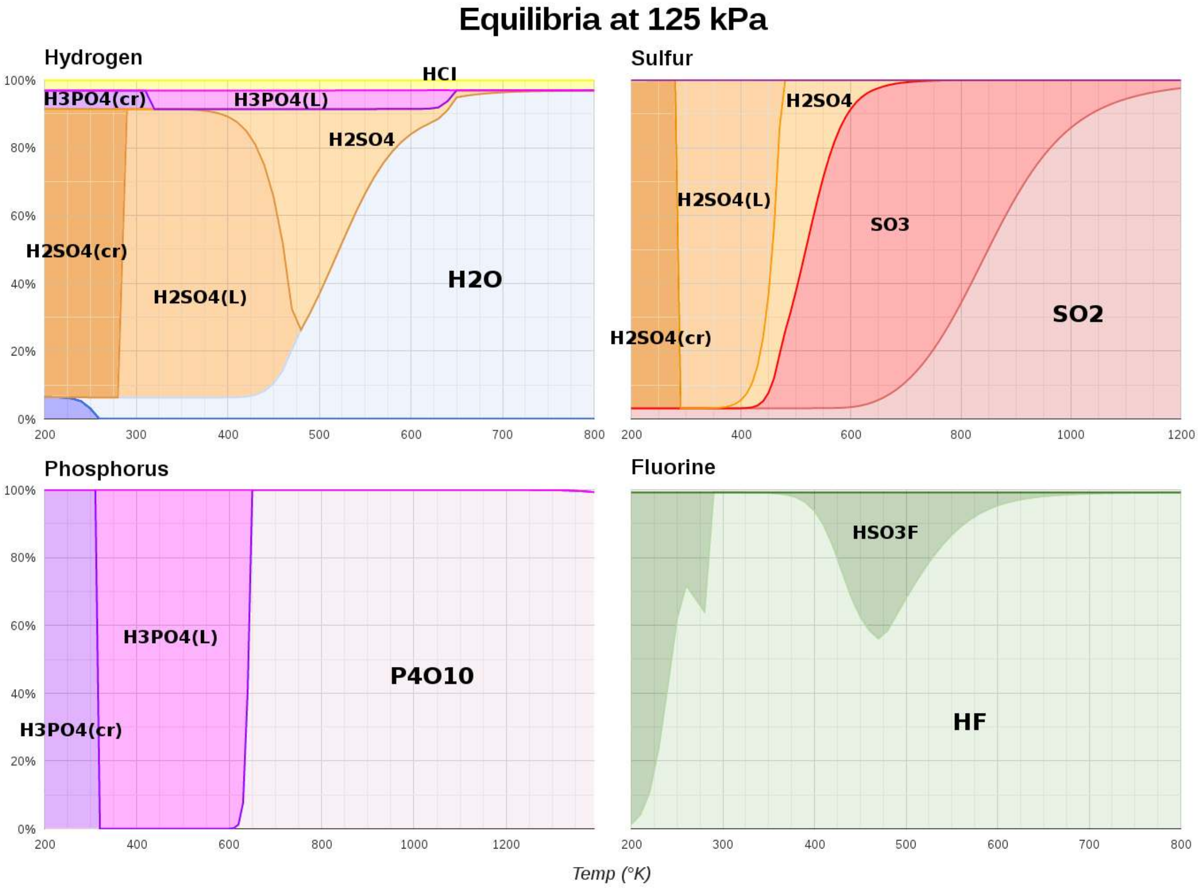
[298] Krasnopolsky, V. A. (2015). Vertical profiles of H2O, H2SO4, and sulfuric acid concentration at 45–75km on Venus. *Icarus, 252*, 327-333. doi:10.1016/j.icarus.2015.01.024
[299] Barbarossa, V., Brutti, S., Diamanti, M., Sau, S., & Demaria, G. (2006). Catalytic thermal decomposition of sulphuric acid in sulphur–iodine cycle for hydrogen production. *International Journal of Hydrogen Energy*, 31(7), 883-890. doi:10.1016/j.ijhydene.2005.08.003

Plotting ratios vs. temperature for a fixed 125 kPa pressure over species of interest, we get the following:



Concerning elements of significance:

- **Carbon**: Making up 95% of the absorbed species due to its high partial pressure (and thus equilibrium solubility), the CO_2 fraction in the boiler does not change significantly under any temperature and pressure combinations.

- **Nitrogen**: Nitrogen remains overwhelmingly as a diatomic gas under almost all conditions, excepting very high pressures where nitric oxide begins to reach relevant quantities (analogous to the Haber and Ostwald process).

- **Chlorine**: At 125 kPa, chlorine remains over 95% as hydrogen chloride, with small amounts of chlorine gas forming between 500° and 800° and tiny quantities of elemental chlorine at very high temperatures. The amount of chlorine gas increases with pressure, but even at 15 MPa does not reach 10% at its optimal temperature (~750°K)

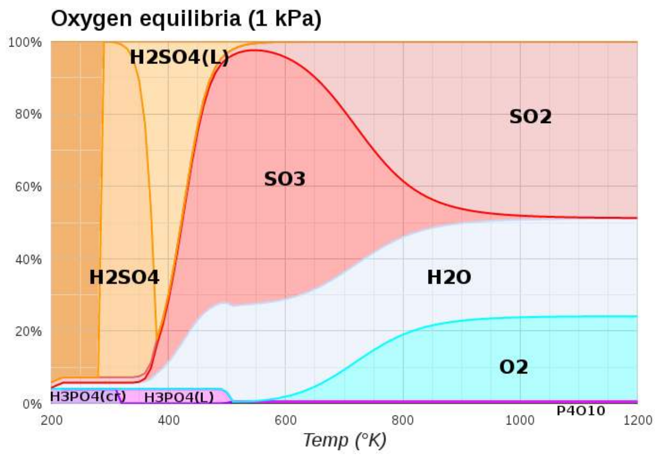
- **Hydrogen**: Hydrogen is distributed among a wide range of species, with the mixture highly sensitive to temperature. The “generally” most desirable form, water vapour, increases in fraction with temperature, leveling off at around 700°K at 125 kPa. Low pressures can bring this temperature down to as little as 500°K.

- **Phosphorus**: Phosphoric acid follows a simple curve relative to its hydration states, fully dehydrated to phosphorus pentoxide at 500-1000°K, depending on pressure (low pressures favouring dehydration). At extreme temperatures, particularly at low pressures, the phosphorus pentoxide dimer begins to break down to the monomer, and ultimately to phosphorus dioxide.

- **Fluorine**: Predominantly existing as hydrogen fluoride, in some conditions (particularly at high pressures) fluorosulfuric acid can predominate. This can be of concern during distillation; fluorosulfuric acid is a superacid, one of the most powerful simple Brønsted acids.[300] Mixed with antimony pentafluoride (possible antimony compounds not analyzed here) it forms the even more powerful magic acid, which is capable of protonating such resistant substances as xenon, methane, hydrogen and halogens.[301]

- **Sulfur**: Temperature and pressure allow for a ready means of selection between favouring sulfur dioxide vs. sulfur trioxide - the latter being useful for reconstituting sulfuric acid and as a scrubber conditioning agent, while the creation of the former releases free oxygen and can be used in the sulfur-iodine cycle to generate hydrogen gas.[302] Note that while equilibria favour sulfur dioxide at high temperatures, this requires a catalyst to proceed at a reasonable rate, generally vanadium pentoxide (reversed contact process).[303]

- **Oxygen**: Plotted to the right at 1kPa (and excluding carbon dioxide), oxygen is distributed widely between non-CO_2 species. Low pressures and high temperatures favour free oxygen.



From considering the above, we can first reach the conclusion that low pressures and moderate to high temperatures yield the best generation of our primary species of interest (oxygen and water). While low pressures generally additionally mean low throughputs, total flow rates are measured in dozens of grams per second (primarily CO_2), and thus this is of limited concern. By contrast, reduced temperatures and pressures generally reduces corrosion, which is very much of concern.

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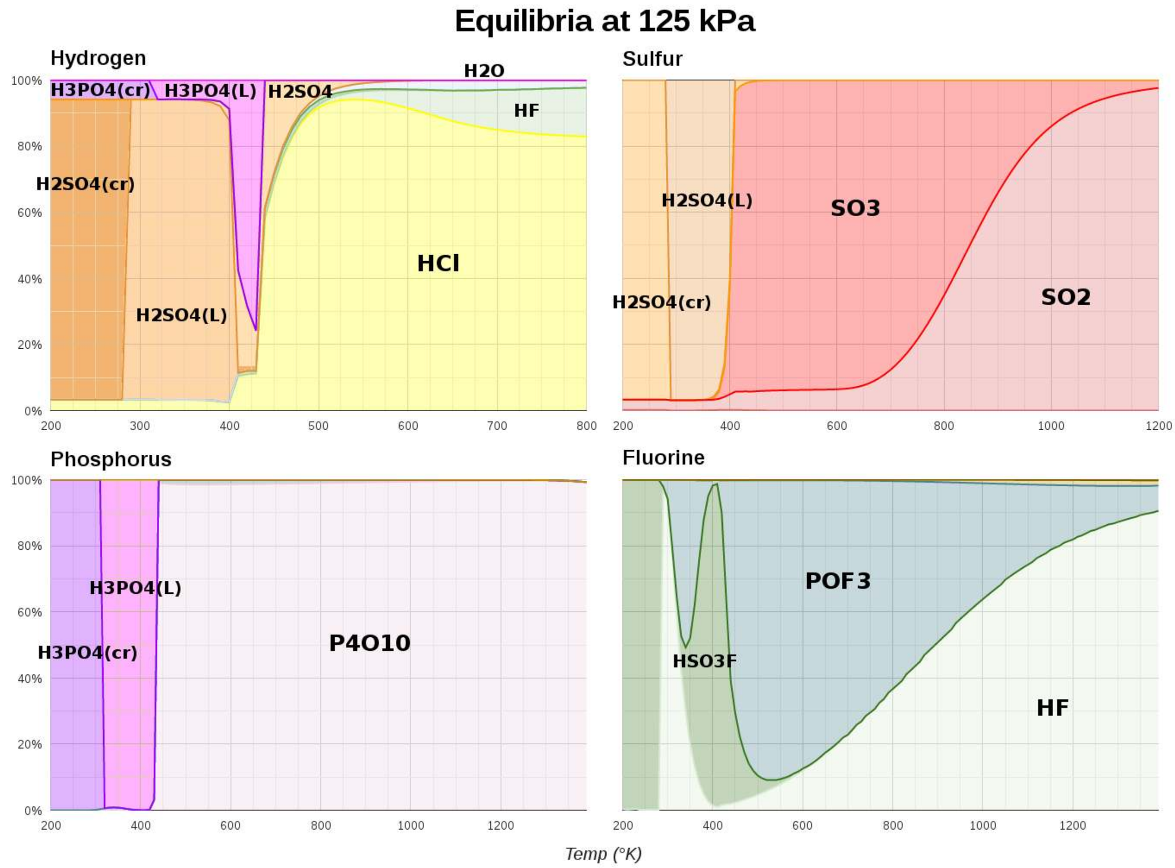
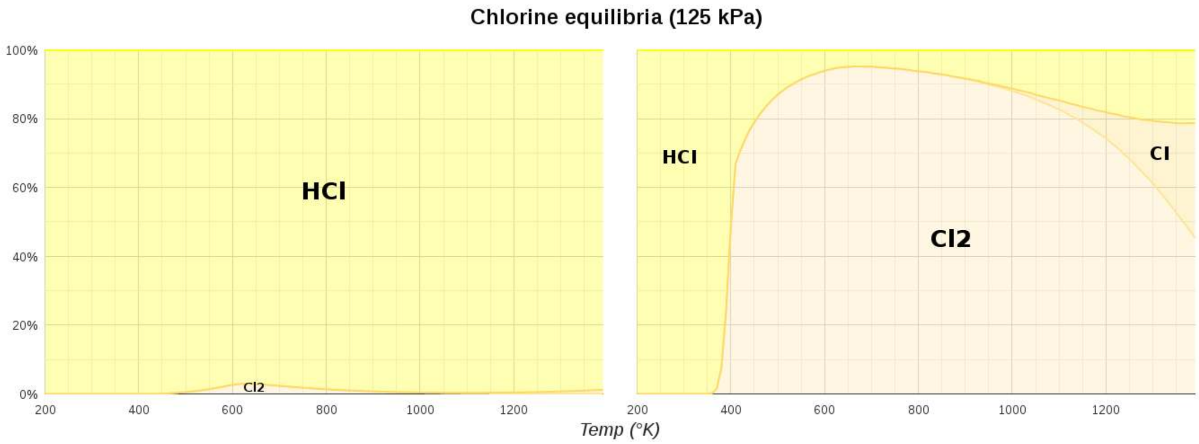
[300] Reed, C. A. (2013). Myths about the Proton. The Nature of H in Condensed Media. *Accounts of Chemical Research, 46*(11), 2567-2575. doi:10.1021/ar400064q
[301] Olah, G. A. (2005). Crossing Conventional Boundaries in Half a Century of Research. *The Journal of Organic Chemistry, 70*(7), 2413-2429. doi:10.1021/jo040285o
[302] Barbarossa, V., Brutti, S., Diamanti, M., Sau, S., & Demaria, G. (2006). Catalytic thermal decomposition of sulphuric acid in sulphur–iodine cycle for hydrogen production. *International Journal of Hydrogen Energy*, 31(7), 883-890. doi:10.1016/j.ijhydene.2005.08.003
[303] Ashar, N.G., Golwalkar, K.R. (2013) *A Practical Guide to the Manufacture of Sulfuric Acid, Oleums and Sulfonating Agents*. Springer. ISBN 978-3-319-02041-9

A perhaps more salient observation is the degree in which outputs can be varied by varying the inputs. Note how the equilibria change when we remove the water vapour down to 1ppmv (such as with a molecular sieve, a common process in the petrochemical industry):[304]



Some of the above data is misleading, such as the purple “phosphoric acid spike” in the hydrogen case; in actuality, what is happening is the total concentration of hydrogen remaining is dropping because of the water removal. However, other differences are very real. At equilibrium, gaseous sulfuric acid is almost nonexistent; phosphoric acid desiccates at a much lower temperature; and fluorine equilibria are radically changed, favouring compounds with phosphorus. Chlorine equilibria too are radically altered, favouring chlorine gas to hydrogen chloride:



Left: without water removal. Right: with water removed to 1 ppmv.

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[304] Molecular Sieve Adsorbents. Zeochem AG. Seestrasse 108 · 8707 Uetikon am See · Switzerland

The key takeaway is that equilibria are very sensitive to their mixture compositions, and alteration of their compositions can have significant effects on the equilibria as a whole. A single system can thus be used to generate a wide range of compounds, subject to a number of caveats:

- Particularly at lower temperatures, but to some extent at higher temperatures as well, compounds do not inherently reach equilibrium in reasonable timescales. Appropriate catalysts must be used.

- For rapid reactions, a desired equilibrium may be reached, but the ratios will generally shift right back as it moves out of the boiler and the equilibrium balance reverts. In such cases, diversion of desirable species must occur under the conditions which led to the desirable equilibrium. Only slower, “frozen” reactions can undergo temperature / pressure changes before separation.

- Not all materials are compatible with all chemicals or environmental conditions. For example, aqua regia can dissolve precious metals, but is readily withstood by most fluoropolymers - but the latter cannot withstand the temperature extremes or powerful organic solvents that precious metals can withstand.

- Not only are different catalysts desirable in different processes, but it is often desirable to suppress certain reactions. The composition of the chamber itself can, however, be catalytic. For example, platinum, a highly resistant compound against corrosion, is often catalytic to many hydrocarbon reactions, while iron pressure vessels help catalyze the Haber process.

- It will frequently be desirable to have multiple processes in operation at the same time, rather than operating in a purely batch process.

- Some processes can pose risks of fouling or contaminating their reaction vessels in a way that can hinder other subsequent processes.

In short, while there is a great potential for mass reduction in the reuse of given reaction vessels for generating a wide range of chemicals, this is not unlimited; a variety of vessels made from a variety of chemicals with a variety of catalysts is needed to create a reasonable local chemical industry. However, it becomes apparent that design flexibility is important - particularly as the number of chemicals needed increases (something that, as we will see shortly, will occur rapidly). The same sort of principles used in robotic chemistry laboratories applies here, with readily reconfigurable plumbing and storage.

To finish up our analysis of initial resource processing: with a high degree of desiccation and low operating pressures, operating temperatures need to only be in the ~650°K range to achieve a high degree of water recovery and boil off the phosphorus pentoxide. If oxygen recovery is not desired, then this is diverted directly to distillation; if not, the temperature is further raised to 800-1000°K. This is sufficient to boil off all expected compounds except for some metallic precipitates, such as ferrous chloride, which at 1ATM boils at 1296°K, and thus represents a precipitate that either requires a periodic removal process. As the $SO_3 \rightarrow SO_2 + ½ O_2$ reaction is slow without a catalyst, oxygen does not need to be removed at high temperatures - although options do exist for high temperature removal, such as certain oxygen-deficient perovskite oxides.[305] Boiler gas distillation is conducted along with direct atmospheric gas distillation, as discussed previously.

Listing a variety of condensation points for distillation (1 ATM for simplicity):

Specie	°K
$FeCl_2$	1296
$InCl_3$	1070
Sb_2S_3	1050
As_4O_6	738
P_4O_{10}	633*
Hg	630
H_2SO_4	610
I_2	457
HSO_3F	439

Specie	°K
H_3PO_4	431
SO_2Cl_2	343
Br_2	332
SO_3	318
HF	293
H_2O	273
SO_2	263
HI	238
POF_3	234

Specie	°K
Cl_2	239
OCS	223
SO_2F_2	218
H_2S	213
HBr	206
CO_2	192*
HCl	188
Xe	165
NO	121

Specie	°K
Kr	120
O_2	90
Ar	87
CO	82
N_2	77
Ne	22
He	4

** Denotes species which lack a liquid phase at 1 ATM, FeCl3 decomposes to $FeCl_2$ and Cl_2 at high temperatures.*

Species which cannot be collected as liquids (a problem which increases at low pressures) must be frozen out A convenient method to do this is analogous to the means by which the MOXIE experiment on Mars 2020 rover collects carbon dioxide: a parallel two-tank condenser. While one tank is freezing out gas, the other is reheating and releasing it; whenever the freezing stage is nearly full, the two tanks reverse roles. This is most important for carbon dioxide, which as noted previously makes up over 95% of captured gases.

In cases where condensation temperatures are close together, it can be difficult to isolate individual species. This is common on Earth in the production of oxygen by air liquefaction; the co-condensed argon is generally left in the oxygen, unless there is reason to remove it (wherein it is extracted in a second distillation stage, as the concentration in the primary stage rarely exceeds 10%).[306]

PCB etching with a ferric chloride solution. Photo: Adam Greig

The fate of metallic precipitates depends on the rate of collection and demand. For example, iron chlorides can be readily converted to fine iron powder,[307] which is immediately useful for metal sintering-based 3d printing. If other metallic precipitates are common as well, however, they can be separated before this stage. Iron chlorides themselves are also valuable in a number of different industrial processes, including as a catalyst.

[305] Yang, Z., Lin, Y. S., & Zeng, Y. (2002). High-Temperature Sorption Process for Air Separation and Oxygen Removal. *Industrial & Engineering Chemistry Research,41*(11), 2775-2784. doi:10.1021/ie010736k
[306] *History and technological progress: Cryogenic air separation*. Linde AG. Engineering Division, Dr.-Carl-von-Linde-Strasse 6–14, 82049 Pullach, Germany
[307] Stanley, I. L. (1930). *U.S. Patent No. US1752348 A*. Washington, DC: U.S. Patent and Trademark Office.

Basic industrial feedstocks

● Sulfuric acid and hydrogen

Sulfuric acid for industrial processes is ideally regenerated either simply by hydration of sulfur trioxide, or from sulfur dioxide in the Bunsen reaction:

$$I_2 + SO_2 + 2\,H_2O \rightarrow 2\,HI + H_2SO_4$$

The hydrogen iodide can be decomposed back to iodine either thermally (673-973°K) or across a specialized ceramic membrane - in each case yielding hydrogen as a useful byproduct:[308]

$$2\,HI \rightarrow H_2 + I_2$$

Beyond the sulfur-iodine process, hydrogen is readily generated via electrolysis, including of water or hydrogen chloride. This represents the storage side of a fuel cell power storage system aboard the habitat. The VIP-INSPR probe proposal calls for doing just this - scrubbing sulfuric acid from Venus's atmosphere, thermal / catalytic decomposition to steam and oxygen, and then electrolysis of the water to generate hydrogen and oxygen - both of which it uses to keep itself aloft.[309]

● Halides, hydrogen halides, and hydrohalic acids

Part of the chlorine output can be converted to hydrochloric acid by steam, yielding another of the major industrial acids. Likewise, hydrofluoric acid can be generated from hydrogen fluoride in the same manner. However, both of their anhydrous forms are needed as well. Indeed, often the reverse reaction is more desirable, converting a hydrogen halide to its halide, which can be done by the Deacon process:

$$4\,HCl + O_2 \rightarrow 2\,Cl_2 + 2\,H_2O$$

This is conducted at 430°C with high stability catalyst like La_2O_3.[310] However, this process is unnecessary so long as hydrogen chloride fuel cells are used, which by the very nature of their operation reversibly convert hydrogen chloride to hydrogen and chlorine.

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[308] Barbarossa, V., Brutti, S., Diamanti, M., Sau, S., & Demaria, G. (2006). Catalytic thermal decomposition of sulphuric acid in sulphur–iodine cycle for hydrogen production. *International Journal of Hydrogen Energy*, 31(7), 883-890. doi:10.1016/j.ijhydene.2005.08.003

[309] Bugga, R. V. (2016) *Venus Interior Probe Using In-situ Power and Propulsion (VIP-INSPR)*. Jet Propulsion Lab., California Inst. of Tech., Pasadena, CA.

[310] Over, H., & Schomäcker, R. (2013). What Makes a Good Catalyst for the Deacon Process? *ACS Catalysis, 3*(5), 1034-1046. doi:10.1021/cs300735e

- ## Ammonia

Hydrogen and nitrogen are used in the Haber process, conducted at 15-25 MPa / 800K over a KOH-doped iron catalyst, to yield ammonia.[311]

$$N_2 + 3\ H_2 \rightarrow NH_3$$

The process is very sensitive to oxygen and carbon-based impurities, requiring very high purity reactants. This is normally a serious challenge on Earth, where hydrogen is predominantly sourced from steam reforming of natural gas, but electrolytic hydrogen is high purity. So long as nitrogen distillation does not lead to significant oxygen contamination, catalyst poisoning should not pose a serious threat. Indeed, a cryogenic purification stage is sometimes employed in Haber feedstock pretreatment on Earth.

The very high pressures involved in the Haber process traditionally have posed compressor challenges. Again, the local feedstocks prove to our advantage; nitrogen injected directly as a liquid yields high pressures as it warms. Additionally, as discussed in the context of fuel cells, metal hydride systems can compress hydrogen to very high pressures, with the only moving parts required being check valves.

Ammonia is recovered by cooling without pressure drop, to allow unused gas to be recirculated back into the reactor without recompression. Hydrogen and nitrogen degas from the ammonia as its pressure is subsequently dropped, and need to be recovered.

- ## Oxides of nitrogen and nitric acid

In addition to being important on its own, ammonia is fed with oxygen into the two-stage Ostwald process. In the first stage, nitric oxide is produced by catalytic reaction at 230-1100 kPa and ~900°C:[312]

$$4\ NH_3 + 5\ O_2 \rightarrow 4\ NO + 6\ H_2O$$

Nitrogen dioxide at different temperatures. Photo: Efram Goldberg

Catalyst loss is a significant problem; high-rhodium platinum catalysts have the longest lifespans. Platinum recovery systems are frequently employed downstream. Ammonia levels are usually kept under 11% to avoid explosion risks; 93-98% yields are typical. Water is removed as steam before the second stage, where the nitric oxide is reacted with more oxygen to yield nitrogen dioxide:

[311] Appl, M. (2006). Ammonia. *Ullmann's Encyclopedia of Industrial Chemistry*. doi:10.1002/14356007.a02_143.pub2
[312] Thiemann, M., Scheibler, E., & Wiegand, K. W. (2000). Nitric Acid, Nitrous Acid, and Nitrogen Oxides. *Ullmann's Encyclopedia of Industrial Chemistry*. doi:10.1002/14356007.a17_293

$$2\ NO + O_2 \rightarrow 2\ NO_2$$

Nitrogen dioxide is then reacted with steam to produce nitric acid.

$$NO_2 + H_2O \rightarrow H_2NO_3$$

Nitrogen tetroxide, the chief component of the rocket propellant oxidizer, MON, is a dimer of NO_2 and is produced by chilling it to room temperature at 6 to 10 atmospheres pressure.[313] [314]

Nitrous oxide is produced in an extra step; ammonia and nitric acid are combined to produce ammonium nitrate, which is decomposed at 100-160°C and the gas scrubbed with aqueous ammonium nitrate. An alternative synthesis route works on the same basis as the Ostwald process (ammonia oxidation), except using pelleted manganese and bismuth oxides as a catalyst.[315]

- ## Carbon monoxide, syngas and oxygen

One of the primary means of generating hydrocarbons is via syngas, a mixture of carbon monoxide and hydrogen widely used in gas to liquids (GTL) processes. The required carbon monoxide can be generated (among other means) by a solid oxide fuel cell - an approach to be demonstrated via the MOXIE experiment on the Mars 2020 rover.[316] In this process, carbon dioxide is decomposed with electricity to yield carbon monoxide and oxygen:

$$2\ CO_2 \rightarrow 2\ CO + O_2$$

Varying mixtures of carbon monoxide and hydrogen, sometimes along with fractions of carbon dioxide, methane or water, have varying names such as town gas, wood gas, and coal gas. This reflects the fact that such gas mixtures are readily generated from almost any organic matter (including waste products) by partial oxidation.[317] Syngas can also be produced from light hydrocarbons (such as methane) by steam reforming:

$$CH_4 + H_2O \rightarrow CO + 3\ H_2$$

Steam reforming is highly endothermic and is generally carried out at 1000-1100°C and 1.5-4 MPa in the presence of a catalyst (nickel coated with potassium oxide).[318]

[313] Wright, A. C. (1976) *Nitric Acid / Nitrogen Tetroxide Oxidizers*. USAF Propellant Handbooks, Volume II. Martin Marietta.
[314] Schmidt, A., Weinrotter, F., Muller, W., & Bohler, W. (1971). *U.S. Patent No. 3607028*. Washington, DC: U.S. Patent and Trademark Office.
[315] Suwa T., Matsushima A., Suziki Y., Namina Y. (1961). Synthesis of Nitrous Oxide by Oxidation of Ammonia. *Journal of the Chemical Society of Japan*, Showa Denka Ltd. 64: 1879–1888.
[316] Meyen, F. E., Hecht, M. H., & Hoffman, J. A. (2016). Thermodynamic model of Mars Oxygen ISRU Experiment (MOXIE). *Acta Astronautica, 129*, 82-87. doi:10.1016/j.actaastro.2016.06.005
[317] Reimert, R., Marschner, F., Renner, H., Boll, W., Supp, E., Brejc, M., . . . Schaub, G. (2011). Gas Production, 2. Processes. *Ullmann's Encyclopedia of Industrial Chemistry*. doi:10.1002/14356007.o12_o01
[318] Bierhals, J. (2001). Carbon Monoxide. *Ullmann's Encyclopedia of Industrial Chemistry*. doi:10.1002/14356007.a05_203

- ## Methane

Apart from syngas, the other base pathway to higher hydrocarbons is the Sabatier reaction, which primarily proceeds as:

$$CO_2 + 4\,H_2 \rightarrow CH_4 + 2\,H_2O$$

The Sabatier process has been extensively studied for spaceflight applications, both for life support[319] and ISRU;[320] Microlith® reactors are popular investigation targets for this role due to their size and efficiency.[321] Hydrogen and carbon dioxide are reacted to produce water and a diverse mix of hydrocarbons, but overwhelmingly dominated by methane. If desired, dry reforming can subsequently generate syngas via the following reaction (ideally over a ruthenium catalyst to minimize coking):[322]

$$CH_4 + CO_2 \rightarrow 2\,H_2 + 2\,CO$$

The heat requirements for the above reaction can be partially provided for by partial oxidation of methane to yield more syngas ("trireforming"):

$$CH_4 + \tfrac{1}{2}\,O_2 \rightarrow 2\,H_2 + CO$$

- ## Ethylene

Ethylene is a critical feedstock to a broad range of industrial processes. Partial oxidation of methane represents a high-TRL pathway to ethylene for off-world needs. As an example, a demonstration system built for in-situ production of ultra-high molecular weight polyethylene (UHMWPE) for Mars employs a cascade of microreactors for the catalytic oxidation of methane to ethylene at 800-900°C:[323]

$$2\,CH_4 + O_2 \rightarrow H_2C{=}CH_2 + H_2O$$

Syngas-based production of higher hydrocarbons also tends to produce a useful ethylene fraction. Methanol, higher hydrocarbons, and a variety of other feedstocks can also be utilized in ethylene production, but with limited utility offworld.[324]

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[319] Junaedi, C., Hawley, K., Walsh, D., Roychoudhury, S. (2012) Compact and Lightweight Sabatier Reactor for Carbon Dioxide Reduction. American Institute of Aeronautics and Astronautics.
[320] Kleinhenz, J. E., & Paz, A. (2017). An ISRU propellant production system for a fully fueled Mars Ascent Vehicle. *10th Symposium on Space Resource Utilization*. doi:10.2514/6.2017-0423
[321] Jahns, G. (2015) Novel Catalytic Reactor for CO2 Reduction via Sabatier Process Project. Space Technology Mission Directorate. NASA.
[322] Havran, V., Duduković, M. P., & Lo, C. S. (2011). Conversion of Methane and Carbon Dioxide to Higher Value Products. *Industrial & Engineering Chemistry Research, 50*(12), 7089-7100. doi:10.1021/ie2000192
[323] Sen, S., Carranza, S., & Pillay, S. (2010). Multifunctional Martian habitat composite material synthesized from in situ resources. *Advances in Space Research, 46*(5), 582-592. doi:10.1016/j.asr.2010.04.009
[324] Zimmermann, H., & Walzl, R. (2009). Ethylene. *Ullmann's Encyclopedia of Industrial Chemistry*. doi:10.1002/14356007.a10_045.pub3

- Hydrogen cyanide

While a wide range of reactions create hydrogen cyanide (as well as cyanogen itself in small quantities), among the most important is the Andrussow process[325] (methane / ammonia oxidation over a platinum catalyst at ~1200°C), which requires no extra energy input:

$$CH_4 + 2\ NH_3 + 3\ O_2 \rightarrow 2\ HCN + 6\ H_2O$$

Another option is the Degussa / BMA process,[326] which requires energy but yields hydrogen. It is likewise conducted over a platinum catalyst, at ~1400°C:

$$CH_4 + 2\ NH_3 \rightarrow HCN + 3\ H_2$$

- Caustics

A number of common processes require a strong caustic agent, generally sodium or potassium hydroxide, which get reduced to their respective chlorides. These are recycled back to hydroxides by the electrolytic chloralkali process.[327] For sodium chloride, dissociated in solution to Na^+ and Cl^-:

$$2\ Cl^- \rightarrow Cl_2 + 2\ e$$
$$2\ H_2O + 2\ e \rightarrow H_2 + 2\ OH^-$$

Sodium hydroxide (caustic soda)
Photo: Martin Walker

Thus, as a net reaction:

$$2\ NaCl^- + 2\ H_2O \rightarrow Cl_2 + H_2 + 2\ NaOH$$

Secondary feedstocks

A number of feedstocks and categories of feedstocks are only required for specific production targets which may or may not be important in a habitat's early stages.

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[325] Andrussow Process. (2010). *Comprehensive Organic Name Reactions and Reagents*. doi:10.1002/9780470638859.conrr018
[326] Gail, E., Gos, S., Kulzer, R., Lorösch, J., Rubo, A., Sauer, M., . . . Hasenpusch, W. (2011). Cyano Compounds, Inorganic. *Ullmann's Encyclopedia of Industrial Chemistry*. doi:10.1002/14356007.a08_159.pub3
[327] Schmittinger, P., Florkiewicz, T., Curlin, L. C., Lüke, B., Scannell, R., Navin, T., . . . Bartsch, R. (2011). Chlorine. *Ullmann's Encyclopedia of Industrial Chemistry*. doi:10.1002/14356007.a06_399.pub3

- ## Cyanogen

Needed for: cyanogen-based propellants

Cyanogen can be produced by a number of means,[328] including:

1) Hydrogen cyanide oxidation over a silver catalyst at ~550°C (22.8% yield):

$$4\ HCN + O_2 \rightarrow 2\ (CN)_2 + 2\ H_2O$$

2) Hydrogen cyanide chlorination over activated carbon at 30-200°C and subsequent in-situ conversion at 400-700°C (reliable process, produces high purity stream after water scrubbing):

$$HCN + Cl_2 \rightarrow CNCl + HCl$$
$$CNCl + HCN \rightarrow (CN)_2 + HCl$$

3) Cyanogen chloride generated as per above, but reduced with hydrogen at 850°C in a quartz tube (95% yield):

$$2\ CNCl + H_2 \rightarrow (CN)_2 + 2\ HCl$$

- ## Higher alkanes

Needed for: PAN/carbon fibre (ammoxidation feedstocks), PET (aromatics feedstocks)

Higher alkanes are produced from syngas by Fischer-Tropsch synthesis, akin to the gas-to-liquids (GTL) processes used to produce synfuels on Earth; the general reaction (~2.5 MPa) is:

$$X\ CO + Y\ H_2 \rightarrow C_X H_{Y/2} + X/2\ O_2$$

Higher temperatures (330-350°) favour short-chain alkanes (gasoline, light olefins) while low temperatures (220-250°C) favour waxes and fuel oils. High temperature production is generally performed in a solid-gas fluidization reactor, while low temperature is performed in a slurry. Catalysts differ with the reaction type, but are most commonly iron promoted with potassium and copper. There is often a significant and useful olefin byproduct, primarily ethylene and propylene.[329] Unwanted fractions are partially oxidized back to syngas.

- ## Methanol

Needed for: PET, one route to acetic acid, industrial solvent.

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[328] Brotherton, T. K., & Lynn, J. W. (1959). The Synthesis And Chemistry Of Cyanogen. *Chemical Reviews, 59*(5), 841-883. doi:10.1021/cr50029a003

[329] Kaneko, T., Derbyshire, F., Makino, E., Gray, D., Tamura, M., & Li, K. (2012). Coal Liquefaction. *Ullmann's Encyclopedia of Industrial Chemistry*. doi:10.1002/14356007.a07_197.pub2

Methanol is produced from carbon dioxide-enriched syngas with high (>99.8%) selectivity at 5-10 MPa / 250°C over copper and zinc oxides on alumina, by the following reactions:[330]

$$CO + 2\,H_2 \rightarrow CH_3OH$$
$$CO_2 + 3\,H_2 \rightarrow CH_3OH + H_2O$$

- ## Acetylene

Needed for: PVF

In addition to occurring as a side product in ethylene production, acetylene is produced from methane by the following reaction:[331]

$$2\,CH_4 \rightarrow HC{\equiv}CH + 3\,H_2$$

The reaction consumes a large amount of energy, and is consequently frequently driven by partial combustion of carbon-bearing material. It also requires a rapid quench from decomposition temperatures (>1230°C) to minimize full decomposition of the methane to carbon and hydrogen. The quench is usually conducted in water for simplicity, but can also be conducted in light hydrocarbons to produce more acetylene, as well as ethylene and other hydrocarbons.

- ## Ethylene oxide

Needed for: PET (ethylene glycol feedstock)

Ethylene is partially oxidized to ethylene oxide over a catalyst of silver on aluminum oxide:

$$2\,H_2C{=}CH_2 + O_2 \rightarrow 2\,C_2H_4O$$

The ethylene oxide is washed in water, then byproduct carbon dioxide is stripped from the stream by reversible absorption in potassium carbonate. The process catalyst generally has a lifespan of 2-5 continuous working years. The ethylene oxide is both highly toxic and reactive, and must be stored carefully to prevent fire or explosion.[332]

- ## Trichloromethane

Needed for: PTFE/FEP

First, methane is chlorinated to a mixture of chlorocarbons at 300-350°C:

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[330] Ott, J., Gronemann, V., Pontzen, F., Fiedler, E., Grossmann, G., Kersebohm, D. B., . . . Witte, C. (2012). Methanol. *Ullmann's Encyclopedia of Industrial Chemistry*. doi:10.1002/14356007.a16_465.pub3
[331] Pässler, P., Hefner, W., Buckl, K., Meinass, H., Meiswinkel, A., Wernicke, H., . . . Mayer, D. (2008). Acetylene. *Ullmann's Encyclopedia of Industrial Chemistry*. doi:10.1002/14356007.a01_097.pub3
[332] Rebsdat, S., & Mayer, D. (2001). Ethylene Oxide. *Ullmann's Encyclopedia of Industrial Chemistry*. doi:10.1002/14356007.a10_117

$$CH_4 + 3\ Cl_2 \rightarrow CHCl_3 + 3\ HCl$$

The reaction is highly exothermic and the mixture ratios and temperature must be controlled to prevent explosion. A number of chloromethane compounds are produced; for trichloromethane, an optimum yield of 40% occurs at a mixture of 2:1 to 3:1 Cl_2 : CH_4. Most of the unwanted partially chlorinated compounds can be recycled with little wastage.[333]

- ## Chloroethane feedstocks

Needed for: PVC (1,2 dichloroethane), PVDC (1,1,2 trichloroethane)

Chloroethane compounds are produced by either chlorination (Cl_2) or oxychlorination (HCl) of ethylene. Processes involving ethane as a feedstock are still in the research stage. For chlorination of ethylene to 1,2 dichloroethane:

$$H_2C{=}CH_2 + Cl_2 \rightarrow H_2ClC\text{-}CH_2Cl$$

The first method is conducted liquid phase using a ferric (iron(III)) chloride catalyst, at 0.1-0.5% by weight. If minimization of side products like 1,1,2 trichloroethane is desired, oxygen is added. Low temperature (20-70°C) processes are also more selective than high temperature (85-200°C) processes, but less energy efficient. Gas phase, and even non-catalytic reactions are possible, but not widely used; however, they bear consideration in ISRU contexts, where low throughputs / efficiencies are acceptable but catalyst consumption comes at a significant cost.

For oxychlorination of ethylene to 1,2 dichloroethane:

$$CH_2{=}CH_2 + 2\ HCl + ½\ O_2 \rightarrow H_2ClC\text{-}CH_2Cl + H_2O$$

This is conducted gas phase and is similar to the Deacon process for creating chlorine gas from hydrogen chloride. Copper chloride is a common catalyst (fixed or fluidized bed), and the reaction is conducted at over 200°C. In addition to side products like 1,1,2 trichloroethane, the oxygen allows for production of side products like ethylene oxide, as well as consuming a small fraction of the ethylene to carbon oxides and formic acid.

For PVDC, 1,1,2 trichloroethane becomes the target rather than a side product. In addition to encouraging its production in the above reactions, 1,2 dichloroethane is selectively chlorinated to 1,1,2 trichloroethane:

$$H_2ClC\text{-}CH_2Cl + Cl_2 \rightarrow HCl_2C\text{-}CH_2Cl + HCl$$

[333] Rossberg, M., Lendle, W., Pfleiderer, G., Tögel, A., Dreher, E., Langer, E., . . . Mann, T. (2012). Chlorinated Hydrocarbons. *Ullmann's Encyclopedia of Industrial Chemistry*. doi:10.1002/14356007.a06_233.pub2

The reaction is carried out liquid phase at 100-140°C with the addition of ethylene as an initiator. The yield per pass must be kept low (10-20%) to prevent overchlorination. Gas phase processes exist but are not as developed.[334]

- Tetrachloroethylene

Needed for: PCTFE/ECTFE

Three primary routes are used for tetrachloroethylene production - chlorination of acetylene, oxychlorination of ethylene or 1,2-dichloroethane, and “chlorinolysis” of C_1-C_3 hydrocarbons. The latter technique - the most common on Earth - is also the most interesting for Venus. In it, simple short-chain hydrocarbons are simultaneously pyrolyzed and chlorinated; it can also be used for recovery of partially chlorinated hydrocarbon waste products. The two primary outputs are tetrachloroethylene, tetrachloroethane and tetrachloromethane, which reach the following equilibria:

$$2\ CCl_4 \leftrightarrow Cl_2C{=}CCl_2 + 2\ Cl_2$$
$$Cl_3C\text{-}CCl_3 \leftrightarrow Cl_2C{=}CCl_2 + Cl_2$$

Tetrachloroethylene is favoured by higher temperatures and reduced pressures / chlorine contents. A typical product mix is 5:1 tetrachloroethylene : tetrachloromethane along with 10% of the carbon forming other chlorinated compounds (which must be recycled). The process is carried out at 500-800°C and a few bar pressure. Output gases must be rapidly quenched, generally by heat exchangers. Chlorine is removed by washing or absorption / desorption and the gas mixture distilled to recover the tetrachloroethylene.[335]

Tertiary feedstocks

The below feedstocks require at least one secondary feedstock in bulk to produce.

Benzene melting at 5.5°C.
Photo: Endimion17

- Aromatic hydrocarbons

Needed for: PET (p-xylene), solvents, numerous laboratory uses.

The most reasonable process for local production of base aromatics is the Cyclar process, involving the cyclization of propane and butane over zeolite catalysts. With propane, the yield is 17.3% wt. C_8 aromatics, while with butane the yield is 19.8%; the xylene yield thereof is around 15%.

[334] Dreher, E., Torkelson, T. R., & Beutel, K. K. (2011). Chloroethanes and Chloroethylenes. *Ullmann's Encyclopedia of Industrial Chemistry*. doi:10.1002/14356007.o06_o01
[335] Rossberg, M., Lendle, W., Pfleiderer, G., Tögel, A., Dreher, E., Langer, E., . . . Mann, T. (2012). Chlorinated Hydrocarbons. *Ullmann's Encyclopedia of Industrial Chemistry*. doi:10.1002/14356007.a06_233.pub2

The four xylene homologues, o-xylene, m-xylene, p-xylene, and ethylbenzene, are produced simultaneously at ratios depending on process conditions. Distillation is difficult due to the similar boiling points; for p-xylene recovery, fractional crystallization between -60 and -68°C is most common. The alternative Parex process uses selective absorption of p-xylene by a molecular sieve for recovery. The raffinate can be restored to its equilibrium mixture of homologues by reaction over an acidic metal zeolite catalyst (the Isomar process). A wide variety of other processes exist for conversion between different fractions that are beyond the scope of this section.[336]

- ## Naphthalene

Needed for: Vectran; production yields additional olefins

On Earth, simple hydrocarbons with high levels of cyclization and double/triple bonds are generally recovered as fractions of coal tar - a resource unavailable offworld. However, low pressure pyrolysis of higher alkanes, often conducted on Earth to produce olefins from petroleum, yields a 10-16% naphthalene fraction. Fractions containing alkylnaphthalenes can be processed to undergo hydrodealkylation in a hydrogen environment at 700°C without a catalyst or 550-650°C with a chromium oxide/aluminum oxide or cobalt oxide/molybdenum oxide catalyst.[337]

- ## Acetic acid

Needed for: PVOH / EVOH, solvent for terephthalic acid (PET)

While best known for being produced by anaerobic fermentation, industrial quantities are mainly produced by methanol carbonylation or oxidation of butane, naphtha or acetylaldehyde. Newer processes involve oxidation of ethane or ethylene.[338]

Methanol carbonylation proceeds as:

$$CH_3OH + CO \rightarrow CH_3COOH$$

The Monsanto process (rhodium catalyst) and newer Cativa process (iridium catalyst) are typically done at ~3 MPa / 180°C, but proceed even at atmospheric pressure, with selectivities of 99% and 90% for methanol and carbon monoxide, respectively. The Cativa process is more desirable, as the iridium catalyst is more stable and no iodine initiator is required. Byproducts include carbon dioxide, methane, hydrogen, and propionic acid.

Processes involving oxidation of hydrocarbons have low selectivity but involve several potentially useful intermediary products, including ethanol, acetaldehyde, organic peroxides and ketones. Some processes are noncatalytic. Processes from ethylene and

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[336] Fabri, J., Graeser, U., & Simo, T. A. (2000). Xylenes. *Ullmann's Encyclopedia of Industrial Chemistry*. doi:10.1002/14356007.a28_433
[337] Collin, G., Höke, H., & Greim, H. (2003). Naphthalene and Hydronaphthalenes. *Ullmann's Encyclopedia of Industrial Chemistry*. doi:10.1002/14356007.a17_001.pub2
[338] Berre, C. L., Serp, P., Kalck, P., & Torrence, G. P. (2014). Acetic Acid. *Ullmann's Encyclopedia of Industrial Chemistry,* 1-34. doi:10.1002/14356007.a01_045.pub3

ethane are more selective (up to 90% for ethane). More passes are required with ethane conversion versus methanol, however, due to the need to keep mixtures with oxygen at below explosive limits.

- ## Ethylene glycol

Needed for: PET

Ethylene oxide is reacted with water to generate ethylene glycol:

$$C_2H_4O + H_2O \rightarrow (CH_2OH)_2$$

This reaction occurs without a catalyst, but only slowly, with a half-life of around 20d at 20°C at neutral pH. The reaction proceeds significantly faster at higher temperatures and either very low or high pH. Alternatively, a variety of catalysts enable the formation of ethylene carbonate with carbon dioxide, which undergoes hydrolysis to nearly pure ethylene glycol without any polymerization byproducts:

$$O{=}C{=}O + C_2H_4O \rightarrow C_2H_4O_2C{=}O$$
$$C_2H_4O_2C{=}O + H_2O \rightarrow (CH_2OH)_2 + O{=}C{=}O$$

Other processes to produce ethylene glycol without requiring ethylene oxide, such as from carbon monoxide or ethylene, are being investigated.[339]

- ## Ammoxidation-based feedstocks

Needed for: PAN/carbon fibre, PVDC comonomers

Nitrogen-bearing organics (such as for carbon fibre production) traditionally begin with the SOHIO process, which generates acrylonitrile, acetonitrile, acrolein and hydrogen cyanide. It involves reacting propene with ammonia and oxygen at 30-200 kPa and 400-500°C (over any of a variety of catalysts), with the primary target generally being acrylonitrile:[340]

$$2\ H_2C{=}CH\text{-}CH_3 + 2\ NH_3 + 3\ O_2 \rightarrow 2\ H_2C{=}CH\text{-}C{\equiv}N + 6\ H_2O$$

Selectivity is high (80-90%). Distillation is performed with aqueous phase products. Ammonia must be scrubbed with sulfuric acid, creating ammonium sulfate in excess of local needs.

More useful on Venus are newer processes which begin with more easily acquired propane (see *Higher hydrocarbons*) instead of propene, operating at higher temperatures (750-1000°).

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[339] Rebsdat, S., & Mayer, D. (2001). Ethylene Oxide. *Ullmann's Encyclopedia of Industrial Chemistry*. doi:10.1002/14356007.a10_117

[340] Langvardt, P. W. (2000). Acrylonitrile. *Ullmann's Encyclopedia of Industrial Chemistry*. doi:10.1002/14356007.a01_177

- Chlorofluorocarbon feedstocks

Needed for: PTFE/FEP (chlorodifluoromethane), PCTFE/ECTFE (1,1,2-trichloro-1,2,2-trifluoroethane)

Halogen exchange in the presence of an antimony chloride catalyst yields a mixture of chlorofluorocarbons which can be distilled. For example, for chlorodifluoromethane:[341]

$$CHCl_3 + 2\ HF \rightarrow CHClF_2 + 2\ HCl$$

The purification process requires a caustic and sulfuric acid wash, and the catalyst requires a small amount of chlorine for renewal between batches.

For 1,1,2-trichloro-1,2,2-trifluoroethane, the feedstock is tetrachloroethylene. Alternative catalysts for this process include zirconium fluoride and hafnium:

$$Cl_2C{=}CCl_2 + 3\ HF \rightarrow Cl_2FC\text{-}CClF_2 + 3\ HCl$$

Other feedstocks

Not all consumable chemicals must be present at the time of arrival of the habitat. Quite the opposite, local production capacity should be stepped up incrementally over time, to spread out the engineering costs. Only the elements necessary to sustain buoyancy, a habitable environment and agriculture must be present in the beginning; stockpiles and shipments of chemicals not available locally are acceptable solutions.

There is an alternative to both import of chemicals from Earth and local hardware dedicated toward specific production processes: laboratory scale production processes. Indeed, a local chemist can be seen as a very valuable member of the crew for both research, medical, manufacturing and agricultural purposes. A robotic chemistry lab which could help automate the production of complex, low-volume substances would be useful on Venus, but this would comprise a whole volume in its own right. We will, however, discuss chemicals with applicability to the envelope and their production in the next section.

Overture, a robotic chemistry lab designed for protein synthesis applications. Photo: © 2010 The Regents of the University of California, through the Lawrence Berkeley National Laboratory.

[341] Siegemund, G., Schwertfeger, W., Feiring, A., Smart, B., Behr, F., Vogel, H., . . . Kirsch, P.(2016). Fluorine Compounds, Organic. *Ullmann's Encyclopedia of Industrial Chemistry*. doi: 10.1002/14356007.a11_349.pub2

6. Manufacturing

Envelope

The external envelope is the critical separation between the habitable area within and the hostile chemical environment outside. It must serve a variety of purposes:

- Transparency, to allow for human factors, plant growth, and solar energy production
- Rejection of near-infrared light to reduce interior temperatures and allow for lower altitude / higher pressure environments at a given latitude.
- Tolerance to the acidic environment outside
- The ability to withstand high tensile loads
- Low permeability to both internal and external gases
- UV tolerance
- Acceptable levels of creep
- Locally producible with minimal manufacturing dependencies
- Preference for maximizing the use of common elements and elements little needed for other purposes, while minimizing the use of rare elements (in order of availability: O, C, N, S, Cl / H, F)
- Vacuum compatibility for during initial habitat transit

In practice, no single polymer well serves all of the needs of the habitat. We will break down various candidates into the properties that they can bring to bear.[342] This is not a complete list of polymers - just a list of polymers of particular interest, with a brief selection of mechanical / permeability properties, averaged across a variety of sources. Transparency figures exclude specular reflection, which increases relative to refractive index differences. Permeability figures[343] are for 300°K.

Short name	**Common market names**	**Density (g/cm^3)**	**Tensile strength (MPa)**	**Melt. °K**	**Permeability (m^3-m / m^2-s-Pa)**			**Transp.% @100um**	**Refrac. index**
					H_2O	**CO_2**	**O_2**		
FEP	*Teflon*	2.14	28	530	3.4e-16	6.5e-17	1.4e-17	96	1.34
PCTFE	*Aclon, Neoflon*	2.13	34	484	2.9e-19	1.1e-18	4.1e-19	95	1.44
ECTFE	*Halar*	1.68	55	515	1.0e-16	1.8e-17	1.1e-18	91	1.45
PVF	*Tedlar*	1.50	90	453	5.5e-17	5.3e-19	1.7e-19	87	1.46
PET	*Mylar*	1.39	230	517	5.7e-17	5.3e-19	1.6e-19	89	1.65
PVDC	*Saran*	1.70	110	450	1.5e-17	2.6e-19	1.5e-20	*85**	1.62
PVOH	-	1.25	High	503	Severe	Superb	Superb	75**	1.53
EVOH	*EVAL, Soarnol*	1.2	210	464	6.6e17	2.0e-21	7.2e-22	75*	1.53
UHMWPE	*Spectra, Dyneema*	0.95	2900	410	-	-	-	-	-
CF	*Carbon*	1.74	5100	*3670*	-	-	-	-	-
Vectran	*Vectran*	1.34	3100	603	-	-	-	-	-
PBO	*Zylon*	1.54	5800	*923*	-	-	-	-	-

[342] Properties not directly addressed here available from datasheets linked under each individual polymer.
[343] McKeen, L. W. (2017). *Permeability properties of plastics and elastomers*. Amsterdam: Elsevier.

Notes:

- PVOH strength / permeation data generally not available due to its water solubility.
- Carbon fibre and PBO do not melt, but rather begin to break down at high temperatures.
- Permeability figures are highly variable; only medians are reported.
- EVOH and PVDC transparency estimated from less reliable data; PVOH based on EVOH.

In the following table, the vacuum compatibility ratings TML (Total Mass Loss) and CVCM (Collected Volatile Condensable Materials) are highly variable,[344] and only median figures are reported; the standard targets to be considered vacuum compatible are <1% and <0.1%, respectively. On all 1-5 scales below, 1 is unfavorable and 5 is favorable.

Short name	%O	%C	%N	%Cl	%H	%F	Mfg. ease	Creep	UV tol.	Acid tol.	H_2O tol.	TML %	CVCM %	UV block	IR block
FEP	0	26	0	0	0.0	76	4	1	5	5	5	0.02*	0.00*	2	1
PCTFE	0	21	0	40	0.0	39	3	2	5	5	5	0.07	0.01	1	1
ECTFE	0	33	0	25	2.8	39	3	3	5	5	5	0.17	0.05	2	1
PVF	0	52	0	0	6.6	41	4	3	5	4	5	0.3	0.06	3	1
PET	34	63	0	0	3.2	0	2	4	4	2	3	0.4	0.05	3	1
PVDC	0	25	0	73	2.1	0	4	4	3	4	5	0.1-31	0-19*	4	1
PVA	36	55	0	0	9.1	0	4	3	4	2	1	1.5*	0.1*	2	2
EVOH	32	58	0	0	9.1	0	4	3	4	2-3	2	1.5	0.1	2	2
UHMWPE	0	86	0	0	14.4	0	5	1	1	4	5	0.4	0.1	-	-
CF	0	95	4	0	1.0	0	4	5	5	3	5	0.1	0.00	-	-
Vectran	22	74	0	0	3.5	0	1	5	3	3	5	0.7	0.05	-	-
PBO	14	72	12	0	2.6	0	1	5	1	2	5	Mid*	Mid*	-	-

Notes:

- FEP outgassing occasionally much higher, although never over limits
- UV is treated as unfavorable - that is, 1 = low blockage, 5 = high blockage.
- Using TML from PVC for PVDC. PVC is highly variable, even by the varying standards of outgassing measurements - but usually not vacuum compatible.
- Using EVOH for PVOH outgassing data
- No outgassing data for PBO. Expected to be moderate.

Surface layers / coatings

Surface layers or coatings are ideally fluoropolymers, although some non-fluoropolymers may prove sufficiently resistant should fluorine collection rates prove insufficient.

General properties of fluoropolymers include: dense, low tensile strength, high UV resistance, high chemical resistance, variable permeability, hydrophobic, anti-fouling, difficult to bond. The degree of fluorination (ordered from most to least below) largely determines how strong these properties are, but even a low level of fluorination tends to lead to this group's superlative properties.

[344] (2008) *Outgassing Data for Select Spacecraft Materials Online*. NASA. Retrieved from https://outgassing.nasa.gov/

- **FEP** (*Teflon*™) [345] [346] [347] [348]

Photo: Saint-Gobain Performance Plastics

A more recent variant of PTFE (also marketed as "Teflon"), FEP is a copolymer of (predominantly) tetrafluoroethylene (TFE) and a small amount of hexafluoropropylene (HFP). Like purely TFE-based Teflon™ (PTFE), the carbon backbone is fully fluorinated. Compared to PTFE, it provides improved strength, reduced permeability and reduced (although still high) creep. FEP is also easier to manufacture into films.

The production route to FEP remains largely the same as for PTFE. Chlorodifluoromethane is heated at 600-800° in a platinum, silver or carbon tubular reactor along with steam to pyrolyze it to tetrafluoroethylene (TFE) at 60-80% yield and 84-93% selectivity:

$$2\ CHClF_2 \rightarrow F_2C{=}CF_2 + 2\ HCl$$

Caustic and sulfuric acid washes are used for purification. Distillation in the presence of a polymerization inhibitor (such as dipentene) separates the two main products, TFE and HFP, as well as unconverted chlorodifluoromethane. Higher pressures yield a greater HFP fraction while lower pressures increase the TFE fraction. TFE is difficult to store, generally requiring inhibitors and/or low temperatures; when improperly stored, it is prone to explosion with similar force to gunpowder. HFP is much easier to store.

Copolymerization of HFP and TFE is carried out with an excess of HFP due to its lower reactivity, and can be conducted in aqueous or non-aqueous media. Periodic restocking of dispersing agents (such as ammonium perfluorooctanate) and initiators (such as persulfate) would be required. Agitation must be conducted gently for even polymerization. The dispersion can be processed into films or coatings as a latex. Without dispersing agents a more granular product can be produced. Melt processing requires corrosion-resistant alloys.[349]

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[345] (2016) Teflon™ FEP Fluoroplastic Film - Properties Bulletin. Chemours.
[346] (2016) Teflon™ FEP Fluoroplastic Film - Information Bulletin. Chemours.
[347] (2016) Teflon™ FEP Fluoroplastic Film - Processing and Use. Chemours.
[348] Biron, M. (2013). *Thermoplastics and thermoplastic composites*. Amsterdam: Elsevier.
[349] Carlson, D. P., & Schmiegel, W. (2000). Fluoropolymers, Organic. *Ullmann's Encyclopedia of Industrial Chemistry*. doi:10.1002/14356007.a11_393

- **PCTFE** (*Aclon™, Neoflon™*)[350] and **ECTFE** (*Halar®*): [351] [352]

Photo: CS Hyde Company

PCTFE and ECTFE are similar fluoropolymers, the latter being a 1:1 copolymer with ethylene. PCTFE, well known for its high transparency, has the lowest water permeation of any plastic; both PCTFE and ECTFE have relatively high permeation resistance in general. Both tolerate deep cryogenic operation (even by the standards of fluoropolymers), particularly PCTFE. ECTFE has reduced fracture and creep behavior at high temperatures. PCTFE is somewhat vulnerable to elevated temperature fracture and creep, although generally not in laminates. ECTFE is easier to manufacture from and to thermally weld together. The time PCTFE spends in the molten state must be minimized, with temperatures as low as possible. Sometimes low molecular weight PCTFE is used as an oil or grease to plasticize the bulk polymer, as well as being used as a lubricant in equipment that handles liquid oxygen and corrosive chemicals.

Manufacture of the fluorinated monomer, chlorotrifluoroethylene (CTFE) begins similar to PTFE / FEP in order to generate its chlorofluorocarbon feedstock, 1,1,2-trichloro-1,2,2-trifluoroethane. The most common process involves dehalogenation in methanol over zinc to CTFE and zinc chloride:

$$Cl_2FC\text{-}CClF_2 + Zn \rightarrow F_2C{=}CClF + ZnCl_2$$

More appropriate for our needs would be to avoid the need to regenerate zinc, and instead rely on a readily oxygen-renewed aluminum fluoride-nickel phosphate catalyst for a gas-phase hydrodechlorination process:

$$Cl_2FC\text{-}CClF_2 + H_2 \rightarrow F_2C{=}CClF + 2\ HCl$$

PCTFE polymerization requires free radical initiators and can be conducted in bulk solution, suspension, or emulsion processes. Emulsions appear the most interesting; polymerization is conducted over a persulfate-bisulfate redox catalyst, with the polymer coagulated by freezing, washed, and dried.

ECTFE polymerization is similar, but must be conducted at under 10°C. A common process is the dissolution of CTFE and ethylene in water, with a trichloroacetyl peroxide catalyst and chloroform (trichloromethane) chain transfer agent. Some processes involve polymerization in media as low as -40 to -80°C to produce more thermal crack-resistant products.[353]

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[350] NEOFLON™ PCTFE M-Series. Daikin. Retrieved from https://www.daikin.com/chm/products/resin/resin_05.html
[351] *Halar® ECTFE.* Solvay. Retrieved from http://www.solvay.com/en/markets-and-products/featured-products/Halar.html
[352] Biron, M. (2013). *Thermoplastics and thermoplastic composites*. Amsterdam: Elsevier.
[353] Carlson, D. P., & Schmiegel, W. (2000). Fluoropolymers, Organic. *Ullmann's Encyclopedia of Industrial Chemistry*. doi:10.1002/14356007.a11_393

- **PVF** (*Tedlar®*): [354] [355]

Photo: DuPont

With its carbon backbone only one-quarter fluorinated, PVF bears an elevated tensile strength and reduced density, while its UV and chemical resistance are somewhat reduced relative to other fluoropolymers. Nonetheless, its environmental tolerance properties remain generally superb. PVF is not as widely used as the above fluoropolymers, but unlike them it has a history of usage in airship envelopes (Zeppelin NT,[356] Airlander 10,[357] etc).

While multiple production routes to the vinyl fluoride monomer exist, the simplest for ISRU is fluorination of acetylene over a mercury catalyst:[358]

$$HC{\equiv}CH + HF \rightarrow H_2C{=}CHF$$

Free radical polymerization is used, like with most fluoropolymers, but the required pressures are higher. A typical process uses water, VF, and a peroxide or azo catalyst at 100°C and 27.5MPa. PVF is unusual in that cannot be melt-processed directly (due to instability above its melting point); it must be dissolved in a solvent and then dried.[359] A 36h@100C outgassing period is recommended for vacuum compatibility.[360]

- **Non-fluoropolymers**

Examples of non-fluoropolymers with potentially acceptable acid resistance, short production chains and good transparency include PVC and similar compounds (CPVC, PVDC) along with polyethylene (particularly LDPE). These polymers will be discussed shortly. Surface layers of other polymers, such as polyethylene, can also be fluorinated, consuming only small quantities of fluorine in the process.[361]

Biaxial reinforcement and barrier layers

Permeation resistance and tensile strength are often associated with high degrees of polymer crystallinity, but highly crystalline polymers are typically opaque. To achieve both, polymers are typically biaxially oriented (stretched during extrusion) and heat quenched,

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[354] *Polyvinyl Fluoride Films (PVF)*. DuPont. Retrieved from http://www.dupont.com/products-and-services/membranes-films/pvf-films.html
[355] Biron, M. (2013). *Thermoplastics and thermoplastic composites*. Amsterdam: Elsevier.
[356] Stockbridge, C., Ceruti, A., & Marzocca, P. (2012). Airship Research and Development in the Areas of Design, Structures, Dynamics and Energy Systems. *International Journal of Aeronautical and Space Sciences, 13*(2), 170-187. doi:10.5139/ijass.2012.13.2.170
[357] Norris, G. (15 May 2015) *Hybrid Hopes: An Inside Look At The Airlander 10 Airship*. Aviation Week.
[358] Siegemund, G., Schwertfeger, W., Feiring, A., Smart, B., Behr, F., Vogel, H., . . . Kirsch, P.(2016). Fluorine Compounds, Organic. *Ullmann's Encyclopedia of Industrial Chemistry*. doi: 10.1002/14356007.a11_349.pub2
[359] Carlson, D. P., & Schmiegel, W. (2000). Fluoropolymers, Organic. *Ullmann's Encyclopedia of Industrial Chemistry*. doi:10.1002/14356007.a11_393
[360] (2008) *Outgassing Data for Select Spacecraft Materials Online*. NASA. Retrieved from https://outgassing.nasa.gov/
[361] Whiteley, K. S. (2011). Polyethylene. *Ullmann's Encyclopedia of Industrial Chemistry*. doi:10.1002/14356007.a21_487.pub2

creating crystals with low thickness relative to the wavelength of light, and thus limiting scattering.[362]

- **PET** (*Mylar®*): [363] [364]

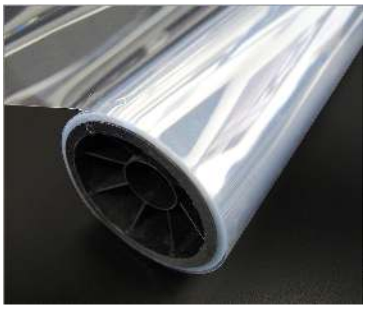

Photo: TAP Plastics

While Mylar® (biaxially-oriented PET) is typically thought of in the context of aluminized balloons, most "Mylar" balloons today are made from aluminized nylon coated in polyethylene.[365] PET is strong and permeation resistant (although somewhat brittle at high temperature and humidity). Its monomers (ethylene glycol and dimethyl terephthalate or terephthalic acid) present a fairly complicated manufacturing process.

Ethylene glycol production has been discussed previously. For the other two monomer options, both begin with p-xylene. Acetic acid is almost always the solvent, oxygen the oxidant, and catalysts are combinations of cobalt, manganese and bromine. [366]

$$\text{p-xylene} + 3\ O_2 \rightarrow \textit{terephthalic acid} + 2\ H_2O$$

The terephthalic acid is poorly soluble in the solvent and precipitates. Small amounts of acetic acid and p-xylene are lost to complete oxidation to carbon oxides and water (as well as the loss of small amounts of bromine catalyst); however, as a whole, yields are excellent with high specificity. Water vapour is removed by condensation. The crude terephthalic acid contains significant impurities of 4-formylbenzoic acid, requiring a purification stage involving high pressure hydrogenation of a terephthalic acid/water slurry at 260°C, with a 98% yield. Conversely, crude terephthalic acid can be esterified to dimethyl terephthalate of sufficient purity by reacting with methanol at 250-300°C in the presence of o-xylene.

An alternative route to dimethyl terephthalate starts similar to terephthalic acid production, with the oxidation stage is split into two segments and an intermediary esterification stage involving reaction with methanol. The product is produced in water rather than acetone and bromine is no longer required. Extraction of the product requires several methanol rinse / evaporation stages, but does not require a separate purification process. Conversely, dimethyl terephthalate can be converted to high purity terephthalic acid in a hydrolysis process.

PET polymerization proceeds in two stages: transesterification and polycondensation, both driven by continuous removal of gases (water and/or methanol in the former, excess ethylene glycol in the latter) via distillation. With DMT, the raw material is

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[362] Brydson, J. A. (1982). *Plastics materials*. London: Butterworth Scientific.
[363] (2003) Mylar® Polyester Film: Product Information. DuPont. Retrieved from http://usa.dupontteijinfilms.com/informationcenter/downloads/Physical_And_Thermal_Properties.pdf
[364] Biron, M. (2013). *Thermoplastics and thermoplastic composites*. Amsterdam: Elsevier.
[365] Mylar - History and Manufacturing. Scientifics Direct. Retrieved from https://www.scientificsonline.com/product/mylar-reflective-film-sheets
[366] Sheehan, R. J. (2011). Terephthalic Acid, Dimethyl Terephthalate, and Isophthalic Acid. *Ullmann's Encyclopedia of Industrial Chemistry*. doi:10.1002/14356007.a26_193.pub2

melted at 150-160°C and then blended with the ethylene glycol, while with TA, 220-260° is required. With DMT transesterification, catalysts (covering almost every element of the periodic table) are essential; with TA, they're optional to accelerate the process. In polycondensation, efficient stirring is required to effectively distill away eliminated ethylene glycol while the viscosity increases. The process is conducted at ~250°C, and is terminated when a set viscosity is achieved.[367]

In biaxial extrusion, a rapid quench is essential to achieve the small crystal size that allows the film to be transparent to visible light.

- **PVDC** (*Saran*™): [368] [369] [370]

Similar to Mylar, the brand name Saran® is often a misnomer, in that today's Saran Wrap is no longer PVDC, but polyethylene. PVDC can be thought of as much more permeation-resistant variant of PVC - the latter being the world's third most widely used plastic, desired for its combination of hardness, easy workability and high chemical resistance. At just above its melt temperature, PVDC is unstable and dechlorinates, and thus must be processed carefully - a process made more difficult by its high melt viscosity. It is often blended with ~5% of other polymers to improve processability.

The monomer, vinylidine chloride (1,1-dichloroethylene / VDC), is produced with high (>90%) selectivity by the dehydrochlorination of 1,1,2-trichloroethane with a caustic agent such as sodium hydroxide:[371]

$$HCl_2C\text{-}CH_2Cl + NaOH \rightarrow H_2C{=}CCl_2 + NaCl + H_2O$$

Caution must be taken with chloroacetylene byproducts, which can be explosive. If one wishes to avoid the need for producing / recycling caustics, a pyrolytic cracking reaction is available, albeit with lower selectivity:

$$2\ HCl_2C\text{-}CH_2Cl \rightarrow H_2C{=}CCl_2 + HClC{=}CHCl + 2\ HCl$$

The latter reaction avoids the chloroacetylene explosion hazards but is still in the research phase, often troubled by polymerization on its catalyst surfaces.

Once produced and cleaned (with caustic or methanol), VDC is readily polymerized - perhaps too readily, as it frequency self-polymerizes and should not be stored for more than

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[367] Köpnick, H., Schmidt, M., Brügging, W., Rüter, J., & Kaminsky, W. (2000). Polyesters. *Ullmann's Encyclopedia of Industrial Chemistry*. doi:10.1002/14356007.a21_227
[368] (2013) *Saran™ Polyvinylidine Chloride (PVDC) Resins*. DOW. Retrieved from http://msdssearch.dow.com/PublishedLiteratureDOWCOM/dh_096d/0901b8038096dac8.pdf?filepath=productsafety/pdfs/noreg/233-00251.pdf&fromPage=GetDoc
[369] *Saran PVDC Resins and the Environment*. DOW. Retrieved from http://msdssearch.dow.com/PublishedLiteratureDOWCOM/dh_007d/0901b8038007d391.pdf?filepath=plastics_ap/pdfs/noreg/190&fromPage=GetDoc
[370] Biron, M. (2013). *Thermoplastics and thermoplastic composites*. Amsterdam: Elsevier.
[371] Rossberg, M., Lendle, W., Pfleiderer, G., Tögel, A., Dreher, E., Langer, E., . . . Mann, T. (2012). Chlorinated Hydrocarbons. *Ullmann's Encyclopedia of Industrial Chemistry*. doi:10.1002/14356007.a06_233.pub2

two days without inhibitors. Polymerization is generally conducted at <80°C with peroxide initiators to accelerate the reaction.

Due to the difficulty of heat processing VDC, comonomers are frequently added (5-25%). Common comonomers include vinyl chloride and various chemicals stemming from ammoxidation reactions (methyl acrylate, ethyl acrylate, acrylonitrile, methyl methacrylate, and butyl acrylate).[372]

- **PVOH** ("water gel")[373] [374] and **EVOH** (*EVAL™, Soarnol™*): [375] [376] [377]

Hydrogel support dissolving away from a 3d print. Photo: Tony Buser

Known by a variety of ambiguous acronyms, polyvinyl alcohol and ethylene vinyl alcohol (a copolymer with ethylene at various percentages, usually 29-44% ethylene by mass) have great strengths and weaknesses. They offer the best permeation resistance to most chemicals for any highly transparent plastic - but at the same time offer little resistance to water vapour. Mechanical and barrier properties decline with increasing humidity levels; indeed, PVOH is so vulnerable to attack by water that it is soluble, forming a hydrogel.

EVOH's ethylene co-monomer grants it improved (albeit limited) water resistance, relative to the ethylene percentage. This comes at a cost of reduced permeation resistance to most compounds other than water. Film extrusion of EVOH requires the use of a solvent - generally water.

These polymers are unusual in that their erstwhile monomer does not exist as an independent, stable chemical. Consequently, PVOH and EVOH are created first by creating PVA and EVA, where VA is vinyl acetate. These are subsequently saponified.

The most reasonable process for producing vinyl acetate in-situ is gas-phase oxidation of ethylene with acetic acid:

$$H_2C=CH_2 + CH_3COOH + \tfrac{1}{2}\, O_2 \rightarrow CH_3COOHC=CH_2 + H_2O$$

The process proceeds at >140°C and 0.5-1.2 MPa over a solid bed of palladium and alkali metal salts on carrier materials. Conversion per pass is low, 8-10% of ethylene and 15-35% acetic acid. However, the process is selective, with 99% of acetic acid and 94% of

[372] Vinas, J., & Dufils, P. E. (2012). Poly(Vinylidene Chloride). *Ullmann's Encyclopedia of Industrial Chemistry*. doi:10.1002/14356007.a22_017.pub2
[373] *PVOH "Gohsenol ™" Technical Site*. Nippon Gohsei. Retrieved from http://www.gohsenol.com/index_e.shtml
[374] *Polyvinyl alcohol for 1001 applications*. Kuraray. Retrieved from http://www.kuraray.eu/en/produkte/product-groups/polyvinyl-alcohol/
[375] *EVOH Barrier Resins and Films*. Kuraray. Retrieved from http://www.eval.eu/media/124484/01b_eval_evoh_resins_and_films.pdf
[376] *High gas barrier resin Soarnol*™. Nippon Gohsei. Retrieved from http://www.soarnol.com/eng/index.html
[377] Biron, M. (2013). *Thermoplastics and thermoplastic composites*. Amsterdam: Elsevier.

ethylene converted to vinyl acetate. Polymerization inhibitors are required in distillation; free oxygen is said to assist in this regard.[378]

Vinyl acetate is polymerized in methanol, either as a homopolymer (PVA) or copolymerized with ethylene (EVA). Low polymerization temperatures and low methanol content cause slow polymerization but high PVA/EVA molecular weight; this molecular weight translates directly to PVOH/EVOH molecular weight.

The most common conversion method is the transesterification in methanol. This generally employs sodium methoxide, which requires sodium metal to produce locally.[379] However, sodium and potassium hydroxide can also be used, making this process more suitable to local production.[380]

Note that PVA and EVA are useful products in their own right. PVA is another hydrogel like PVOH when dissolved in water. EVA is commonly sold as “hot glue”. Mixed in with other thermoplastics, it tends to make them "clingy". Reacted with a tackifier it forms the adhesive of sticky tape. EVA is readily foamed, and marketed as "foam rubber", used in a wide variety of footwear and sporting goods.

Of the two hydrogels, PVOH forms a glue when mixed with boric acid; acts as a glue thickener and eye drop base; functions as a mould release; and as a soluble 3d printing substrate. Reacted with nitric acid, it becomes PVN, a plastic explosive useful for mining and accelerating solid rocket propellants. PVA in water is otherwise known as wood glue / Elmer's glue (usually with various additives included). Reacted with boric acid, PVA becomes a tackifier, to be used in other adhesives to help them stick better.

fibre reinforcement

While biaxial orientation can yield tensile strengths an order of magnitude higher than unoriented polymers, uniaxial orientation can yield strengths an order of magnitude higher still. This comes at a cost: uniaxial fibres are generally opaque. fibres can be embedded into films randomly, or for greater strength, as an ordered mesh. For even greater strength per unit mass, fibres are made into cables and netting to which envelope loads can be transferred. Each step up to larger, more orderly fibre bundles decreases the amount of light blocked by the reinforcement, at the cost of requiring that the transparent film material bear increasing spans on its own.

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[378] Roscher, G. (2000). Vinyl Esters. *Ullmann's Encyclopedia of Industrial Chemistry*. doi:10.1002/14356007.a27_419

[379] Hallensleben, M. L. (2000). Polyvinyl Compounds, Others. *Ullmann's Encyclopedia of Industrial Chemistry*. doi:10.1002/14356007.a21_743

[380] Saxena, S. K. (2004). *Polyvinyl Alcohol*. FAO. Chemical and Technical Assessment, 61st JECFA.

The below list of reinforcement fibres only scratches the surface of the available options, as examples. One was chosen which is easy to produce and in an advance state of development (UHMWPE); one with a moderate-length production chain, which has much lower creep, higher heat resistance, far lower hydrogen consumption, etc; and two advanced fibres frequently proposed for Venus missions, but with difficult local production. Reinforcement of plastics by such fibres is common in fields that require lightweight, strong fabrics, such as camping and sailing.

A sail made of Cuben, a loose-fill UHMWPE-reinforced mylar. Note how the loose fibres add haze and some loss of transmission. Before their acquisition by DSM Dyneema, Cubic Tech was working to market the fabric for use in airships.[381] Photo: WARDOG ® SurfingSports.com, Inc.

- **UHMWPE** (*Spectra®, Dyneema®*): [382] [383] [384]

Photo: fibre Line

It can be surprising that polyethylene, the simplest of hydrocarbon polymers, might end up yielding among the best high strength fibres. It boasts not only a very high ratio of tensile strength to mass, excellent chemical resistance, and among the best abrasion resistances of all plastics, but it is also the only plastic that has already been produced by a system designed for off-world usage from in-situ resources.[385] It does, however, come with the same disadvantages of polyethylene in general: creep, vulnerability to UV, and low melt temperatures. UHMWPE is extremely slick, and feels almost oily to the touch. In addition to use as fibres, it can also be used for traditional polyethylene uses, such as films, molded products, etc.

Gas-phase and slurry phase processes are effective for UHMWPE polymerization; in the ISRU system developed in Carranza et al (2010), slurry phase was utilized. Gas phase allows for lower "catalyst" (initiator) consumption but requires more careful temperature control to prevent runaway polymerization. In general, several thousand grams of product are typically produced per gram of catalyst consumed. Before the 1960s, stages to recover catalyst from the product were frequently employed, but seldom are today. Easily producible oxygen can be used as the catalyst, but it makes control of polymerization rates (and thus product control) more difficult.[386]

The dried product can be used either as an unoriented (bulk) plastic or oriented (high tensile) fibres. UHMWPE powder can be fed to film production systems; blended with

[381] Downs, R. (2005) Very Lightweight High Tenacity Fabric for High Altitude Airships. SBIR contract HQ0006-05-C-7162.
[382] Honeywell Spectra®. Honeywell. Retrieved from https://www.honeywell-spectra.com/products/fibers/
[383] Dyneema®. Royal DSM. Retrieved from http://www.dsm.com/products/dyneema/en_AU/home.html
[384] Biron, M. (2013). *Thermoplastics and thermoplastic composites*. Amsterdam: Elsevier.
[385] Sen, S., Carranza, S., & Pillay, S. (2010). Multifunctional Martian habitat composite material synthesized from in situ resources. *Advances in Space Research, 46*(5), 582-592. doi:10.1016/j.asr.2010.04.009
[386] Whiteley, K. S. (2011). Polyethylene. *Ullmann's Encyclopedia of Industrial Chemistry*. doi:10.1002/14356007.a21_487.pub2

foaming agents (such as short-chain alkanes and halocarbons); cast into foam via expansion moulding; used in 3d sintering directly; or die-extruded into unoriented strands for use in filament printers. Contrarily, it can be gel spun into UHMWPE fibre, which can then be fed into the production of cordage, mesh, or (in combination with UHMWPE-compatible resins) die extruded into UHMWPE-composite products such as tubing and structural profiles.

- **Carbon fibre**: [387]

Photo: fibre Line

By nature of being produced in an extremely heat-intensive process, carbon fibre can withstand extreme temperatures; in anoxic environments, it experiences no melting point, rather sublimating at several thousand degrees. It likewise only contains small amounts of residual elements such as nitrogen and hydrogen, being primarily (abundant) carbon. The dark colour may be a disadvantage as an envelope reinforcement, absorbing rather than reflecting light.

The initial fibre, PAN, can be produced from acrylonitrile by either precipitation or solution polymerization with initiators. From an ISRU perspective, solution polymerization in nitric acid followed by gel spinning is appealing (with a nitric acid solvent, temperatures must be kept below 5°C).[388] No more than 3% comonomer should be used for PAN destined for carbon fibre production, and the stretching factor in spinning should be at least 12:1.

Following drying, the PAN is first stabilized. This partial oxidation process occurs at 0.1-5 bar and for 1-2 hours at 470-560°K. This is followed by carbonization in a nitrogen atmosphere, with the temperature ultimately rising to up to 3200°K for graphitization. The resultant carbon fibre is surface-treated with sulfuric acid. Each progressive stage shifts the composition as volatiles are driven off:[389]

Material	%C	%H	%N	%O
PAN	68	6	26	0
Stabilized PAN	65	5	12	8
Carbonized PAN (up to 770°K)	67	11	19	3
Carbonized PAN (up to 970°K)	72	7	18	2
PAN-based carbon fibre (1750°K)	>95	0.3	4.5	0.2
HM (2500°K)	99	<0.1	<0.2	<0.1

As with UHMWPE, the resultant fibre can be used for cordage, mesh, and extruded composites when combined with suitable resins. Carbon fibre mesh is in particular valuable

[387] Biron, M. (2013). *Thermoplastics and thermoplastic composites.* Amsterdam: Elsevier.
[388] Nogaj, A., Süling, C., & Schweizer, M. (2011). fibres, 8. Polyacrylonitrile fibres. *Ullmann's Encyclopedia of Industrial Chemistry*. doi:10.1002/14356007.o10_o04
[389] Fitzer, E., Foley, A., Frohs, W., Hauke, T., Heine, M., Jäger, H., & Sitter, S. (2012). fibres, 15. Carbon fibres. *Ullmann's Encyclopedia of Industrial Chemistry*. doi:10.1002/14356007.o11_o04

for use in composite layups (ideally prepreg), and carbon yarns for composite overwrap vessels.

Cutting carbon fibre cloth for a layup. Photo: SkiBuilders.com

- **Vectran**®: [390]

Photo: fibre Line

One of the newer "superpolymers", vectran is a strong, resilient, extremely permeation resistant, virtually creep-immune liquid crystal polymer. While it is frequently proposed to make balloon envelopes for unmanned probes on Venus (and is used in the Airlander 10 on Earth)[391] in the form of a dense weave fabric, it is unsuitable for that usage in a Landis habitat in that, as a liquid crystal polymer, it is highly opaque.

While it would make for an excellent reinforcement / cable fibre, this is tempered by the long dependency chains in its production - so long that we will only skim over them. We begin with simple aromatics and naphthalene:

Phenol:

benzene + ½ O_2 → phenol

toluene + O_2 → phenol + CO_2 + H_2O

cumene + O_2 → phenol + acetone

… and many others. All begin with benzene derivatives.[392]

4-hydroxybenzoic acid (Kolbé-Schmidt synthesis[393]):

phenol + KOH → potassium phenoxide

potassium phenoxide + CO_2 → (KOH + 4-hydroxybenzoic acid)

(KOH + 4-hydroxybenzoic acid) + H_2SO_4 → 4-hydroxybenzoic acid + K_2SO_4

K_2SO_4 + H_2O → 2 KOH + SO_3 (electrolysis)

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[390] *Vectran*. Kuraray. Retrieved from http://www.vectranfiber.com/

[391] Norris, G. (15 May 2015) *Hybrid Hopes: An Inside Look At The Airlander 10 Airship*. Aviation Week.

[392] Weber, M., Weber, M., & Kleine-Boymann, M. (2004). Phenol. *Ullmann's Encyclopedia of Industrial Chemistry*. doi:10.1002/14356007.a19_299.pub2

[393] Boullard, O., Leblanc, H., & Besson, B. (2000). Salicylic Acid. *Ullmann's Encyclopedia of Industrial Chemistry*. doi:10.1002/14356007.a23_477

2-hydroxynaphthalene (2-naphthol):[394]

naphthalene + H_2SO_4 → naphthalene-2-sulfonic acid

naphthalene-2-sulfonic acid + NaOH → 2-hydroxynaphthalene + Na_2SO_4

Na_2SO_4 + H_2O → 2 NaOH + SO_3 (electrolysis)

6-hydroxy-2-naphthoic acid:[395]

2-hydroxynaphthalene + KOH → potassium 2-naphthoxide

potassium 2-naphthoxide + CO_2 → (KOH + 6-hydroxy-2-naphthoic acid)

(KOH + 6-hydroxy-2-naphthoic acid) + H_2SO_4 → 6-hydroxy-2-naphthoic acid + K_2SO_4

K_2SO_4 + H_2O → 2 KOH + SO_3 (electrolysis)

Lastly, the 4-hydroxybenzoic acid is polymerized with the 6-hydroxy-2-naphthoic acid to yield vectran. The polymerization requires acetic anhydride (generating acetic acid),[396] and thus we must add it to the production list:

Acetic anhydride (Ketene process)**:**[397]

CH_3COOH → $H_2C{=}C{=}O$ + H_2O

$H_2C{=}C{=}O$ + CH_3COOH → $(H_3C\text{-}C{=}O)_2O$

- **PBO** (*Zylon*®): [398]

Photo: fibre Line

Another "superpolymer" often discussed in the context of Venus. PBO (*poly(p-phenylene-2,6-benzobisoxazole)*) - has no true melting point, just a (high) temperature range in which it begins to decompose. A similar polymer, PIBO, shares many of PBOs properties but is amorphous rather than crystalline; it has additionally gained interest for Venus applications.

A thermoset liquid crystal polymer, PBO has one of the highest strength to weight ratios of any known fibre. Compared to vectran, the production chains for PBO’s monomers are even longer and more complicated, and thus our consideration of them will be even briefer.

Terephthalic acid, the simpler monomer, has already been discussed. The other monomer, 4,6-diamino-1,3-benzenediol dihydrochloride, is produced in the following production process chain:

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[394] Booth, G. (2000). Naphthalene Derivatives. *Ullmann's Encyclopedia of Industrial Chemistry*. doi:10.1002/14356007.a17_009

[395] Montgomery, C. (1981). *U.S. Patent No. US4329494 A.* Washington, DC: U.S. Patent and Trademark Office.

[396] Köpnick, H., Schmidt, M., Brügging, W., Rüter, J., & Kaminsky, W. (2000). Polyesters. *Ullmann's Encyclopedia of Industrial Chemistry*. doi:10.1002/14356007.a21_227

[397] Held, H., Rengstl, A., & Mayer, D. (2000). Acetic Anhydride and Mixed Fatty Acid Anhydrides. *Ullmann's Encyclopedia of Industrial Chemistry*. doi:10.1002/14356007.a01_065

[398] (2005) *PBO fibre Zylon*®. Toyobo Co. Ltd. Retrieved from http://www.toyobo-global.com/seihin/kc/pbo/zylon-p/bussei-p/technical.pdf

Resorcinol: [399]

Benzene...	*Benzene…*
+ propene...	*+ SO_3...*
+ O_2...	*+ NaOH…*
+ O_2...	*+ NaOH…*
+ H → resorcinol + acetone	*+ H → resorcinol + $NaSO_2$*

… → 4,6-diaminoresorcinol[400]

… → 4,6-diamino-1,3-benzenediol dihydrochloride[401]

Polymerization is conducted in polyphosphoric acid with sulfolane as a cosolvent, the production of which will not be elaborated on here.[402]

Other polymers of note

- **PFA** is another fully fluorinated polymer of note, similar to FEP, but more complex to synthesize and without particularly exceptional properties relative to FEP, excepting a superior melting point.

- **ETFE** is a half-fluorinated fluoropolymer, with properties as would be expected from such. As its properties don't generally exceed PCTFE/ECTFE (and performs worse on corrosion resistance comparisons), and fluorine makes up a larger percentage of its mass, its desirability is reduced.

- **PVDF** (*Kynar*™) is another half-fluorinated fluoropolymer with properties that, while good, don't make it a standout relative to its level of fluorination. Spontaneous combustion of PVDF deep in Venus's atmosphere is a possible cause of the "Pioneer anomaly".[403]

- **PMMA** (*acrylic, Plexiglass*™) is among the most transparent of all polymers (and as a consequence is frequently used in fibre optic waveguides). However, its barrier and chemical resistance properties make it an inferior choice for a laminate layer.

- **Polycarbonate** suffers the same barrier and chemical resistance problems as PMMA, as well as being relatively difficult to produce, not as transparent, and tending to yellow over time. Its vulnerability to chemical attack is however lower.

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399 Schmiedel, K. W., & Decker, D. (2000). Resorcinol. *Ullmann's Encyclopedia of Industrial Chemistry*. doi:10.1002/14356007.a23_111
400 Nader, B. S. (1994). *U.S. Patent No. US5371291 A*. Washington, DC: U.S. Patent and Trademark Office.
401 Pubchem. Retrieved from https://pubchem.ncbi.nlm.nih.gov/compound/4_6-Diaminoresorcinol_dihydrochloride#section=Parent-Compound
402 Kricheldorf, H. R. (1992). *Handbook of polymer synthesis*. New York: Dekker.
403 Seiff, A., Sromovsky, L., Borucki, W., Craig, R., Juergens, D., Young, R. E., Ragent, B. (1993) Pioneer Venus 12.5 km *Anomaly Workshop Report (Volume I)*. Proceedings of a workshop held at Moffett Field, California September 28-29, 1993

- **PAN**: While PAN fibres are produced as a precursor to carbon fibre, and it has barrier processes similar to PVDC, it cannot be made into biaxially oriented films without heavy blending.

- **Barex**™ is a PAN/PMMA copolymer used as a barrier film, but most of its properties are inferior to others previously discussed.

- **COC** (cyclic olefin copolymer) has nearly as good transparency as PMMA and similar permeation resistance to PVDC. Its tensile strength is a relatively unimpressive 46-63 MPa. Production chains are very long and complex.

- **Nylons** and **aramids** not previously discussed: In general, the length of their production chains do not justify their material properties in terms of their utility as reinforcing fibres.

Layering discussion

The numerous factors involved in developing a proper envelope film are made more complicated by the fact that the properties of a single "type of polymer" can vary wildly depending on the mechanisms used to produce, polymerize, and manufacture the product. The product must furthermore have installation and maintenance planned from the beginning, including a method for replacing damaged envelope sections. General polymer data is insufficient in its own right except for preliminary planning; every sample produced must be qualified on its own.

Concerning exterior coatings:

PCTFE stands out. More halogenated than PVF, and thus more inert, it still uses about the same amount of fluorine per unit thickness. It is not as strong as ECTFE and certainly not PVF, but it does not need to be; its job is to protect the underlying layers from damage by Venus's atmosphere. Its superb water permeation resistance, a standout trait, also frees underlying layers from having to provide that capability on their own.

Alternative candidates may prove superior in some circumstances:

ECTFE: … if PCTFE workability proves too challenging, or chlorine is more limited than hydrogen.
PVF: … if chlorine is highly limited.
FEP: … if fluorine is not limited but service lifespan for other polymers cannot meet requirements
Stabilized LDPE, PVC, etc: … if fluorine is highly limited and can only be used for surface treatments, if that.

Concerning barrier layers:

PVOH and **EVOH** are tempting due to their incredible barrier properties, tempered by their water sensitivity. On Earth, PVOH could likely be ruled out, due to its extreme sensitivity to humidity; however, the extremely dehydrating nature of Venus's atmosphere makes it a potential option for a layer near the atmosphere side. This however might complicate manufacture and testing, both on Earth and locally. A low-ethylene EVOH seems a more likely choice. Production of EVOH, a relatively simple process, inherently also produces EVA, a valuable product in its own right - particular in its ability to help polymer layers bond and to form bonding agents. Combined with PCTFE, a high degree of permeation resistance could be achieved at low density. Interior humidity may, however, prove a problem, and certainly will if there are no further interior layers and coatings. A simple polyethylene layer is a possible protective layer, albeit providing little permeation resistance, poor strength to weight performance and consuming significant amounts of hydrogen. Either a fluoropolymer inner coating or another strength/permeation layer would be superior.

Alternative or additional barrier layers have merit:

PVDC is stable and likewise relatively easy to produce, and brings with it the production of PVC. However, the production of polyethylene can compete with PVC in many applications, rendering it not as essential of a product. PVDC also carries the disadvantages of sensitivity to manufacturing conditions and potential outgassing en route to Venus; its surrounding layers would need to reduce outgassing to an appropriate level.

PET is a fallback; strong and with good (although not exceptional) scores in almost every category, it has widely been proposed for use in unmanned Venus probes. However, its moderately long production chains temper enthusiasm for its use somewhat.

Whether a coating layer for the inside of the habitat is needed depends on how much protection the core layer(s) of the film need, as well as how prone the envelope is to fouling. Fouling can exist in the form of dust, fog, algal growth, abrasion, and other factors which can be reduced or eliminated by a fluoropolymer coating. The primary downside is that this consumes an additional amount of fluorine. Any such coating, such as PCTFE, would be expected to be as thin as possible, in contrast to exterior coatings which should be designed to wear.

Individual layers must be bonded together, and this raises their own challenges. Some produced films cling so strongly to each other without any adhesive or thermal bonding that a find dusting of inert material (slip / antiblock agent) must be used in production to enable the individual layers to be pulled apart. Others strongly resist secure bonding of any type. Fluoropolymers in particular are notoriously difficult to bond. Among other techniques to improve bonding, exposure to plasma and flame are most applicable to a Venus habitat environment; these roughen and in some cases dehalogenate the surface, allowing it to bond better.[404] Plasma surface treatments can also be used to make the external surface less hydrophobic, if further research determines that this would enable

[404] Matheison, I. (1995). *Pretreatments of fluoropolymers to enhance adhesion* (Unpublished master's thesis). Loughborough University.

faster ISRU liquids collection rates.[405] Imported chemical products such as FluoroBonder can also aid in adhesion.[406]

A PVA / EVA, PVOH / EVOH route might enable the local production of adhesives useful for bonding layers. In some cases, layers can be melt-processed together during manufacturing; this includes some of the more desirable fluoropolymers like PCTFE.[407] An option for cases where further melting may reduce desirable properties is a "quilted" approach, where individual layers are melt-joined only at a series of points spaced out from one another. There is a great deal of nuance and experimentation that will be needed to determine the optimal solution. In the worst case, however, adhesives and additives can always be sent from Earth, so long as their total percentage of the mass of the envelope remains low.

Permeation calculations

For the sake of permeation analysis, we will consider a sample envelope fabric comprised of 20μm PCTFE, 70μm PVDC, and another 10μm PCTFE (183g/m², not counting reinforcement). We will analyze it at 22.5°C and 50kPa external pressure / 50.5kPa internal pressure, 55% N_2 / 40% O_2 / 4.9% H_2O / 0.1% CO_2 atmosphere inside, for a 330x80x50 elliptical habitat with no pinholes, over species of concern. Limits in italics are due to effects on agriculture rather than humans. Acid permeability is based on data for liquids. The effect of ballonets on permeation is not considered.

Specie	**Permeability (m³-m/m²-s-Pa)**	**Daily permeation w/ continuous scrubbing**	**Daily permeation w/o continuous scrubbing**	**Recommended limit**
H_2O	6.09e-15	-1.44 kg	-1.44 kg	-
O_2	1.50e-16	-0.29 kg	-0.29 kg	-
N_2	8.85e-17	-0.22 kg	-0.22 kg	-
HF	6.04e-17	2.91 ppb	1.46 ppb	*200 ppt*
H_2S	9.88e-17	19.1 ppb	9.53 ppb	10 ppm
HCl	6.04e-18	23.3 ppb	11.6 ppb	*15 ppb*
H_2SO_4	4.83e-19	294 ppb	147 ppb	*15 ppb*
SO_2	1.28e-15	92.7 ppm	46.3 ppm	*50 ppb*
CO	2.56e-16	98.8 ppm	49.4 ppm	20 ppm
CO_2	2.56e-15	11.9 kg	11.9 kg	3500 ppm

First off, it would appear that we would need to scrub the internal air approximately fifteen times per day to maintain the desired limitation to avoid effects on agriculture. This equates to 120 m³/s, a very high rate of flow. Surprisingly, the tiny amounts of hydrogen fluoride are just as significant as the much greater amounts of sulfuric acid, due to extreme plant sensitivity. While celery can withstand 20 ppb of hydrogen fluoride for 3-4 weeks

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[405] Vandencasteele, N., Merche, D., & Reniers, F. (2006). XPS and contact angle study of N2 and O2 plasma-modified PTFE, PVDF and PVF surfaces. *Surface and Interface Analysis, 38*(4), 526-530. doi:10.1002/sia.2255

[406] *FluoroBonder*®. Technos Corporation. Retrieved from http://technos-corp.co.jp/english/publics/index/7/

[407] Voltalef® PCTFE Technical Brochure. Arkema. Retrieved from http://www-eng.lbl.gov/~shuman/NEXT/MATERIALS&COMPONENTS/MISC/PCTFE_voltalef.pdf

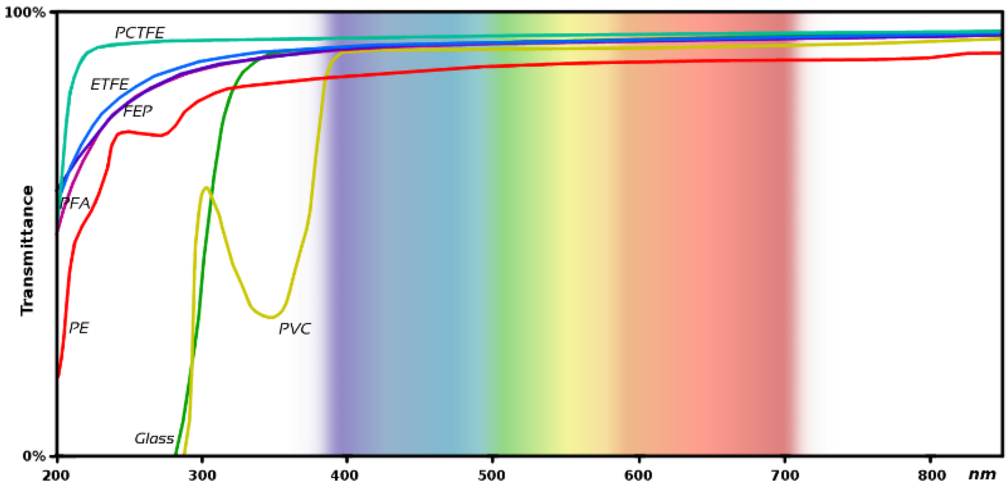
without injury, apricots, peaches and corn suffer severe injury at 0.4-0.6 ppb for several months.[408]

Rather than circulating air so quickly through a scrubber, some other strategies might bear consideration. The first is passive absorption, which may occur on its own to varying degrees into condensation on the envelope. As these species are highly hygroscopic, mist sprays may also be very effective at removing them from the atmosphere (at the cost of increasing dehumidification requirements). Another option is that, as the daily permeation rates are so tiny, the envelope could simply contain or be coated on the interior with basic compounds to neutralize permeating acidic species. Lastly, plants could simply be selected or bred for greater acid tolerance, as the plant safety limits are so much less than those for humans.

Removing the permeated carbon dioxide is not so great of a challenge; at 0.1% concentration and 0.6 kg/m³, 7140 m³ of air (roughly 1% of the habitat volume) must be processed per day. Carbon monoxide scrubbing requirements are more significant, and may be best dealt with by increasing the concentration of CO-reactive species, such as hydroxyl radicals. Sulfur dioxide and hydrogen sulfide, due to their solubilities and low permeation rates, would likely be scrubbed out along with whatever process is chosen to deal with acids.

While the loss of oxygen and nitrogen are relatively insignificant, the loss of water is not. Water is a small polar molecule and highly prone to permeation in polymers. 1.44kg of water equates to 0.16kg of hydrogen, or about 5% of our previously calculated hydrogen recovery. While this is acceptable, it does show the importance of having at least one layer that offers significant resistance to water permeation, such as PCTFE. For resisting the permeation of toxic species, however, layers like PVDC or particularly EVOH have much more effect; increasing the thickness of these layers is an effective means to reduce indoor scrubbing requirements.

UV tolerance improvement



Left: Optical transmittance of various plastics. All are for 25μm films, except PVC (40μm) and glass (135μm).

[408] Hill, A. C. (1969) Air Quality Standards for Fluoride Vegetation Effects. *Journal of the Air Pollution Control Association*, 19:5, 331-336, DOI: 10.1080/00022470.1969.10466495

Most transparent plastics hinder UV-A transmission, but absorption of UV-B and UV-C are quite varied. UV transmission is not entirely an undesirable property. The human body uses UV to create vitamin D,[409] while UV exposure frequently causes plants to produce carotenoids and other compounds which are beneficial to the diet.[410] Should an attempt be made at apiculture, bees utilize UV light for navigation and suffer when it is missing (a problem that became clear in the Biosphere 2 project); this and related problems have been specifically researched in the context of offworld habitation.[411] Nor does Venus's cloud environment present an abnormally strong source of ultraviolet light that must be blocked (see *Solar power*). However, some polymers (such as polyethylene and PBO), are sensitive to long-term exposure to solar UV. Thin-film polyethylene without UV stabilization, exposed to the sun for a single summer can begin to cloud and become brittle.[412]

The first category of compounds for preventing UV damage is absorbers, which absorb UV light, and commonly visible light as well. Common examples include carbon black, titanium dioxide, zinc oxide, hydroxybenzopenone, and hydroxyphenylbenzotriazole. Organic absorbers tend to have only short lifespans, and would be difficult to produce locally. While it has the disadvantage of darkening the color of what it's added to, carbon black is otherwise an excellent candidate for local production, being produced simple carbonization process (its old name, lamp black, refers its formation as the soot left behind on oil lamps). Optically opaque absorbers can only be used in fibres, not transparent films.

Another category is quenchers, generally complex nickel-based organic compounds, but occasionally copper or manganese-based compounds. Rather than absorbing UV, they provide excited polymers with a "safe" route to the ground state; as a consequence, they work synergistically with absorbers. The cation usage and complex chemistry, however, would render these a likely Earth import (in small quantities).

Radical scavengers and hydroperoxide decomposers form a third category. Both are consumed in the process of breaking the oxidative chain, but work synergistically with absorbers. However, quenchers also function in the same role and are not consumed, and are likely a more appropriate solution. Radical scavengers furthermore are generally complicated organic compounds that would be impractical to produce locally.

The most recent development in the UV protection of plastics is hindered amine light stabilizers, or HALS. These complex organic compounds provide long-term protection by blocking radicals in multiple phases of the oxidation process.[413]

As a general rule, UV-controlling additives make up no more than a few percentage of the polymer that they're protecting. HALS absorbers are commonly used at only 0.2-0.5%

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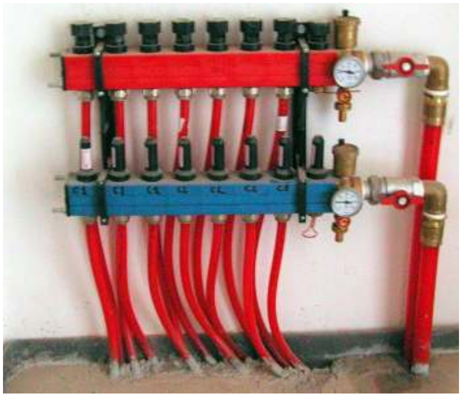
[409] Holick, M. F. (n.d.). Sunlight, UV-Radiation, Vitamin D and Skin Cancer: How Much Sunlight Do We Need? *Sunlight, Vitamin D and Skin Cancer Advances in Experimental Medicine and Biology,* 1-15. doi:10.1007/978-0-387-77574-6_1
[410] Solovchenko, A. E., & Merzlyak, M. N. (2008). Screening of visible and UV radiation as a photoprotective mechanism in plants. *Russian Journal of Plant Physiology,55*(6), 719-737. doi:10.1134/s1021443708060010
[411] Cockell, C. S., & Andrady, A. L. (1999). The Martian and extraterrestrial UV radiation environment—1. Biological and closed-loop ecosystem considerations. *Acta Astronautica, 44*(1), 53-62. doi:10.1016/s0094-5765(98)00186-6
[412] Unpublished personal experience.
[413] Ye, Y., & King, R. E., III. (2006). Additives for polyolefin film products: an overview of chemistry and effects. Ciba Specialty Chemicals.

by mass.[414] 0.2% HALS Tinuvin 783 was reported to give gas pipes in accelerated aging tests a lifetime increase from 1000 hours to 16000, equivalent to 12.5 years in direct Florida sun.[415]

Creep improvement

Creep - the elongation of material over time while under stress - is a potential problem for an airship envelope. If reinforcing fibres elongate more than the substance they're reinforcing, the tensile loads that they're bearing become increasingly transferred to the supported structure, ultimately causing it to fail. Uneven creep in catenary cables might cause loads to be unevenly borne, tilting or misaligning objects. As a general rule, creep should be reduced as much as possible, and engineering calculations must take into account elongation over time.

One way to reduce creep, in particular with high-creep fibres like UHMWPE, is crosslinking. UV crosslinking in particular is suitable to use on Venus, compared to chemical mechanisms that require complicated feedstocks (chlorosulfonation, peroxide crosslinking, etc); it can reduce creep by an order of magnitude without relevant consequences to tensile strength.[416] Crosslinking also increases the wear resistance, and even allows for operation at higher temperatures (~250°C) for several hours at a time.[417] Crosslinked polyethylene is commonly used in both medical implants and home water piping, sold as PEX.[418]



PEX piping. Photo: Chixoy

An additional factor which is (to a degree) under the manufacturer's control is the degree of polymer crystallinity; highly crystalline polymers generally suffer from less creep than amorphous ones. UHWMPE "Hylamer" is heated at >300°C at >235MPa, then slowly cooled, in order to induce a high degree of crystallinity in the structure, achieving a degree of creep reduction.[419] Such high pressures may hinder its usefulness for offworld applications.

Infrared rejection

While Venus's cloud tops are the most Earthlike place in the solar system outside of Earth, the climate conditions there are not identical. For a given level of air pressure and

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[414] Butola, B. S., & Joshi, M. (2013). Photostability of HDPE Filaments Stabilized with UV Absorbers (UVA) and Light Stabilizers (HALS) . *Journal of Engineered fibres and Fabrics, 8*(1).
[415] Stahmer, M, Micic, P (2003) Weathering of PE Pipes. Technical note VX-TN-6C. Retrieved from http://www.vinidex.com.au/technote-parent-page/weathering-of-pe-pipes/
[416] Penning, J. P., Pras, H. E., & Pennings, A. J. (1994). Influence of chemical crosslinking on the creep behavior of ultra-high molecular weight polyethylene fibres. *Colloid & Polymer Science, 272*(6), 664-676. doi:10.1007/bf00659280
[417] Wang, H., Xu, L., Li, R., Hu, J., Wang, M., & Wu, G. (2016). Improving the creep resistance and tensile property of UHMWPE sheet by radiation cross-linking and annealing. *Radiation Physics and Chemistry, 125*, 41-49. doi:10.1016/j.radphyschem.2016.03.009
[418] (2006). PEX Information. Tradesman Supply Inc. Retrieved from http://www.pexinfo.com/
[419] Jauffrès, D., Lame, O., Vigier, G., Doré, F., & Fridrici, V. (2008). Yield, creep, and wear properties of ultra high molecular weight polyethylene processed by high velocity compaction. *Journal of Applied Polymer Science, 110*(5), 2579-2585. doi:10.1002/app.28697

latitude, Venus tends to be hotter than Earth (discussed under *Deployment: Where and How*). Further compounding this problem is the greenhouse effect within the envelope: solar energy is absorbed but convection with the atmosphere is blocked by the envelope, causing the interior temperature to rise until the radiative/convective balance equalizes. Rejecting all light (as in unmanned probes) is not an option, and UV represents only a tiny fraction of the solar energy. Hence, one seeks to reject as much near-IR as possible.

Such low-E additives and coatings are most commonly one of two chemicals: antimony-doped tin oxide (ATO) and indium tin oxide (ITO), both of which have relatively similar chemical and emissivity properties. These can be blended in with either the sol-gel process simple mixing of surfactant-modified ATO or ITO.[420] Both compounds are widely used, particularly ITO, which is used to make transparent conductors (such as for displays), flexible electronics, and transparent solar cell conductors. A typical concentration for low-e purposes in fluoropolymers is 0.2-0.5% by mass.[421]

While neither antimony nor indium have been detected directly in Venus's atmosphere, antimony is strongly suspected to be a minor middle cloud component, while indium has been theorized to exist well (see *Species of interest*). Tin, however, is not likely present in relevant quantities - hence, while ITO and ATO are relatively simple to synthesize, they would require tin either from the surface or the Earth, in small quantities.

A problem exists with low-E coatings in general, in that by blocking lower frequency electromagnetic radiation, they also tend to block radio waves, and thus would hinder any interior radar or communications systems if applied as a continuous coating. A technique to avoid this is to pattern the low-E areas such that any conductive pathways are broken by narrow channels.[422] A further difficulty with low-E additives and coatings comes if the envelope is to be used as its own entry vehicle; emissivity is inversely correlated with peak temperatures (see *Ballute considerations*).

An alternative approach being investigated for use on Earth is metamaterials which constrain infrared radiation to wavelengths which are poorly absorbed by the atmosphere, thus enabling radiative exchange with space rather than the upper atmosphere. This can be accomplished via the embedding of polar dielectric microspheres in the film.[423]

Other additives

Adding tiny amounts of liquid crystal polymers (as little as 0.01% vectra) to difficult to process resins can increase the processability in creating biaxially oriented films by means of creating microprotrusions, which serve to greatly decrease friction on the sheet.[424]

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[420] Puetz, J., & Aegerter, M. A. (2005). Chemical nanotechnology for transparent conducting coatings on thin-glass and plastic-foil substrates. *Journal of the Society for Information Display, 13*(4), 321. doi:10.1889/1.1904934
[421] Van Nutt, C. N., Enniss, J. P., Li, J. A., Port, A. B., Pickett, S. E., Stegall, J. B., Hubbard, C. L., Phillips, R. M., & Barth, S. A. (2013). *U.S. Patent No. US8613822 B2.* Washington, DC: U.S. Patent and Trademark Office.
[422] Estinto, E., & Winsor, R. (2015). *U.S. Patent No. US 8927069 B1*. Washington, DC: U.S. Patent and Trademark Office.
[423] Zhai, Y., Ma, Y., David, S. N., Zhao, D., Lou, R., Tan, G., . . . Yin, X. (2017). Scalable-manufactured randomized glass-polymer hybrid metamaterial for daytime radiative cooling. *Science*. doi:10.1126/science.aai7899
[424] Wong, C. P. (1994). *U.S. Patent No. US5330697 A*. Washington, DC: U.S. Patent and Trademark Office.

Other additives such as plasticizers may be required in certain situations.

Ballute considerations

As previously discussed, having the habitat enter the atmosphere as its own ballute entry vehicle offers tremendous mass advantages and simplifies inflation. However, while ballutes do not suffer nearly the level of heating that rigid aeroshells do, the heating still poses challenges that must be dealt with.

In a ballute, disc or toroidal shapes are optimal for maximizing drag at entry speeds; hence, we will operate on the assumption of an initial inflation with with the envelope "pinched" flat, with the central winch holding the center together and temporary wires securing the habitat in taught positions elsewhere. Tube rigidization, as discussed previously under *Structural integrity*, can useful for helping inflate the envelope to a desirable shape in a vacuum.[425] In order to minimize heating, we will base our entry profile around burning off the transfer energy with one or more circularization passes, followed by entry. As per McRonald 1999 and unlike VAMP,[426] we will assume no lift during entry; lift slows down the entry process and lowers peak temperatures.

Performing a curve fit on the data from McRonald (1999), we arrive at the following approximation for heating:

$$T = 790 * CdA^{-0.18}\ m^{0.15}\ \ \varepsilon^{-0.23}$$

Where:

- T is the temperature, in kelvins
- CdA is the drag coefficient times the area in square meters
- m is the total mass in kilograms
- ε is the emissivity

This is admittedly a crude approach to estimating surface heating; a proper examination of the issue requires first CFD testing the form, then doing real-world validation. However, this should yield a rough sense of the viability of the concept.

Our previously described baseline model, oriented gondola first, has a fully-inflated cross section of approximately 21k m^3, and a surface area of around 54k m^3. We will operate on the basis of a "squished" cross section of 26k m^3 (assuming any burble fence / stability hardware does not add significantly to the cross section) and a hypersonic drag coefficient Cd = 2. With a baseline entry mass of 46.5 tonnes (see *Mass budget*), we get the following relationship between emissivity and peak temperature:

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[425] McRonald, A.D. (1999). A lightweight inflatable hypersonic drag device for Venus entry. AAS/AIAA Astrodynamics Specialist Converence, Girdwood, AK, August 16-19

[426] Lee, G., Polidan, R.S., Ross, F. (2016). Venus Atmospheric Maneuverable Platform (VAMP) - A Low Cost Venus Exploration Concept. *American Geophysical Union*, Fall Meeting 2015

E	T (°K)
0.1	952
0.3	740
0.5	658
0.7	609
0.8	590
0.95	568

If accurate, these figures would be troublingly high. If we select carbon fibre as our reinforcement, the temperature becomes irrelevant for the fibres themselves (so long as they do not delaminate / detach). Being produced at temperatures of thousands of degrees, these sort of temperatures have only minimal effect on its properties. Transparent polymers, however, are much more vulnerable.[427] [428] [429]

As a general rule, as a substance nears its melting point, its mechanical properties such as tensile strength dramatically decline. Hence, for all of the polymers listed to the right, the maximum operating temperature is lower than the melting point. Even at those temperatures the polymer is substantially weakened.. Thankfully, dynamic pressures are low during peak heating - approximately 10 pascals for an entry vehicle of 1 kg/m².[430]

Material	Melting point (°K)	Max continuous operating temperature (°K)
FEP	530	473
PET	517	413
ECTFE	515	438
PCTFE	484	448
EVOH	464	373
PVF	453	383
PVDC	450	393

As has been discussed previously, low-E coatings or additives are desirable to reduce the greenhouse effect within the envelope. But high emissivity lowers entry temperatures. How can this conflict be addressed? And what other means can be used to keep entry heating under control?

- **Use no low-E additives/coatings**. This means accepting lower pressures in the habitat (and lower lift, as the habitat must fly at a higher altitude). The above polymers at the thicknesses in question tend to have naturally relatively high emissivities, generally upwards of 80%.[431]

- **Apply the coating after entry**. The problem with this is that low-E materials should be on or near the outside of the film, not the inside.

- **Coat in accordance with temperature**. Note that the prior tables concerned peak temperatures; most of the surface is well below the peak.

- **Use a lifting body for entry**: As with the LEAF concept, a lifting body extends the deceleration period and thus lowers peak heating.

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[427] Biron, M. (2007). *Thermoplastics and thermoplastic composites: technical information for plastics users.* Oxford: Butterworth-Heinemann.
[428] Baboian, R. (2005). *Corrosion tests and standards: application and interpretation.* West Conshohocken, PA: ASTM International.
[429] *Max Continuous Service Temperature*. Omnexus. Retrieved from http://omnexus.specialchem.com/polymer-properties/properties/max-continuous-service-temperature
[430] McRonald, A.D. (1999). A lightweight inflatable hypersonic drag device for Venus entry. AAS/AIAA Astrodynamics Specialist Converence, Girdwood, AK, August 16-19
[431] Fujikura, Y., Suzuki, T., & Matumoto, M. (1975). Polymer Emissivity. *Sen'i Gakkaishi, 31*(9). doi:10.2115/fiber.31.9_t381

- **Use more heat-tolerant materials on the highest-temperature areas**. Not all heating is even; high-temperature areas can use opaque, heat-tolerant materials.

- **Use a sacrificial high-E coating**. A high-E material (typically opaque) designed to erode away in the atmosphere can be added as a temporary outer layer.

- **Go lighter**. The lower the density of the habitat, the lower the peak temperature. Fabrics designed for ballutes typically target densities of only 10-20g/m². As noted previously, our envelope mass estimate could prove to be pessimistic; a lighter envelope makes for dramatically lower entry temperatures.

- **Add an extended inflatable ring around the habitat**. The greater the area, the lower the peak temperatures. However, this partially defeats the purpose of limiting ourselves to available airship hangar dimensions, as full integration testing could not be conducted within the hangar. The ring can be either retained or lost; however, if designed only for entry usage, it can be made much lighter.

- **Use an entirely separate ballute for entry than for descent**. Using a system optimized to be a ballute, with much lighter, higher temperature fabric and larger cross section, effectively transforms the problem to the situation described in McRonald (1999).

- **Use an aeroshell for entry**. This comes with a higher mass penalty, but is mature technology. The habitat must inflate in free-fall after detaching from the aeroshell.

Manufacturing - nonrigid components

fibre manufacture

Most primary fibres under consideration would be ideally produced via gel spinning. A UHMWPE production case from Russell et al (2013) will be given as an example. UHMWPE is dissolved in a solvent at 150°C and is pressurized into a spinneret containing several hundred capillaries. Fluid filaments form directly into water as gel fibres. These are then pulled through 120°C air at $1s^{-1}$ strain at a 30x or greater draw ratio, creating 17um fibres. In the example case, the fibres are to be bonded together by a thermoplastic to make a composite. The fibres are laid up into the desired form, and the coating's solvent is evaporated off. The form is then hot-pressed to melt the coating to unify the fibres.[432]

[432] Russell, B., Karthikeyan, K., Deshpande, V., & Fleck, N. (2013). The high strain rate response of Ultra High Molecular-weight Polyethylene: From fibre to laminate. *International Journal of Impact Engineering, 60*, 1-9. doi:10.1016/j.ijimpeng.2013.03.010

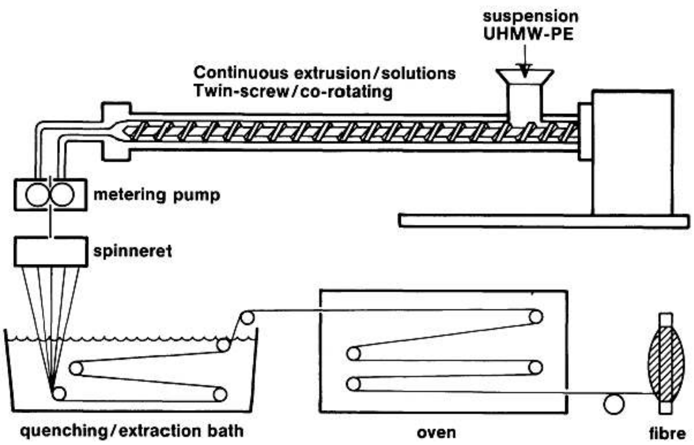

Image from Yao et al (2014)[433]

The key aspect in all cases is a high draw ratio; it is the stretching process that orients the polymer molecules, giving the polymer its high tensile strength. fibre can be wound onto bobbins to be prepared for creating cordage, or fed to be chopped for loose fill.

There is relatively little about gel spinning processes that needs to be customized to the local conditions, apart from general weight reductions where possible - which means by and large swapping out steel for lighter alloys and, where possible, composites.

An ideal goal to strive for is a single multi-use gel spinning system which can handle multiple feedstocks, rather than having to provide a dedicated system for each polymer.

Film production

For the purpose of this section, we will assume that the envelope is relatively thick (hundreds of microns). While the envelope may reach into sufficient thickness to be considered “sheeting” rather than “film”, for consistency we will refer to it simply as film in this section.

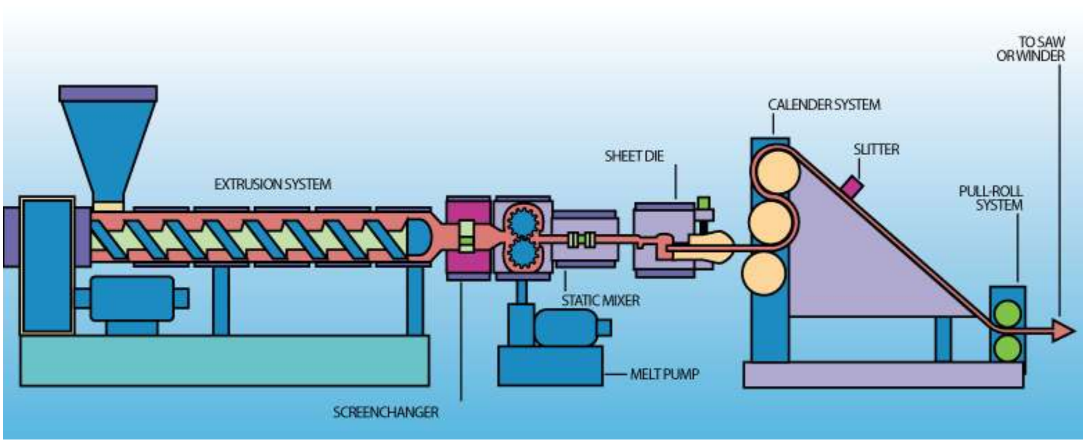

Photo: Vitasheet Group

In order to discuss issues pertaining to a film production system, we will examine the process for PCTFE film.[434] To maintain properties, different parts of the system must be kept at different temperatures. In this case, the following temperatures are maintained (where applicable):

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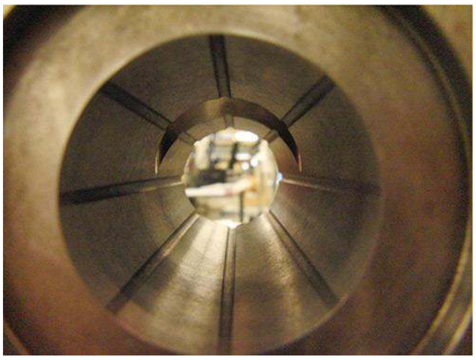
[433] Yao, J., Bastiaansen, C., & Peijs, T. (2014). High Strength and High Modulus Electrospun Nanofibers. fibres, *2*(2), 158-186. doi:10.3390/fib2020158
[434] Neoflon PCTFE Molding Powder. Daikin Industries Ltd. EG-71j. Retrieved from http://www.daikinchem.de/downloads/PCTFE.pdf

- Gradual transition metering screw, 2.5-3.0 compression ratio, 10-15 rpm
- 25-50mm barrel, L/D ratio = 20-25, rear/center/front: 230/280/290°C
- Adapter: 295°C
- Die head: 310°C
- Die tip: 320°C
- Melt temperature: 260-280°C, 10 minutes for each 2mm of thickness, 6.9 MPa, cooled to 250°C / 30 mín.

In order to maintain steady temperatures, thick steel is often favored, but this is anathema to a lightweight, flight-ready system; hence a greater number of heaters and thermocouples may be required. In-situ-produced fluids can help provide a heat reservoir where required. Passive temperature maintenance systems, such as fluids which change phase at target temperatures, may be of utility.

High viscosity resins often benefit from a grooved barrel, where regular grooves jut toward or away from the screw. This helps ensure more stable, even, faster heating of the feed - at a downside of generally increased torque requirements, and sometimes greater wear.



Gloucester LGF (Light Groove Feed) film extrusion barrel.
Photo: Plastics Technology

As with uniaxial orientation, biaxial orientation of films involves tensioning the sheet while below its melting point but while it is still in an amorphous state. This is usually done with heated rollers pulling the film in the forward direction, then transverse rollers pulling it opposite the direction of travel. The film must be held in tension until crystallization has completed. The rate of time at which the film is held at various temperatures during this process is critical to controlling the percentage of crystallization and the size of the crystals that form. Where film needs to be cooled more quickly, cooling ("chill") rollers are used.

Since the envelope exists not only as a single layer but a composite, the different layers can be joined at any stage, including options ranging from being extruded through the same die (coextrusion), to being produced by separate dies to merged before heat set, to being produced entirely independently and merged in a separate stage. The optimal process will depend on the choice of polymers and will take experimentation to determine what produces the best bond and combined material properties.

Note that other film production processes exist - most notably, die blowing. However, this is mainly of use for films thinner than those of concern for envelope production. If it turns out to be possible for the habitat to utilize a film in the range of a couple dozen to a couple hundred microns thick, particularly on the lower end, then blown film extrusion may be a superior choice.

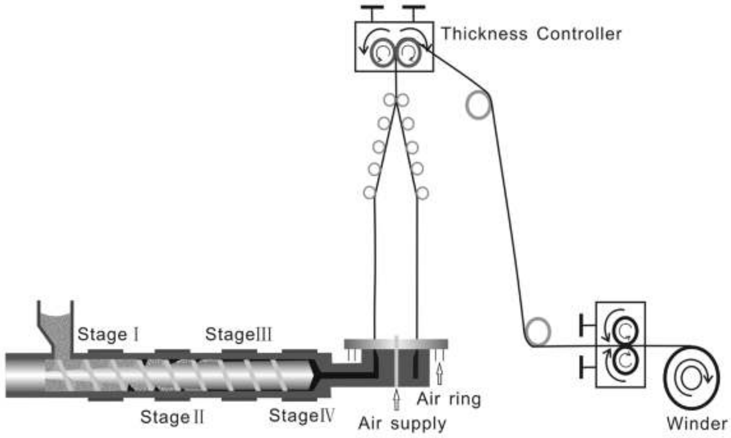


Image from Li et al 2014.[435]

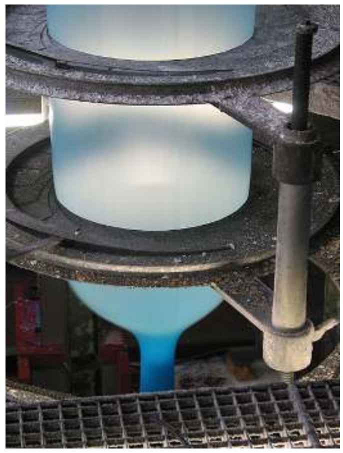


Photo: Maarten Gielen

The primary difference between extrusion and die blowing is that rather than being linear, a die-blowing die forms a ring, with air pressure maintained in the center to form an elongated bubble. The bubble is then narrowed with rollers and cut before spooling. Expansion of the bubble provides the lateral expansion of the film, while the primary rollers maintain tension in the direction of travel.

As with fibre production, it would be desirable to have any film/sheet extrusion systems be adaptable. While the primary film need is for envelope fabric (for maintenance and ultimately to accrue sufficient amounts to be able to build new, larger habitats), sheeting will also be needed for various substrates, construction purposes, agricultural needs, workshop safety sheeting, and so forth.

Spinning and weaving

Spinning fibres into cordage of various types is an activity that has been done by hand as far back as prehistory. In its simplest form, one takes one or more fibres in a bundle and twists both ends opposite each other, causing a kink to form in the middle. With continued twisting, the kink continues to grow; with new fibres fed into the bundle as old ones disappear, strings and ropes materialize, with the stress in the twists allowing friction to hold the fibres against each other and compensating for the effects of breakage of individual strands.[436]

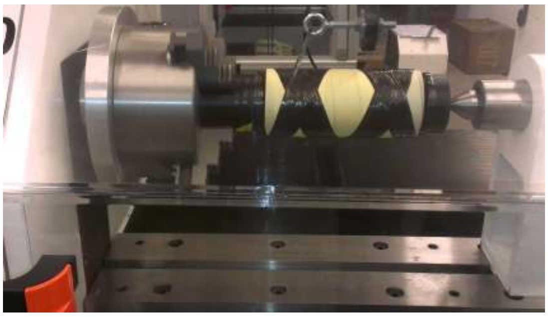
[435] Li, H., Chang, J., Qin, Y., Wu, Y., Yuan, M., & Zhang, Y. (2014). Poly(lactide-co-trimethylene carbonate) and Polylactide/Polytrimethylene Carbonate Blown Films. *International Journal of Molecular Sciences, 15*(2), 2608-2621. doi:10.3390/ijms15022608

[436] Kidder, N. (2013) *Making Cordage By Hand*. Primitive Ways.

In a Venus habitat, however, cordage demands are far too high for primitive hand manufacturing methods. In modern cordage manufacture, bobbins (each loaded with continuous fibre or threads) move rapidly amongst each other while twisting, tracing out the path of the weave which is desired for the rope. This simultaneously forms the core and jacket in multilayer rope designs. Like with thread manufacture, a shuttle guides the rope to its destination on a spool. There is little that requires adaptation to local Venus conditions.

Photo: Dvortygirl

Weaving, too, is a process dating back to prehistory, improved by a variety of technological improvements up to the modern loom. As there are many different designs and there is relatively little adaptation required for local Venus conditions apart from mass reduction, we will not go into details at this point. In addition to creating sparse netting for envelope reinforcement, the same loom should be designed to handle dense weaves for composite reinforcement and general-purpose fabrics. The ability to weave different patterns is important for composite reinforcement, as different patterns yield different mechanical properties in the resultant composite.[437]



Composite Fibre Winder - WT300 PCWM.
Photo: Winding Technology Ltd

A third process tangentially related to the two is that of overwrap winding, particularly useful to producing composite overwrap tankage. The process of overwrapping is similar to that of winding a reel onto a bobbin, except that the fibres are first coated in a thermoplastic or thermoset resin, with the tank going through a bake stage after winding. Carbon fibre is the traditional fibre for this purpose, and very likely the best option for a Venus colony. Depending on the substance to be contained, the inner liner may be either plastic or metal - ideally plastic, given its greater availability until large-scale surface dredging brings greater supplies online.

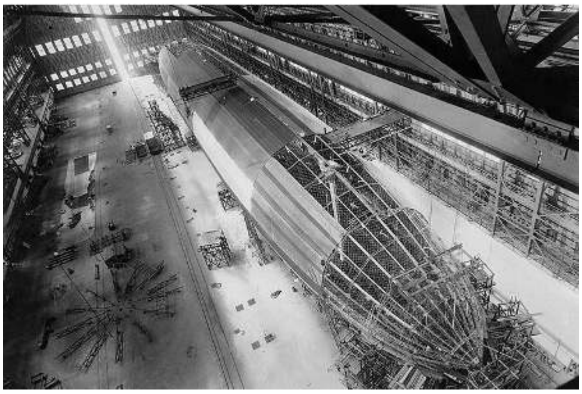
Gore assembly and maintenance

Airships are generally built out of gores - strips of fabric joined at the seams, with taper as needed to provide for shape constraints.

As discussed under *Surface layers / coatings*, fluoropolymers are notoriously difficult to bond, although not impossible. It is common for unmanned Venus balloon proposals to include the use of a polyurethane inner liner to allow for easy adhesive bonding with connecting connecting strips of fabric at each gore (aka, briefly doubled up) - this process is

[437] (2015) Understanding Carbon Fibre Cloth Reinforcement. Easy Composites.

while appealing, has a relatively complicated route to manufacture and would ideally be avoided. Simpler polymers such as EVA might suit for the same purpose, but they must demonstrate longevity in the habitat environment. Furan thermoset resins, created by hydrogenation of furfural from the sulfuric acid distillation of biomass, present another option. An alternative approach is thermal bonding, also discussed previously in the context of lamination. If no suitable options readily available to local production can be found, more complicated bonding agents are an acceptable temporary dependency from Earth.



USS Shenandoah, under construction.
Photo: U.S. Naval Historical Center, image # NH 82262

Maintenance on Venus poses particular challenges. For simplicity, it would be desirable to be able to conduct all maintenance from within the habitat, which gives access to only one side. In order to avoid the need for external maintenance craft, techniques should be developed for replacing segments of gores entirely within the habitat. Of particular "interior" challenge is maintenance within the ballonets, as the gas inside is the same as that in the exterior atmosphere. This will require the installation of a temporary airlock (or presence of a permanent one) over the area(s) of interest, and the operation therewithin while fully suited up.

Photo: Lockheed Martin

An interesting option for envelope maintenance is in development by Lockheed Martin. Known as SPIDERs (*Self-Propelled Instruments for Damage Evaluation and Repair*), they consist of outside and inside halves, magnetically held together, to crawl across the surface. This allows them to conduct inspections and patch pinholes.[438]

Manufacturing - rigid components

Beyond the production of envelope film, a wide variety of other types of production are needed as well.

[438] (2016) *Skunk Works' SPIDER: Self-Propelled Instrument for Airship Damage Evaluation and Repair*. Lockheed Martin.

Extrusion

Tube extrusion die plates. The plate on the right blocks off the flow from the center, while the plate on the left subsequently constraints the exterior shape. Photo: Stephen Woolverton

A significant number of parts will need to be extruded, including pipes and structural profile segments. Extrusion of such larger elements proceeds relatively similar to sheet extrusion. Hollows are achieved by having the inner portion of the die supported earlier in the extrusion barrel, with the flow that diverted around the support legs re-merged after passing them. In an early-stage colony, extrusion would be expected to be primarily plastics-based (optionally including loose-fill high strength fibres). However,
in the more distant future, metal extrusion needs will be expected to increase.

Metalworking

Photo: Jason Kaechler

While metals are not abundant when working primarily within the cloud of Venus, some metal varieties (most notably iron) can be found. Additionally, metallic components sent from Earth will require varying degrees of assembly, maintenance, alteration and disassembly over time. This is particularly true with industrial hardware elements.

Among cutting mechanisms on Venus, oxyacetylene cutting lends itself naturally to the environment, with oxygen being a fundamental requirement and acetylene being producible from methane. However, not all cutting needs are well suited to oxyacetylene.

Cutting with an angle grinder, while effective, steadily consumes grinding discs, which involve abrasives not readily replaceable without surface access. That said, only relatively small numbers of discs are utilized for a relatively large amount of cutting. If discs are to be manufactured locally, they are not particularly structurally complicated. The abrasive is supported in a plastic matrix, which in turn has a fibre reinforcement weave in it to maintain structural strength. Any local production of discs must proceed with caution, as breaking discs are hazardous, both to the operator and the surrounding area, and discs must be well balanced.

A local abrasive option not requiring surface materials for production is diamond. Discs utilizing a diamond abrasive are often favored for use over those with other abrasives, with use on Earth limited mainly by price.

Photo: Emilian Robert Vicol

Fine metalwork, as well as work on ceramics, is often suited by a Dremel-style tool. As the bits for these are generally quite small, treating them as an Earth import should not be a concern early on.

Welding can be conducted by a variety of different processes. For Venus operation, MIG (fed by a spool of fill wire) and TIG (using a manual feed rod for fill) are most appropriate, as wire and shielding gases are easier to produce locally than SMAW electrodes. The ever-abundant carbon dioxide is an effective shielding gas for steel, although not for many other metals, such as aluminum, which require argon or - for very sensitive tasks - helium.[439] Thankfully, noble gases are recoverable from Venus's atmosphere in distillation, and only small quantities are required. Like oxyacetylene spray (and unlike grinding sparks), welding drips contain a great amount of heat energy and readily burn through or ignite things that they come into contact with. The work environment must be designed with durability and fire safety in mind.

Photo: Rob Lambert

Clothes used in metalworking can be expected to be worn through at a regular rate, including gloves, which must be designed for high temperatures. Gloves are most commonly made out of leather, although high temperature polymers are used in some brands.

Sandblasting is used to remove corrosion and prepare surfaces, an issue certainly of relevance in a place where the internal environment is humid and the external environment acidic. There will be no shortage of compressors required on Venus regardless, due to the various industrial processes; a high pressure line to an existing compressor that uses an atmospherically-acceptable gas should be sufficient. Sandblasting systems are very simple, often consisting of nothing more than a plastic box of abrasive and a simple venturi nozzle to suck in abrasive as it is ejected. Abrasive is consumed relatively quickly, although it can be recycled to some extent; higher end designs include a vacuum system for recovery of used abrasive. Sandblasting creates a great deal of dust as well as occasional stray streams of abrasive.

Photo: Andrea / Ancar

[439] (2017) *Mig Welding Shielding Gas Basis*. Bernard Welding. Retrieved from http://www.bernardwelds.com/mig-welding-shielding-gas-basics-p152080#.WMXrVHWLRhE

It is worth examining the local atmospheric iron stream and its applicability toward local production. Steel is at a minimum comprised of iron and carbon, but almost always contains various alloying agents to improve its properties. As these are generally metallic cations not found in Venus's atmosphere (Mn, Ni, Co, Al, Cr, Nb, Zr, V, W, Ti, Si, Se), they are unavailable without surface dredging operations except via shipments from Earth, and thus are ideally minimized. There are, however, a few potential exceptions:[440]

- ***Nitrogen***, while sparingly soluble in steel at low pressures, can substitute for carbon at high pressures, where it functions as a strong austenite stabilizer, interstitial solution strengthener and pitting corrosion resistance agent.[441] The strengthening effect can be significant, at 5-10 MPa per 0.001% N. However, nitrogen reduces steel workability. If controlled precisely along with carbon, "interstitial free" steels can be produced, with superb workability and no strain aging.
- ***Sulfur***, in small quantities, can be used to increase machinability and tool life, at the cost of increased rates of corrosion.
- ***Phosphorus*** also increases machinability, strength and corrosion resistance, particularly in conjunction with copper in weathering steels. However, it is embrittling if the carbon concentration is too high.
- ***Lead*** *and* ***bismuth*** significantly improve machinability without sacrificing mechanical properties.
- ***Boron*** is sometimes added in miniscule quantities (0.0015% to 0.0030%) to increase hardness. It has not been detected in Venus's atmosphere, but does have a number of gas-phase acidic species, and only tiny quantities are required.
- **Tellurium** is added to steel to increase machinability without sacrificing material properties. It is among the most potent microalloying agents in this role, but has the downside of making the steel difficult to hot work.
- **Selenium**, like lead, bismuth, and tellurium, increases machinability without sacrificing mechanical properties. Unlike tellurium, selenium steels can be readily hot worked. Only 0.05-0.1% are required. Selenium works synergistically with sulfur and reduces nitrogen absorption. It also reduces hydrogen susceptibility.

Among the most important need for steel on Venus may be that of tool steels. There are many excellent low-alloy tool steels that use little to no alloying agents not available from Venus's atmosphere.[442] While they can achieve tremendous hardness, they can suffer from reduced lifespans compared to various higher alloy tool steels.

On the issue of keeping imports or surface requirements low, the "microalloyed" steels are of note. These use alloying agents only required in small quantities (0.05%-0.15%), which includes Nb, V, Ti, Mb, Zr, B and rare-earth metals. For steels that

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[440] Bristow, D. J., Carter, R. J., Frankes, H. E. Jr., Lewis, D. A., Mang, J. F., Sattelberger, S., Wardle, D. (2000) Ferroalloys and Alloying Additives Online Handbook. AMG Vanadium. Retrieved from http://amg-v.com/contents.html
[441] Simmons, J. (1996). Overview: high-nitrogen alloying of stainless steels. *Materials Science and Engineering: A, 207*(2), 159-169. doi:10.1016/0921-5093(95)09991-3
[442] MatWeb Material Property Data. Retrieved from http://www.matweb.com/search/CompositionSearch.aspx

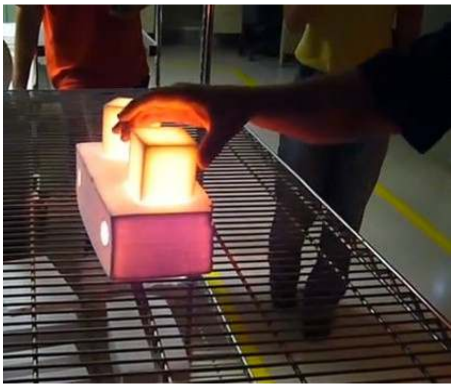
need exposure to the external environment, copper-based weathering steels (0.15-0.25% Cu) are worthy of investigation, although they do not offer the same level of protection as stainless steels.

When surface material becomes available, smelting becomes an option. Smelting involves chemothermic reduction of an ore in the optional presence of fluxes, most commonly via carbothermic reduction. In this reaction a combustible carbon source strips the oxygen from an ore at high temperatures. Fluxes assist in the formation of an oxide slag, which is skimmed from the metal stream before casting. In steel smelting, gaseous oxygen is frequently injected to control carbon content. Some smelting processes, such as aluminum, are electrolytic (employing consumable carbon electrodes as well as fluxing agents to reduce the melting point). High purity silicon production can be combined with aluminum smelting via the Silicor process.[443] Hence, a single adaptable, multipurpose smelter involving common high-temperature hardware could keep system masses low system mass while providing for a broad range of processes.

Photo: Skeeze

While it's easy to think of smelters as massive structures, there is no fundamental requirement that they must be; smelting began its history at very humble scales, and can be conducted at such scales with modern processes. Scale does however tend to improve efficiency.

Ceramics



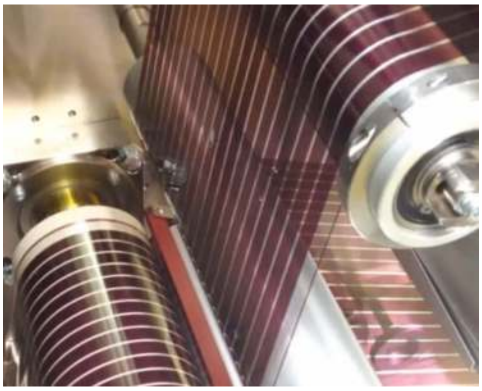
Ceramic heat tiles.
Photo: Roscket Tasartir

Again hindered by a lack of access to most suitable raw materials, ceramic production can be expected to be only a minor portion of an early colony's local production. Until surface access becomes widespread, most ceramic parts, such as burner nozzles, ceramic engines, heat shields, refractory linings and so forth can be expected to be imported from Earth. Local application of ceramic coatings or local castings may be conducted with slip imported from Earth. Some 3d printing processes involving spraying and laser sintering are suitable for use with ceramic, and some ceramics are suitable for use with CNC milling.

[443] The Silicor Process: Environmentally Friendly Solar Silicon. Retrieved from http://www.silicormaterials.com/component/docman/doc_download/5-environmental-white-paper.html

Solar cells

While the concept of fully-independent production of solar cells has little immediate likelihood on Venus, some of the various reel to reel "printing" processes are of note for many types of organic, CIGS, quantum dot, perovskite, CdTe and thin-film silicon cells. In these, various conductive layers, electron donor/acceptor layers and coatings are continuously deposited onto a substrate. Since the substrates make up the vast majority of the mass of the produced solar cells, this raises the prospect of importing the "low quantity" consumables and printing onto locally-produced substrates - ideally integrated into the envelope production process itself.



Organic solar cell printing at VICOSC. The semiconductor inks can be printed onto almost any substrate, from plastics to steel. Photo: CSIRO

Wiring

While silver, followed immediately by copper, is generally thought of as the best non-superconducting metallic conductor, this is only with respect to volume. With respect to mass (the more critical aspect for space applications), the top elemental metallic contenders are listed to the right.[444] By contrast, copper comes is 151.6 nΩ·m·g/cm³. Unfortunately for a Venus habitat, sodium, lithium, calcium and potassium are unsuitable for either interior or exterior wiring usage due to their highly reactive natures. Hence, aluminum wiring would appear to be the mass-optimal solution. This must be tempered by a few factors:

Material	nΩ·m·g/cm³
Sodium	45.5
Lithium	50.3
Calcium	52.7
Potassium	59.9
Aluminum	70.2
Beryllium	73.9
Magnesium	76.5

- Pure aluminum also has around 1000x the creep rate of copper, although dramatically reduced with alloying agents; copper is sometimes a superior choice where tensile loads may be present. However, superior still is composite-core aluminum wiring, which use composites for loadbearing but aluminum for transmission.[445]

- Higher gauge aluminum wiring can require more insulation mass.

[444] Tables of resistivity and density sourced from http://periodictable.com/Properties/A/Resistivity.an.html and http://periodictable.com/Properties/A/Density.an.html, respectively.
[445] HVCRC Smart Conductor. Mercury Cable and Energy. Retrieved from http://mercurycable.com/products/hvcrc-smart-conductor/

- Aluminum wiring is less forgiving of improper installation than copper (ultimately leading to numerous problems in home wiring, since remedied by newer standards and the use of AA-8000 series aluminum wire).[446]

NASA and US defense satellites have historically relied on copper wiring,[447] but aluminum is used by European spacecraft. NASA is seeking to increase its own TRL for using aluminum wiring as a weight saving measure.[448]

No reasonable traditional wiring candidate can be produced locally without surface dredging. Iron is a relatively poor conductor, as well as being prone to corrosion. Organic conductors exist, but their conductivity is generally orders of magnitude lower than that of metals. An interesting unconventional option, however, appears to be emerging: carbon nanotube wire.[449]

Carbon nanotube-based wire simultaneously suspends and illuminates a bulb. Photo: Rice University

Formerly a product of research interest, carbon wire now has some commercial producers. For example, Curtran / LiteWire recently announced their first large-scale test in a $7B oilfield development contract.[450] It boasts similar conductivity to copper on a volumetric basis and five times better on a mass basis, as well as being highly corrosion and water resistant and having 20 times higher tensile strength than copper.[451]

Further test work validating carbon wire's long-term suitability in interior and exterior Venus environments could lead to its use as an excellent candidate for wiring on Venus. That said, the TRL on carbon wiring for aerospace applications is at present low.

Wiring inside the habitat involves long spans of fine, low-capacity wires forming a multiple-route grid. In order to increase their visibility to avoid inadvertent collision, they

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[446] Quinn, J. P. (2014). *Down To The Wire: Copper And Aluminum Wiring Fight To The Finish*. Electrical Contractor.
[447] Patel, M. (2004). Spacecraft Power Systems. doi:10.1201/9781420038217
[448] Dillard, M. Advancing Aluminum Wiring. NASA. Reference No. NNJ14ZBH026L.
[449] Sprovieri, J. (2016). *Can Carbon Nanotubes Replace Copper?* Assembly Magazine.
[450] Ryan, M. (2014) *Meet the Houston startup that is going to make billions replacing copper wire*. Houston Business Journal.
[451] *LiteWire vs. Copper*. CurTran. Retrieved from http://curtran.com/benefits/litewire-vs-copper/

should be marked by brightly colored and/or glowing indicators at regular intervals. Conductors should be spaced out as greatly as is practical.

General discussion

While much emphasis has been provided on ensuring that everything can be produced locally, it should be noted that not everything for the initial habitat must be. It is perfectly possible, and may in some instances be quite desirable, to build major habitat components out of things that cannot be readily produced locally. This, however, should be undertaken cautiously; by building out of inaccessible materials, you advance the tech readiness level for use of those materials in a Venus habitat environment, not the tech readiness level of the materials that actually matter. This must be taken into strong consideration when making material sourcing decisions for the initial habitat.

7. Food

Rather than treating local food production as an afterthought for the future, it is arguably best to see as a fundamental aspect of colonization requiring significant time to optimize, and thus something that should be begun immediately. At the same time, it is fraught with challenges, and plants can be unforgiving of errors. Hence, simple precautionary planning dictates that at all time a sufficient supply of stored food should be available - initially from Earth - to sustain the crew until they could arrive back at Earth at the next return window, or otherwise receive an emergency resupply.

Before we can investigate what should be produced, we need to examine what is required.

Nutrition

Human nutrition can be broken up into two broad categories: macronutrients, such as protein, fat, carbohydrates and fibre, as well as water; and a broad range of micronutrients. As the primary concern in an offworld environment would be a diet that lacks some of the latter, we will examine them and consider the implications for what dietary sources[452] can provide them.

Essential fatty acids

There are two essential fatty acids: alpha linolenic acid (ALA) and linoleic acid (LA)[453]. Additionally, docosahexaenoic acid (DHA) can become limited when the ALA/LA ratio is low,[454] while gamma-linolenic acid (GLA) can occasionally become limited by external factors.[455]

Of the two essential fatty acids, ALA makes up the majority of some seed oils, such as flax and chia, and is found in sizeable quantities in a number of others, including hemp, walnut, soybean, and rapeseed.[456] [457] Such ALA-rich oils tend to be "drying oils", with little heat tolerance and limited non-refrigerated lifespans after pressing, and hence are best served cold. When cooked, use of spices such as rosemary and oregano can increase heat stability.[458]

LA can be found abundantly in most common plant oils, including sunflower, grape, safflower, hemp, corn, cottonseed, and soybean.[459]

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452 *Vitamins and Minerals* (2015). NHS choices. Retrieved from http://www.nhs.uk/Conditions/vitamins-minerals/Pages/vitamins-minerals.aspx

453 Whitney, E. N., Rolfes, S. R. (2008). *Understanding Nutrition (11th ed.).* Belmont, CA: Wadsworth (pp. 154)

454 Sanders, T.A. (2009) DHA Status of vegetarians. *Prostaglandins Leukotrienes and Essential Fatty Acids*; 81(2-3):137-41. doi:10.1016/j.plefa.2009.05.013 PMID 19500961

455 Horrobin, D.F. (1993) Fatty acid metabolism in health and disease: the role of delta-6-desaturase. *Am. J. Clin. Nutr*. 57 (5 Suppl): 732S–736S; discussion 736S–737S. PMID 8386433.

456 Orsavova, J., Misurcova, L., Ambrozova, J., Vicha, R., & Mlcek, J. (2015). Fatty Acids Composition of Vegetable Oils and Its Contribution to Dietary Energy Intake and Dependence of Cardiovascular Mortality on Dietary Intake of Fatty Acids. *International Journal of Molecular Sciences*, 16(6), 12871-12890. doi:10.3390/ijms160612871

457 Abedi, E., & Sahari, M. A. (2014). Long-chain polyunsaturated fatty acid sources and evaluation of their nutritional and functional properties. *Food Science & Nutrition,* 2(5), 443-463. doi:10.1002/fsn3.121

458 Bhale, S., Xu, Z., Prinyawiwatkul, W., King, J., & Godber, J. (2007). Oregano and Rosemary Extracts Inhibit Oxidation of Long-Chain n-3 Fatty Acids in Menhaden Oil. Journal of Food Science, 72(9). doi:10.1111/j.1750-3841.2007.00569.x

459 Orsavova et al 2009; Abedi et al 2014

Like its parent molecule LA, GLA is also found commonly in plant oils, although not as widely; evening primrose, borage, and currant oils naturally contain significant quantities,[460] as does a genetically modified safflower oil.[461]

Unlike ALA, DHA is not found in plant sources; strict vegetarians must produce all of theirs from ALA. Rich dietary sources of DHA include fish and algal oils.[462] A low dietary intake of DHA has not been associated with negative health consequences.[463]

Minerals

Minerals are a relatively simple thing to provide offworld, with necessary anions being common and nearly all cations ending up recycled (more on this shortly). That said, not all plants are equal when it comes to taking up minerals into their edible portions. For many minerals, deficiencies are rare, except in cases of disease. However, among those deficiencies which do not fall into that category:

- **Calcium**: Deficiency is primarily an issue among women and the elderly, and often secondary to vitamin D deficiency.[464] Good sources include leafy vegetables, nuts, seeds, many spices, milk, eggs, and canned whole fish (aka, bones).

- **Iron**: Iron deficiency is the most common nutritional deficiency in the world;[465] a shortage of iron is most notably associated with anemia. Animal sources of iron ("heme") are common and readily digested. Plant sources of iron ("non-heme"), although abundant (frequently in leafy vegetables, nuts, legumes and whole grains), are more poorly absorbed. Some relatively rich plant iron sources, such as spinach and swiss chard, also contain oxalic and phytic acid, which bind iron and hinder its absorption. Other inhibitors include tannins, calcium, polyphenols, and other micronutrients such as zinc and copper. Consumption of promoters (citric acid, ascorbic acid, lysine, carotene, etc) and spreading out sources of iron over the day help increase rates of iron absorption, as does a higher total iron intake.[466] Perhaps surprisingly, cooking in an uncoated iron pan yields a meaningful increase in dietary iron consumption.[467]

- **Zinc**: A fairly common deficiency similar to iron in its properties, both in terms of dietary sources and risk of binding with oxalic and phytic acid. However, low zinc in

[460] Abedi et al 2014
[461] Nykiforuk, C., Shewmaker, C. (2011). High level accumulation of gamma linolenic acid in transgenic safflower (Carthamus tinctorius) seeds. *Transgenic Research*. 21 (2): 367–81. doi:10.1007/s11248-011-9543-5. PMID 21853296.
[462] Abedi et al 2014
[463] Sanders 2009
[464] Cooper, M. S., Gittoes, N. J. (2008). Diagnosis and management of hypocalcaemia. *Bmj*, 336(7656), 1298-1302. doi:10.1136/bmj.39582.589433.be
[465] Iron Deficiency—United States, 1999-2000. (2002). *Jama*, 288(17), 2114. doi:10.1001/jama.288.17.2114-jwr1106-2-1
[466] Collings, R., Harvey, L. J., Hooper, L., Hurst, R., Brown, T. J., Ansett, J., . . . Fairweather-Tait, S. J. (2013). The absorption of iron from whole diets: a systematic review. *American Journal of Clinical Nutrition*, 98(1), 65-81. doi:10.3945/ajcn.112.050609
[467] Kollipara, U. K., & Brittin, H. C. (1996). Increased Iron Content of Some Indian Foods Due to Cookware. *Journal of the American Dietetic Association*, 96(5), 508-510. doi:10.1016/s0002-8223(96)00140-x

plant sources is often caused by growing plants in zinc-deficient soils, an issue of limited applicability in a properly managed hydroponics environment.[468]

- **Iodine**: Iodine deficiency is common in areas far from the ocean where there is little consumption of marine foods.[469] It is, however, relatively simple to prevent by including iodine into a hydroponics nutrient mix. While plants do not require it (and their growth hindered by too high of quantities), it is readily taken up and stored.[470]

Vitamins

Vitamins, being produced by specific biologic processes, are not as readily supplemented offworld, except either by significant laboratory effort or by supplements sent from Earth. Hence, consuming proper dietary sources is more important.

- **Vitamin A** *(retinol, retinal, carotenoids)*: Vitamin A deficiency is the leading cause of childhood blindness and a common cause of death among malnourished children.[471] Vitamin A is common in colourful vegetables (squash, carrots, etc), leafy vegetables, milk, and abundantly in liver.

- **Vitamin B1** (*thiamine*): Usually only common among people with poor diets (such as alcoholics), but also those who overconsume husked white rice (not whole rice) in their diet.[472] [473] Thiamine is found in a wide range of foods including meat, potatoes, brown rice, vegetables, eggs, etc.

- **Vitamin B2** (*riboflavin*): A condition which hinders the absorption / metabolism of other nutrients (such as iron), mild riboflavin deficiencies are common in third world (although rare in the first world).[474] Good sources include dairy, eggs, meat, leafy vegetables, legumes, and mushrooms.

- **Vitamin B3** (*niacin and related forms*): Niacin deficiency (pellagra) is primarily found in locations which overconsume maize; however, nixtamalization - the soaking / cooking of maize in a caustic solution, such as ash or limewater - generally prevents this.[475] Sources of niacin are common, including meat, eggs, dairy, vegetables, mushrooms, nuts, etc.

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[468] Alloway, B. J. (2009). Soil factors associated with zinc deficiency in crops and humans. *Environmental Geochemistry and Health*, 31(5), 537-548. doi:10.1007/s10653-009-9255-4
[469] Zimmermann, M. B., Jooste, P. L., & Pandav, C. S. (2008). Iodine-deficiency disorders. The Lancet, 372(9645), 1251-1262. doi:10.1016/s0140-6736(08)61005-3
[470] Smoleń, S., Kowalska, I., & Sady, W. (2014). Assessment of biofortification with iodine and selenium of lettuce cultivated in the NFT hydroponic system. *Scientia Horticulturae*, 166, 9-16. doi:10.1016/j.scienta.2013.11.011
[471] Whitcher, J. P., Srinivasan, M., Upadhyay, M. P. (2001). Corneal blindness: a global perspective. *Bull World Health Organ* vol.79 n.3 Genebra Jan. 2001. doi:10.1590/S0042-96862001000300009
[472] Barennes, H., Sengkhamyong, K., René, J. P., & Phimmasane, M. (2015). Beriberi (Thiamine Deficiency) and High Infant Mortality in Northern Laos. *PLOS Neglected Tropical Diseases*, 9(3). doi:10.1371/journal.pntd.0003581
[473] Abdou, E., & Hazell, A. S. (2014). Thiamine Deficiency: An Update of Pathophysiologic Mechanisms and Future Therapeutic Considerations. Neurochemical Research, 40(2), 353-361. doi:10.1007/s11064-014-1430-z
[474] Shi, Z., Zhen, S., Wittert, G. A., Yuan, B., Zuo, H., & Taylor, A. W. (2014). Inadequate Riboflavin Intake and Anemia Risk in a Chinese Population: Five-Year Follow Up of the Jiangsu Nutrition Study. PLoS ONE, 9(2). doi:10.1371/journal.pone.0088862
[475] *Maize in human nutrition* (1992). Food and Agriculture Organization of the United Nations.

- **Vitamin B9** (*folic acid, folinic acid*): Folate deficiency is relatively common, and is especially of concern among pregnant women for the prevention of serious birth defects.[476] The primary source of folate is green leafy vegetables, although it can also be found in whole grains, liver, and other sources.

- **Vitamin B12** (*cyanocobalamin, etc*): A common deficiency, and of particular concern for offworld environments as it is not found in plant sources. B12 is only produced by certain types of microorganisms and concentrated in higher animals - thus its common dietary sources are meat, eggs and dairy products.[477] Supplements can be produced by bacterial culture or imported. A fortunate property of B12 is that the body stores it for long periods of time (deficiency can take five to ten years to manifest[478]), and only very small quantities (2.4 µg/d) are required in the diet.

- **Vitamin C** (*ascorbic acid*): Humans are one of the few animal species incapable of synthesizing ascorbic acid from glucose, and thus must consume it in their diet; bodily stores are only sufficient for overwintering (160-200 days).[479] Formerly one of the greatest causes of malnutrition-related suffering, scurvy is rare today. Vitamin C is found in large quantities in many plant sources, and even some animal sources contain it in sufficient quantities.

- **Vitamin D** (*cholecalciferol, ergocalciferol*): Deficiency is common, particularly among women and those living at high latitudes, and causes a broad range of symptoms - from bone loss to cancer to diabetes to autoimmune disease. Its prevalence and severity has led to its consideration as a major global public health problem.[480] Sources of vitamin D include sun exposure (the primary source) as well as dietary sources such meat, eggs, and mushrooms exposed to UV light.[481]

Protein

Protein in general is often misattributed to being primarily available only in animal products. Calorie per calorie, vegetables are often richer sources of protein than meat. For example, 100 grams of 80% lean ground beef, cooked, contains 51% of one's daily value of

[476] Czeizel, A., Dudás, I., Vereczkey, A., & Bánhidy, F. (2013). Folate Deficiency and Folic Acid Supplementation: The Prevention of Neural-Tube Defects and Congenital Heart Defects. *Nutrients*, 5(11), 4760-4775. doi:10.3390/nu5114760
[477] Woo, K., Kwok, T., & Celermajer, D. (2014). Vegan Diet, Subnormal Vitamin B-12 Status and Cardiovascular Health. *Nutrients*, 6(8), 3259-3273. doi:10.3390/nu6083259
[478] Andrès E, Loukili NH, Noel E, et al. Vitamin B12 (cobalamin) deficiency in elderly patients. *Can Med Assoc J* 2004;171:251–9
[479] Armelagos, G. J., Sirak, K., Werkema, T., & Turner, B. L. (2014). Analysis of nutritional disease in prehistory: The search for scurvy in antiquity and today. *International Journal of Paleopathology*, 5, 9-17. doi:10.1016/j.ijpp.2013.09.007
[480] Palacios, C., & Gonzalez, L. (2014). Is vitamin D deficiency a major global public health problem? *The Journal of Steroid Biochemistry and Molecular Biology*, 144, 138-145. doi:10.1016/j.jsbmb.2013.11.003
[481] Chen, S., Yu, H., Kao, J., Yang, C., Chiang, S., Mishchuk, D. O., . . . Slupsky, C. M. (2015). Consumption of vitamin D2 enhanced mushrooms is associated with improved bone health. *The Journal of Nutritional Biochemistry*, 26(7), 696-703. doi:10.1016/j.jnutbio.2015.01.006

protein and 14% of its daily calories.[482] The same amount of calories from broccoli would contain 62% of one's daily value of protein.[483]

The issue arises that it takes a much greater quantity of vegetables - some might say unreasonably large - to meet one's daily caloric needs, and thus people tend to turn to gain the majority from other caloric sources, such as carbohydrates and fats. However, even in these cases, protein deficiency is rarely a problem. For example, the classic "carb" - bread - provides over twice as much of one’s daily protein needs as it does one's daily caloric needs.[484] Humans surviving on "bread and water" would not be possible if bread was devoid of protein provided protein.

In short, consuming sufficient amounts of protein is not problematic for a vegan diet. However, it is not only protein as a whole that is required, but specific amino acids as well.

Essential amino acids

Beyond basic protein requirements, it is essential that one receive enough of the constituent amino acids which the human body cannot synthesize. The essential amino acids are isoleucine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan, valine, and in the long term, histidine. In unusual states, some amino acids become conditionally essential, including arginine, citrulline, ornithine, cysteine, and tyrosine. Taurine's status as essential is controversial, but appears to at least be essential for pre-term neonates.[485]

Animal proteins are considered "complete proteins", in that they have a roughly balanced mixture of amino acids in accordance with human needs, while plant proteins are usually not as well balanced. However, in practice this is rarely a problem;[486] eating different plant sources of protein tends to cancel out such imbalances, and it is difficult to design a realistic vegan diet which is deficient in any essential amino acid.[487]

Many amino acids are also made synthetically. For example, taurine is unquestionably essential for cats, and can be synthesized from ethanolamine, isethionic acid, or aziridine. As cooking denatures it, pet foods are typically re-supplemented with synthetic taurine.[488]

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[482] Beef, ground, 80% lean meat / 20% fat, patty, cooked, broiled [hamburger, ground chuck]. SELF Nutrition Data. Retrieved from http://nutritiondata.self.com/facts/beef-products/6204/2
[483] Broccoli, frozen, spears, cooked, boiled, drained, without salt. SELF Nutrition Data. Retrieved from http://nutritiondata.self.com/facts/vegetables-and-vegetable-products/2361/2
[484] Bread, whole-wheat, commercially prepared. SELF Nutrition Data. Retrieved from http://nutritiondata.self.com/facts/baked-products/4876/2
[485] Laidlaw, S. A., Kopple, J. D. (1987). Newer concepts of the indispensable amino acids. *Am J Clin Nutr* October 1987 vol. 46 no. 4 593-605
[486] Young, V. R., Pellet, P. L. (1994). Plant proteins in relation to human protein and amino acid nutrition. *Am J Clin Nutr*. PMID: 8172124
[487] McDougall, J (2002). Plant foods have a complete amino acid composition. *Circulation*. DOI: 10.1161/01.CIR.0000018905.97677.1F
[488] Tully PS, ed. (2000). *Sulfonic Acids*. Kirk-Othmer Encyclopedia of Chemical Technology. John Wiley & Sons, Inc. doi:10.1002/0471238961.1921120620211212.a01.

Summary

There exists a natural temptation to allocate land towards as calorie-intensive agriculture as possible to minimize the required cultivated area and delivery mass. However, this runs contrary to proper human nutrition. While nutrition can most certainly be maintained via supplementation, including stocks supplied from Earth, this is a less desirable alternative to the crew consuming diets that naturally meet their needs.

A healthy vegan diet, with the exception of B12, can be maintained without the use of any animal products at all. This involves a mixture of whole grains, green leafy vegetables, legumes, colourful (vitamin A-rich) vegetables, a variety of plant fats, and ideally mushrooms raised under UV light. In such a case, B12 can be brought from Earth or produced locally via microbial culture.

That said, a number of nutrients are easier to get via animal sources. Iron in particular should be given attention if animal sources of food are not available to ensure adequate absorption. Care also needs to be taken in designing hydroponic solutions such that nutrients healthy for humans but not required for plant metabolism (such as iodine) are nonetheless provided.

Nixtamalization of corn (hominy, masa / tortillas, etc) should be given serious consideration over water-cooked corn, from a number of different nutritional standpoints, as well as for its use in destroying mycotoxins.[489] The required caustics are available onboard the habitat for a number of industrial processes in which they are regenerated, in addition to mixed oxide/hydroxide ash being produced in the high temperature incineration of waste.

Agriculture

Growing plants not only provides the most efficient conventional means for nutrient production for humans, it also forms the basis of feedstocks for animal and fungal-based food production. In an ideal situation, plant growth also perfectly offsets carbon dioxide exhalation and produces the perfect amount of oxygen for breathing. In practice, these are unachievable goals, and industrial scale gas production and waste scrubbing is still required.[490] Nonetheless, human presence offworld will invariably be tied to plants.

Plant growth requirements begin with a substrate for their roots to be anchored in, where the roots will receive both oxygen and water. The need for oxygen is easy to overlook; few crop plants can withstand full submersion, and with insufficient oxygen their roots begin to brown, rot, emit a foul odor, and the plant exhibits symptoms of water deficiency and ultimately death by dehydration. On Earth, the vast majority of plants are grown in various soil media; however, even lightweight media tend to amount to significant amounts of mass

[489] FAO 1992

[490] Among the other problems experienced in Biosphere 2, oxygen levels soared and carbon dioxide levels plummeted during the daytime, followed by the inverse situation at night. Plant gaseous waste products also soared to problematic levels. Gases also permeate through the envelope; see *Permeation calculations*.

and volume on the scale of full-sized farms, as well as increasing the mass needed to support them. As a consequence, hydroponic systems with locally produced water generally have the most appeal. Common variants include:[491]

Static solution raft tank.
Photo: Bryght Knight

- **Static solution**:

Plants grow in containers of nutrient solution, either aerated, or with the plants suspended above the solution with a wicking medium, or alternately with intent for roots to exist near the surface. As a general rule, non-aerated static solution is only effective for small plants and plants that tolerate oxygen deficiency.

Corn growing in a hydroponic trough.

- **Continuous flow**:

A continuous film of liquid flows past the plant roots, thin enough that the roots retain contact with the air and the liquid stays well oxygenated. The trays slope continuously downward and may contain protrusions to help keep the flow even. Trays generally must be covered to prevent light from reaching the roots / prevent evaporation, and roots must be prevented from clogging the channels. Care must be taken to ensure that water makes it all the way down to the final plants on the row as the plants grow and their water needs increase.

- **Ebb and flow**

A less sensitive variant of continuous flow, trays are flooded with a thick film or deep flood of nutrient solution at periodic intervals, then drained in-between for aeration. The greater amount of liquid helps ensure that all roots get thoroughly soaked regardless of level of growth.

Inspecting growing roots in an aeroponics system in Israel.
Photo: Yaakov Saar

- **Aeroponics / fogponics**

Rather than bulk or flowing liquid, water is provided to roots by a nutrient mist or fog, ensuring that they continually receive both water and oxygen. A large area can be kept moist with a very small amount of nutrient solution, rather than roots having to run along a trough or sit in aerated solution.

Of these, aeroponics and ebb and flow seem the most appealing. Static solution requires bearing large loads, and producing large amounts of solution. Continuous flow is

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[491] Roberto, K. (2005). [How-to hydroponics.]() Farmingdale, NY: Futuregarden Press.

sensitive to alignment and plant consumption rates. Ebb and flow allows one channel to be flooded, then the next, then the next, allowing one to use less total liquid and less pumping capacity (although the peak mass loading per channel is higher than with continuous flow). By contrast, aeroponics may be challenging in terms of ensuring that fogs can reach the end of their conduits without fully condensing out; however, if aeroponics could be shown to be suitable for long (50-100 meter) runs (aka: very fine fogs, large conduits, fast air speeds), it would allow for lower weight and more root space.

While flexible or segmented / folding hydroponic conduits would be possible, the most appealing design would be to colocate rollable conduits into rollable trusses. The unified structure would function as structural support, agricultural channels and walkways all in one. Rope handrails would ideally be collocated with the trusses. Troughs need to be openable in order to inspect and clean out roots, particularly in the event of root overgrowth / clogs. Indeed, trough designs need to be failsafe against clogging events, preventing excessive accumulation of water. Underneath each trough, extending roughly a meter to each side of the plants at their maximum size, needs to be plastic sheeting in order to catch plant debris. As with any area where humans may be regularly working, safety netting needs to be located underneath.

The level of hygiene to be utilized is an open question. Continuous nutrient solution sterilization with UV light is simple enough, but it may prove more challenging to sterilize entire troughs between harvests, whether with UV or disinfectants (see *Medicine*). On the other hand, sterilization between harvests appears to increase the risk of pythium root rot by killing off colonies of competing bacteria.[492] A no-sterilization growth approach would be ideal, but requires experimentation to ensure its viability.

Seeds are typically started in small pieces of semirigid substrate, such as foam. An initial batch of seeds could be pre-embedded in the habitat for shipment, to sprout as soon as water is provided; this would allow plants to be sprouted before the crew arrives, reducing time before the first harvest. Stems and/or roots must be supported.

Climbing plants may need plant clips and supporting cables, or a way to access them when hanging free. Plants with heavy fruits that normally rest on the ground likewise need support. Hanging of large, heavy fruits such as pumpkins tends to distort their growth into elongated shapes.

Some Venus-specific aspects concerning plant growth:

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[492] Sutton, J. C., Sopher, C. R., Owen-Going, T. N., Liu, W., Grodzinski, B., Hall, J. C., & Benchimol, R. L. (2006). Etiology and epidemiology of Pythium root rot in hydroponic crops: current knowledge and perspectives. *Summa Phytopathologica, 32*(4), 307-321. doi:10.1590/s0100-54052006000400001

Phototropism


Seedlings near a window growing in the direction of the light. Photo: Russell Neches

A curious aspect for plants grown on Venus would be the effects of phototrophism. Plants control the direction of their growth by two factors: phototrophy (growth toward light) and gravitropy (growth against gravity). While gravitropy exists in a normal manner on Venus, light comes from all sides on a Venus habitat, nearly evenly; hence, shade from their neighbors could encourage growth toward the undersides of the hydroponic channels as well as the tops. This is would appear to be a good thing; the greater the cross section of light intercepted by plants per unit of agricultural conduit mass, the more mass efficient agriculture becomes.

Photoperiod

The photoperiod on Venus is variable, depending on the habitat's altitude and latitude, from nearly a week near the equator to a low, roughly constant light at the poles. As discussed previously, the VeRa estimate of 48 hours for a ~70° latitude position may be an optimal compromise between day length/temperature on one hand and light levels / potential turbulence risk from the polar vortices on the other.

Plants are not adapted to 48 hour photoperiods on earth. Some, such as tomatoes and potatoes, find long photoperiods injurious. Many, such as strawberries, require specific photoperiods for fruit set.[493] However, it's not such a simple relation. Direct multiples of 24 hours seem more tolerable to photoperiod-sensitive plants than fractional multiples - aka a 36 hour day can actually be worse than a 48 hour day. In such cases it appears that plants interpret the light levels as if they "missed a day".[494] [495]

For problematic plants, light levels can be artificially adjusted. A simple incarnation would be a hanging solar shade / lighting tent. One set of plants could be shaded during part of the day while storing energy, while the same or a different set of plants could be lit up for part of the night. While the amount of energy made available by the lighting would be well less than the energy of the sunlight that was intercepted by the tent (after account for photovoltaic, storage and illumination losses), the important factor is not total energy content, but simulating a proper day length. Since this is mostly an issue for triggering fruiting, a tent would not need to be a permanent fixture, but could rather be relocated between different groups of plants at different stages of growth as needed.

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[493] Wheeler, R. M., Sager, J. C., Prince, R. P., Knott, W. M., Mackowiak, C. M., Stutte, G. W., . . . Goins, G. D. (2003). *Crop Production for Advanced Life Support Systems - Observations From the Kennedy Space Center Breadboard Project.* NASA Kennedy Space Center. doi:Document 20030032422, NASA/TM-2003-211184, NAS 1.15:211184

[494] Hsu, J. C., & Hamner, K. C. (1967). Studies of the Involvement of an Endogenous Rhythm in the Photoperiodic Response of Hyoscyamus niger. *Plant Physiology,42*(5), 725-730. doi:10.1104/pp.42.5.725

[495] Coulter, M. W., & Hamner, K. C. (1964). Photoperiodic Flowering Response of Biloxi Soybean in 72-Hour Cycles. *Plant Physiology, 39*(5), 848-856. doi:10.1104/pp.39.5.848

A further option is the selective breeding of plants for reduced photoperiod sensitivity. This is in addition to the simplest option, of simply choosing plants which are not photoperiod sensitive (for example, wheat).

Plant nutrition

In hydroponics, nutrient solutions are generally variants on the "Hoagland Solution",[496] which is traditionally comprised of:

Potassium	235 ppm
Nitrogen	210 ppm
Calcium	200 ppm
Sulfur	64 ppm
Magnesium	48 ppm
Phosphorus	31 ppm

Iron	1-5 ppm
Boron	0.5 ppm
Manganese	0.5 ppm
Zinc	0.05 ppm
Copper	0.02 ppm
Molybdenum	0.01 ppm

Nitrogen can be in the form of ammonia or nitrate, but ammonia is harmful in too high quantities as it hinders the absorption of other cations. Iron typically works best with chelation, but non-chelated iron would be more suitable in that it does not require the local production of chelating agents. Silicon is now sometimes added in tiny quantities as a micronutrient, in the form of sodium silicate. Different types of plants prefer somewhat different types of solutions, as well as at different stages in their lives, and it would be best to maintain three or four different tanks of solution.

A common misconception is that the goal of solution management is to maintain a constant concentration of each nutrient. In practice, nutrients are absorbed at dramatically different rates from solution, and if rapidly absorbed nutrients are constantly refreshed, their concentration in plant tissue can become too high. Excess uptake of some well absorbed nutrients, such as potassium, can cause deficiencies of poorer-absorbed nutrients, such as calcium. The goal is to ensure that levels of nutrients in the plants remains balanced. Indeed, it is often easier to measure nutrient levels within plant tissues than within the solution itself, and adjust the solution based on what nutrients need more or less uptake. This comes with the caveats that all plants on a given "circuit" of troughs must have similar nutritional needs at the same points in their growth cycles. The consequence of this is that different circuits should be fed by their own tanks. In each case, nitric acid should be added as needed to keep pH in the 4-7 range).[497]

On Earth, solution is frequently discarded when it is considered imbalanced. On Venus, a closed-loop system must be used; there can be no "throwing away" of nutrients. Anions are in general easily provided by Venus's atmosphere; however, most cations require recycling.[498] Fractional crystallization can isolate specific salts from a solution concentrate.

[496] Hoagland DR, Arnon DI (1950). The Water Culture Method for Growing Plants Without Soil. *Calif. Agric. Exp. Stn. Circ*., pp. 39-347.
[497] Bugbee, B. (2004). Nutrient Management In Recirculating Hydroponic Culture. *Acta Horticulturae,* (648), 99-112. doi:10.17660/actahortic.2004.648.12
[498] Bubenheim, D., & Wignarajah, K. (1997). Recycling of inorganic nutrients for hydroponic crop production following incineration of inedible biomass. *Advances in Space Research, 20*(10), 2029-2035. doi:10.1016/s0273-1177(97)00937-x

Air pressure

A Venus habitat does not experience the exact same sort of ratios of pressure to temperature, generally requiring a reduced air pressure to maintain comfortable temperatures (around 50 kPa, or one-half atmosphere). Thankfully, this works out well for plants. Plants can survive pressures down to the Armstrong limit (6.3 kPa), and where the pressure reduction is performed via reduction of nitrogen levels, growth rates are usually similar to (and sometimes better than) growth rates at atmospheric pressure. Turnip growth at 50 kPa is similar to at atmospheric pressure. Tomatoes plants grow to similar sizes at 33 kPa as at atmospheric pressure, but with stronger stems. Lettuce grows better at 70 kPa than atmospheric pressure. Rice only needs 10kPa partial pressure of oxygen to grow normally. Wheat has been shown to grow better at 20kPa than at atmospheric pressure. While there are exceptions, such as mung beans, a general trend becomes clear: reduction in total pressure corresponds to similar or enhanced growth so long as oxygen and carbon dioxide partial pressures remain constant.[499]

The reasons for this are not entirely clear, but it appears that reduced pressures makes it easier to uptake carbon dioxide due to faster diffusion rates. The low pressures help draw out chemicals such as ethylene from plant tissue. This latter phenomenon has the side effect of increasing the shelf life of harvested plant products.

The one negative growth effect from reduced pressure growing is that the faster loss of water vapour tends to triggers a drought response in plants, inducing behavior that can have negative consequences to their growth. This raises the interesting prospect that with selective breeding or genetic engineering, even faster growth rates could be achieved for plants in reduced pressure environments. This is an active topic of research for Martian greenhouses.[500]

Transpiration

While transpiration is a normal feature of plant growth, in an enclosed environment it represents a significant source of humidity. Large enclosed greenhouses tend to experience high levels of humidity and large amounts of condensation. Habitat designs must include dehumidification for human comfort and the prevention of excessive condensation / runoff to the bottom of the envelope. In Biosphere 2, condensation systems had to be designed to remove 20-40 tonnes of water per day (0.23-0.46 kg/s).[501] Condensation systems have the side benefit (as in Biosphere 2) of producing potable water, thus preventing water from having to be pumped all the way up from the industrial section at the bottom of the habitat; the water is distilled in the process.

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[499] Paul, A., Ferl, R. J. (2006) The Biology of Low Atmospheric Pressure - Implications For Exploration Mission Design and Advanced Life Support. *Gravitational and Space Biology 19(2) August 2006.*
[500] *Greenhouses for Mars*. NASA. Published 24 Feb. 2004. Retrieved from https://science.nasa.gov/science-news/science-at-nasa/2004/25feb_greenhouses
[501] Guo, T., Englehardt, J., & Wu, T. (2014). Review of cost versus scale: water and wastewater treatment and reuse processes. *Water Science & Technology, 69*(2), 223. doi:10.2166/wst.2013.734

To estimate our level of transpiration, we start with some base assumptions: 20°C at night, 25°C at noon; 55 kPa at night, 45 kPa at noon; 10 crew members; and air with a dry fraction of 59.9% nitrogen, 40% oxygen, and 0.1% CO_2, with humidity held at 60% (see the discussion under *Climate control*). A simple estimation of leaf saturation vapour pressure (with a night leaf temperature of 19°C, and 30°C at noon) is 2487 Pa at night and 4245 Pa at noon. Conditions at night are kept constant; daytime conditions are scaled by time of day.

With a variety of plausible assumptions - a diet of 3000 kcal per day, an average of 1.4 kcal/gram of harvest, two harvests per year, and 10.6 tonnes of harvest per hectare - we arrive at 3691 m² in cultivation. With a leaf area index of 3, the leaf area is 11075 m².

We need to declare some additional parameters relating to the plants. We will assume a boundary layer diffusion resistance of 1.5 s-atm/cm; a 5x difference between day and night stomatal diffusion resistance and the stomatal resistance otherwise defined by $0.8 + 0.02\,(T - 32°C)^2$ s-atm/cm. We can then use following formula to determine transpiration:

$$kg/s = A * kg/mol * (mol/m^3_{leaf} - mol/m^3_{air}) / (resistance_{stomata} + resistance_{boundary})$$

… where A is area in square centimeters. From this we derive a nighttime transpiration of 0.051 kg/s; a noon transpiration of 0.513 kg/s; an average transpiration of 0.183kg/s; and an average 24-hour transpiration of 15.9 tonnes. With an assumed dehumidifier energy factor of 3.1 (1.16MW/kg), this requires 212 kW average power consumption, with a peak at 595 kW. We do not investigate how dehumidifier energy factors vary based on local (low pressure) conditions. In considering existing commercial systems, a water generator array designed 0.4kg/s under standard conditions can weigh nearly 17 tonnes.[502] It seem unlikely that mass reduction would bring the system much below 4-5 tonnes.

If a reduced transpiration is desired, the easiest way is to simply let the relative humidity rise; this also increases the rate of dehumidification. Plant selection and/or breeding to encourage greater stomatal closure or lower leaf area indices can also lower this figure, as can higher internal pressures. In the above, we also do not account for food sources other than plants; the lower the cultivated area, the lower the transpiration rate. However, we also do not account for other sources of transpiration or evaporation, such as humans, livestock, aquaculture, or hydroponics channels.

As noted under *Climate control*, air conditioning can generate significant amounts of dehumidification - and the water collection rates are more to the point adjustable by varying the air output temperature. While air conditioning systems are heavier - and air conditioning power consumption a significant extra over that which must be expended for dehumidification - it comes with numerous advantages: lower altitude (greater lift, greater ISRU recovery), greater comfort, a broader range of latitude/altitude combinations, etc. The decision on the balance of factors for dehumidification and climate control systems thus requires careful implementation-specific analysis.

[502] *Large Scale Water Generator*. WaterGen. Retrieved from http://water-gen.com/products/water-from-air/large-scale-water-generator/

A final note is that we are treating the habitat as a uniform body of air surrounded by an equal-temperature envelope. In practice, the envelope is large enough to sustain temperature differentials and convection currents. The interior is hotter than the exterior environment, and thus hotter than the envelope. The differential is amplified by opacity variations, such as sections of envelope covered by solar cells.

Condensation from convecting humid air is frequently problematic; it hinders light transmission, allows for the growth of algae and mold, and can lead to water accumulation in unwanted areas. However, properly managed, condensation could be encouraged to drip onto catenary curtains, thus onto support cables, and ultimately to be collected in the hydroponics channels. The greater the ratio of saturation pressures between the cold and warm air, the more passive dehumidification will occur.

Mushrooms

As decomposers, mushrooms can rapidly convert inedible waste plant matter into edible material, and in effect increase the mass efficiency of agriculture. The amount of area needed per unit production is also small, allowing them to be collocated in a large kitchen. A few caveats should be mentioned:

Small-scale oyster mushroom cultivation. Photo: Rudi Ardiansyah

- **Mushroom type**: Many commonly consumed mushrooms, such as button mushrooms, are secondary decomposers, and require a substrate that has already undergone proper decomposition from a primary decomposer. This is a mass and complexity cost that is difficult to justify. Primary decomposers, such as oyster mushrooms, can decompose plant matter directly, and need only be feed a continuous new supply to grow new productive mycelium.[503]

- **Enclosed environment**: Most mushrooms grow best in high humidity environments. Additionally, high density mushroom cultivation poses a risk for “mushroom worker's lung” among people who work with them (excessive spore inhalation causing hypersensitivity pneumonitis).[504] Hence mushrooms should be grown in sealed systems with air filters embedded.

- **UV light**: Mushrooms do not require light to grow. However, the addition of UV light during the growth process has been shown to dramatically increase levels of vitamin D in mushrooms; hence, embedded UV LEDs could significantly improve crew nutrition.[505]

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[503] Sharma, S. (2012). *Advances in fungal biotechnology*. New Delhi: Random Publications.
[504] Mori, S., Nakagawa-Yoshida, K., Tsuchihashi, H., Koreeda, Y., Kawabata, M., Nishiura, Y., . . . Osame, M. (1998). Mushroom worker's lung resulting from indoor cultivation of Pleurotus osteatus. *Occupational Medicine, 48*(7), 465-468.
[505] Chen, S., Yu, H., Kao, J., Yang, C., Chiang, S., Mishchuk, D. O., . . . Slupsky, C. M. (2015). Consumption of vitamin D2 enhanced mushrooms is associated with improved bone health. *The Journal of Nutritional Biochemistry, 26*(7), 696-703. doi:10.1016/j.jnutbio.2015.01.006

Animal products

General philosophical issues

To many people, incorporation of animal products into meals is critical to quality of life. Being deprived of eggs, dairy, and/or meat is like punishment. As part of the success or failure of a Venus colony depends on it being an appealing place to live, this is an issue that should not be ignored.

To many other people, however, moral or religious issues strongly conflict with this. Pescatarians will consume fish, eggs, and dairy, but not meat from land animals. Vegetarians do not consume any meat. Vegans do not consume any animal products. For people with a moral or religious objection to the killing of animals, having to live in a place where animals are being slaughtered - perhaps animals that they interact with and have formed a bond with - would range from disconcerting to traumatic.

This could, of course, be addressed with crew selection - whether via a formal selection process or self-selection. One could make it clear that there will be no meat production, and thus artificially select those who do not feel a need for it and//or are morally opposed to it. One could contrarily make it clear that there will be meat production, and thus artificially select in the other direction. In short, the moral/personal viewpoints of mission planners could dictate to future colonists how their lives should be and what sort of person should live there.

We can, however, examine the issue purely on its technical merits. Are livestock logical, from a mass / productivity perspective? It's an easy argument to make; many types of livestock can consume inedible plant waste, and from that can be produced food that provides nutrition that can be difficult to acquire from other sources. But this only applies up to a point; agricultural waste quantities are limited. Eggs and milk are more efficient than meat production from a feed mass perspective, and particularly from the perspective of space requirements. This would seem to argue for raising a limited amount of livestock, maximizing their time in production of milk and eggs, and then slaughtering them when they are no longer productive, yielding only small amounts of meat.

Ultimately, however, when it comes to moral issues, it's the people affected by them who should be making the decisions. If people on Venus wish to allocate their resources toward one thing or another, or make calorically / nutritionally suboptimal decisions, to a large extent that should be their decision to make. It seems reasonable to give people options in how to feed themselves, but leave it up to them to decide what is appropriate. If colonists wish to keep unproductive animals around to the natural end of their lives, or not harvest any animal products at all from them and treat them as pets, that should be their choice. If they want to raise animals in excess for slaughter, that should likewise be their decision. The only critical aspect is that the decisionmaking process be done in a manner that prevents strife to the greatest extent possible. Potential colonists should be encouraged to discuss this and any other moral issues with other existing and future colonists before travel, and as much as possible, have decisions within a given habitat made by consensus.

All animals should be sent as the smallest breeds available to simplify environmental management and food needs en route to Venus. Once at the habitat, animals can be backbred to larger sized breeds using frozen sperm or embryos.

Where eggs and milk are the primary goal, sex selection is an option. For highly accurate sex selection, IVF is an option, albeit with high labour. For lower labour options, sperm can be sexed with over 90% accuracy (in the case of cattle) via flow cytometry, where sperm are stained with a fluorescent DNA-staining dye and then run through a selection gate based on how much they fluoresce.[506] All selection labour can be done on Earth.

Eggs

Birds can be brought as unhatched eggs in an incubator plus a secondary pen, as the incubator would be desirable in the habitat regardless. The younger the birds are at takeoff, the less physical resources they will consume in transit.

While any bird can be a source of eggs, only a relatively small number are used commercially to any meaningful extent. In the below table, feeds are assumed to be high caloric / grain based, for comparison purposes. Ostriches and emus are omitted due to size reasons.

General data

Type	Adult mass (kg)	Peak eggs / day	Egg mass (g)	Feed / day (g)	Natural diet	Matur. (wks)	Life span (y)	Min. pen area (m²)	Pen height (m)
Chicken	1.1	0.75	58	81	Mixed	20	8	0.13	0.4
Duck	2.1	0.75	60	~170	Green	21	10	0.23	0.6
Goose	3.25	0.57	125	~195	Green	37	20	0.23	0.8
Quail	0.15	0.78	11	25	Seed	7	2.5	0.023	0.16
Turkey	10.6	0.4	86	290	Mixed	28	3	0.46	1.3
Guinea Fowl	1.7	0.47	45	90	Protein	37	12.5	0.3	0.5
Partridge	0.4	0.11	17	35	Seed	9	10	0.1	0.3
Pheasant	1.2	0.14	32	50	Mixed	27	8	0.3	0.4

Nutrition per gram of egg [507]

Egg type	kcal	Protein (g)	Fat (g)	Folate (µg)	B12 (µg)	A (IU)
Chicken	1.43	0.126	0.099	0.47	0.013	4.87
Duck	1.85	0.128	0.124	0.80	0.054	6.74
Goose	1.85	0.139	0.133	0.76	0.051	6.50
Quail	1.58	0.131	0.111	0.76	0.016	5.43
Turkey	1.35	0.137	0.111	0.66	0.016	5.43

[506] Garner, D. L., Evans, K. M., & Seidel, G. E. (2012). Sex-Sorting Sperm Using Flow Cytometry/Cell Sorting. *Methods in Molecular Biology Spermatogenesis,* 279-295. doi:10.1007/978-1-62703-038-0_26
[507] (2014) *SELF Nutrition Data*. Conde Nast.

Nutrition per kilogram animal mass per day

Egg type	kcal	Protein (g)	Fat (g)	Folate (µg)	B12 (µg)	A (IU)
Chicken	53	4.7	4.7	17.3	0.45	180
Duck	39	2.7	2.7	17.1	1.16	144
Goose	41	3.1	2.9	16.8	1.13	144
Quail	90	7.5	6.4	37.8	0.92	311
Turkey	4.4	0.4	0.3	1.8	0.04	14

Nutrition per kilogram feed

Egg type	kcal	Protein (g)	Fat (g)	Folate (µg)	B12 (µg)	A (IU)
Chicken	717	63	50	236	6.5	2440
Duck	490	34	33	212	14	1780
Goose	682	51	49	280	19	2400
Quail	542	45	38	227	5.5	1860
Turkey	160	16	11	67	1.5	520

Before we do a species breakdown, some generalities. While the natural diets of species vary, most species raised commercially are fed diets that are predominantly energy-rich grains, as this reaches mature weight as fast as possible and maximizes laying rates. This, however, has two disadvantages. First, grain-fed birds usually lay eggs that lack some of the nutrition of those fed greens and insects; such wild feeds can result in over an order of magnitude higher omega-3 fatty acid levels.[508] [509] Secondly, grains are not a waste product on a Venus colony; one of the primary advantages of livestock is their ability to take wastes and convert them into food.

At least in the beginning, “enriched cages” would likely be optimal housing. Enriched cages separate hens and eggs from waste, provide perching and dust bathing, automatic egg collection, and more room for hens versus traditional battery cages. They provide a combination of high density / ease of maintenance without compromising humane living conditions. As additional habitat space becomes available, colonists can choose whether to allocate more space for “free range” style living conditions. Top netting will, however, be required in any situation.

Six-cage enriched system. Photo: F. Bailey Norwood

Considering each species individually:

- **Chickens**:

While many breeds are available, only a few breeds have been highly optimized. For our purposes, the bantam

[508] Speake, B. K., Murray, A. M., & Noble, R. C. (1998). Transport and transformations of yolk lipids during development of the avian embryo. *Progress in Lipid Research, 37*(1), 1-32. doi:10.1016/s0163-7827(97)00012-x

[509] Speake, B. K., Surai, P. F., Noble, R. C., Beer, J. V., & Wood, N. A. (1999). Differences in egg lipid and antioxidant composition between wild and captive pheasants and geese. *Comparative Biochemistry and Physiology Part B: Biochemistry and Molecular Biology, 124*(1), 101-107. doi:10.1016/s0305-0491(99)00108-x

Mature bantam (left) vs. 9 week old full leghorn. Photo: Terry Golson

leghorn appears best, having similar feed conversion and mass ratios as the full-size leghorn, but with a much smaller size; bantam genes are being used to improve feed conversion of full-sized birds.[510] Chickens dominate the egg industry for a reason; they have been highly optimized with excellent feed conversion ratios. Their eggs, however, aren't as nutritious as those of waterfowl, and hens are known for random behavioral issues. Light control helps prevent feather pecking and cannibalism.[511] Roosters are famously loud; hens are quieter.

- **Ducks**:

Khaki campbell. Photo: Valencia Marky

We choose for analysis the khaki campbell, a small, quiet species of duck that is an excellent layer. As a waterfowl species, it tends to lay highly nutritious eggs. The record number of eggs per year for any bird species is held by a khaki campbell, who laid one every day for an entire year; ducks can mature an egg in 24 hours, faster than a chicken can, and lay at the same time every day.[512] Ducks are also better tempered than chickens. Daily feed ranges for ducks are broad, ranging from 125-230 g/day;[513] [514] this in part reflects the nutrition density (typically, grain content) of the feed.

- **Geese**:

Anser cygnoides / Swan geese. Photo: 4028mdk09

Only one species of goose lays large numbers of large eggs per year - *Anser cygnoides*, the Swan Goose. They are however not in widespread use for egg production, and not very refined; laying rates vary by half an order of magnitude (we choose a median figure for the breed "Huoyan").[515] Their general statistics are reasonably good, but not as good as ducks, and their temperaments are more varied. One arguable advantage is their long productive lifespans.

- **Quail**:

Bowl of quail eggs. Photo: Fach Lectorat

Quail have outstanding egg production relative to their tiny sizes. This is tempered by their moderate feed conversion ratios and the fact that they are not adapted to consume diets of greenery.

[510] Parkinson, G. B., Cransberg, P. H. (2006) Evaluation of a bantam cross egg layer. Proceedings of the 18th Australian Poultry Science Symposium, Sydney, New South Wales, Australia, 20-22 February 2006
[511] Jacob, J. (2015) Feather Pecking and Cannibalism in Small and Backyard Poultry Flocks. Extension.
[512] Walbert, D (2008). Khaki Campbell egg production. The New Agrarian.
[513] Duck Management Guide. Central Poultry Development Organization (Southern Region). Hesserghatta, Bangalore.
[514] Meulen, S. J., & Dikken, G. D. (2004). Duck keeping in the tropics. Wageningen: Agromisa Foundation.
[515] Buckland, R. B., & Guy, G. (2002). Goose production. Rome: Food and Agriculture Organization of the United Nations.

- **Turkeys**:

Turkey egg. Photo: Jason Hollinger

Not commonly marketed, turkey eggs represent neither good feed conversion ratios nor utilization of space, and the large size of turkeys is a disadvantage for shipping. Their eggs are relatively poor in nutrition and harder to open. Turkeys are mainly raised for their meat; eggs could be a potential byproduct of this.

- **Guinea fowl**:

Helmeted guineafowl. Photo: Ken Goulding

No egg-laying statistics related to guinea fowl are particularly outstanding. They can be noisy. Their natural diet, rich in insects rather than greenery, makes them a suboptimal choice for conversion of agricultural waste.

- **Partridge, pheasant**:

Red-legged partridge. Photo: Pierre Dalous

Neither partridges nor pheasants represent good sources of eggs, primarily due to the low numbers of eggs laid per year. No nutritional information on their eggs is available.

From this, it appears that quail, with their tiny size and superb laying rate, would be an excellent “starter bird” for egg production, fed with seeds from fruit and vegetables that humans find undesirable or inedible. For larger-scale egg production in the future, however, any combination of leghorns and khaki campbells would be optimal, with the former fed predominantly from waste greenery, and the latter entirely so. Other breeds in the future can be backbred from shipments of frozen semen or eggs as desired.

Dairy

The same backbreeding and transport-as-young principles that applies to laying birds apply equally to dairy livestock. This may be more important due to the dramatically larger sizes. Indeed, the size of dairy animals and their high rates of waste production make proper pen design important; it should be easy to shovel waste into collection troughs for either incineration/cation recovery or reuse as feed in aquaculture. Preventing unintentional falls of such large animals, or their waste, implies very secure pens and overhead netting. Where offspring are not desired, hormone treatment can induce milk production (demonstrated in cattle, expected to be viable in other species).[516]

Type	Adult mass (kg)	Liters / day	Milking days / gestation	Gestation period (d)	Concentr. kg/day	Dry matter kg/day	Matur. (wks)	Life span (y)	Min. pen area (m²)
Goat	35	2	305	150	0.6	1	51	10	0.9
Sheep	50	1.4	210	150	1.5	2.2	65	11	1.3
Cow	280	12	300	280	1.7	6	113	18	7
Water Buffalo	550	8	280	320	3.8	5	120	25	12
Yak	250	3	168	260	1.5	7	190	22	6
Camel	350	6	Years	410	0	10	235	45	12
Alpaca	55	0.8	245	345	*0*	1.5	61	20	1.5
Horse	25	0.6	183	345	0.4	0.4	60	40	0.6
Donkey	90	0.9	200	365	1.3	0.6	105	30	2.3
Reindeer	60	0.4	170	215	0	2.8	95	20	1.6

Concentrate and dry matter are based on typical lactation feeds; a decrease in concentrates (fats, protein, carbohydrates) will correspond with a decrease in milk yields. The above table is far from comprehensive; other species that have been used for milk production include zebra, elk, moose, llama, pig, mithun and musk ox, among others. As with laying birds, breeds have been chosen for combinations of small size and high productivity. Nutritional content varies significantly between types of milk:

Nutrition per 100g [517] [518] [519]

Type	kcal	Protein (g)	Fat (g)	Lactose (g)	B12 (µg)	Calcium (mg)	Notes
Goat	119	4.9	8	6.8	0.10	201	Short-chain fatty acids Easy to digest
Sheep	100	5.6	6.4	5.1	0.71	197	Efficient for cheese
Cow	62	3.3	3.3	4.7	0.36	122	80% of world production Easy to process
Water Buffalo	99	4	7.5	4.4	0.4	112	Used in mozzarella Easy to process
Yak	82	3.5	5.8	3.9	-	-	Easy to process
Camel	64	3.1	3.2	4.3	0.2	115	30x more vitamin C vs. cow's milk; antibiotic; difficult to process.
Alpaca	67	5.8	5.1	5.6	-	*195*	Calcium figure from llamas
Horse	48	2	1.6	6.6	-	133	Similar to human milk
Donkey	37	1.6	0.7	6.4	-	68	Similar to human milk
Reindeer	184	10.4	16.1	2.9	-	-	Easy to process

[516] Magliaro, A., Kensinger, R., Ford, S., O'Connor, M., Muller, L., & Graboski, R. (2004). Induced Lactation in Nonpregnant Cows: Profitability and Response to Bovine Somatotropin. *Journal of Dairy Science, 87*(10), 3290-3297. doi:10.3168/jds.s0022-0302(04)73465-7
[517] Muehlhoff, E., Anthony, B., Deirdre, M. (2013) *Milk and Dairy Products in Human Nutrition*. Food and Agriculture Organization of the United Nations.
[518] Barłowska, J., Szwajkowska, M., Litwińczuk, Z., & Król, J. (2011). Nutritional Value and Technological Suitability of Milk from Various Animal Species Used for Dairy Production. *Comprehensive Reviews in Food Science and Food Safety, 10*(6), 291-302. doi:10.1111/j.1541-4337.2011.00163.x
[519] (2014) *SELF Nutrition Data*. Conde Nast.

Nutrition per kilogram animal mass per day

Type	mL	kcal	Protein (g)	Fat (g)	Lactose (g)	B12 (μg)	Calcium (mg)
Goat	48	53	2.2	3.6	3.0	0.04	90
Sheep	16	15	0.86	0.98	0.78	0.11	30
Cow	20	12	0.6	0.6	0.9	0.07	23
Water Buffalo	11	10	0.41	0.78	0.46	0.04	11
Yak	5.5	5.4	0.28	0.37	0.26	-	-
Camel	11	5.3	0.29	0.3	0.4	0.02	10.9
Alpaca	8.9	6.5	0.53	0.47	0.52	-	18
Horse	12	5.3	0.22	0.18	0.73	-	15
Donkey	3.8	1.2	0.05	0.02	0.21	-	2.2
Reindeer	3.8	7.7	0.41	0.64	0.11	-	-

- Concentrates treated as requiring 25% more animal mass vs. dry forage

Nutrition per kilogram dry forage

Type	Liters	kcal	Protein (g)	Fat (g)	Lactose (g)	B12 (μg)	Calcium (mg)
Goat	0.4	442	19	28	30	0.4	741
Sheep	0.34	208	12	13	11	1.5	409
Cow	1.3	430	23	23	33	2.5	847
Water Buffalo	0.8	641	26	49	29	2.6	726
Yak	0.29	160	8.3	11	7.7	-	-
Camel	0.58	193	11	11	15	0.69	398
Alpaca	0.43	261	21	19	21	-	718
Horse	0.67	165	6.7	5.5	23	-	457
Donkey	0.32	61	2.6	1.2	11	-	112
Reindeer	0.11	166	8.8	2.5	2.5	-	-

- Concentrates treated as yielding 25% more milk vs. dry forage

By species:

- **Goats**

Nigerian dwarf goat and kids. Photo: Woodland Trails Farm

Goat milk has a good nutritional profile except for B12, which is unfortunately poor. Our data here is for the Nigerian Dwarf, an AA-genotype (little to no “goaty” odour to the milk)[520] variety with an unusually high butterfat content. Milking periods are long, daily production large, and fecundity is high, with 2-5 kids per kidding and less than a year to maturity. Nigerian dwarfs are often raised as pets and are renowned for having a good temperament. The West African Dwarf is smaller (20-25 kg) but not as efficient of a milk producer, so the benefit of elevated milk production probably justifies avoiding the backbreeding delay. As with all goat breeds, bucks have a strong "animal smell" to them.[521]

[520] Barłowska, J., Szwajkowska, M., Litwińczuk, Z., & Król, J. (2011). Nutritional Value and Technological Suitability of Milk from Various Animal Species Used for Dairy Production. *Comprehensive Reviews in Food Science and Food Safety, 10*(6), 291-302. doi:10.1111/j.1541-4337.2011.00163.x

[521] Starbard, A. (2015). *The dairy goat handbook: for backyard, homestead, and small farm*. Minneapolis, MN: Voyageur Press.

- **Sheep**

Awassi ram. Photo: Steven Walling

While the sheep data is for the awassi,[522] the ouessant would make a better transport species, at 30% the size (50kg vs. ~13-16kg); the latter is the smallest sheep breed on Earth.[523] However, the ouessant is a poor dairy breed, so it's a question of how fast one wishes to get production online vs. minimizing transport mass. Crossbreeds may be able to yield the best benefits of each.

Sheep milk has a superb nutritional profile including, opposite to goats, large amounts of B12. It additionally provides particularly high yields in cheesemaking. Significant variability is reported in Awassi milk production levels.[524]

Ouessant sheep. Photo: Eponimm

- **Cows**

Miniature cows generally produce roughly the same milk to body mass ratio with similar or better feed conversion as their full-size counterparts, at ⅓ to ½ the mass.[525] Zebus (a meat breed) are even smaller. The major dairy breeds, such as Holsteins and Jerseys, each have miniature variants; Jerseys are somewhat lighter/better feed conversion with a longer productive life.[526] Cow milk has the best creaming rate (formation of a fat layer on the surface).[527] The nutritional profile is average. Even as a miniature, a 280kg (adult mass) ruminant would still represent a significant transportation cost. Mini jersey bulls have unusually good temperament.[528]

Miniature jersey cow. Photo (crop): Hatchet Cove Farm

- **Yak**

Yak in Tajikistan. Photo: Ekrem Canli

While proving a fairly nutrient dense, easy-to-process milk, a yak's 2 l/day milk production does not justify its large size; indeed, on Earth active breeding programmes exist to improve Yak production by crossbreeding with cattle.[529] That said, the ability to breed with cattle would allow for backbreeding if desired.

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[522] Shoenian, S (2007). *Sheep 101*. Retrieved from http://www.sheep101.info/breeds.html
[523] Glenday, C., Delgado, A., Montsech, D., Miciulevicius, G., & Soms, R. (2015). *Guinness world records 2016*. Barcelona: Planeta Pub Corp.
[524] Epstein, H. (1985). *The Awassi sheep with special reference to the improved dairy type*. Rome: Food and Agriculture Organization of the United Nations.
[525] Roth, A. *The Many Benefits of Miniature Cows*. Modern Farmer. 15 June 2006.
[526] Capper, J., & Cady, R. (2012). A comparison of the environmental impact of Jersey compared with Holstein milk for cheese production. *Journal of Dairy Science,95*(1), 165-176. doi:10.3168/jds.2011-4360
[527] Barłowska, J., Szwajkowska, M., Litwińczuk, Z., & Król, J. (2011). Nutritional Value and Technological Suitability of Milk from Various Animal Species Used for Dairy Production. *Comprehensive Reviews in Food Science and Food Safety, 10*(6), 291-302. doi:10.1111/j.1541-4337.2011.00163.x
[528] *Guide to Miniature Cattle Breeds for Your Small Modern Homesteading Farm*. Modern Homesteading.
[529] Park, Y. W., Haenlein, G. F., & Wendorff, W. L. (2017). *Handbook of milk of non-bovine mammals*. Hoboken, NJ: John Wiley & Sons.

- **Water buffalo**

Murrah water buffalo. Photo: Kleo Marlo

Like sheep's milk, buffalo milk provides a high yield in cheese production. The nutritional profile is similar to cow's milk, but with significantly greater amounts of milkfat. However, the large size and shortage of dwarf breeds makes them a generally inferior transport option. They cannot be backbred from cattle directly,[530] but as a closely related species, an embryo could likely be carried using a cow as a surrogate. One advantage of water buffalo is that they are slightly more efficient at converting fibre than cattle.[531]

- **Horses**

Falabella miniature mare and colt. Photo: Jono Bacon

Like other equids, mare's milk is relatively nutrition-poor milk (2g protein / 100g, 1.6g fat /100g), more similar in composition to human milk.[532] While this is often thought of as desirable from a health perspective, it is less so from a nutrient conversion perspective. While horses are generally thought of as large animals, some breeds can reach surprisingly small sizes; the falabella is the smallest breed, with an average mature size of 18-45 kg.[533]

- **Donkeys**

Sardinian donkeys. Photo: JLAN

Miniature mediterranean / Sardinian donkeys have the smallest adult sizes, with the Asinara variety weighing only 80-90kg.[534] While donkeys can't be backbred from horses (mules and hinnies generally being sterile), a horse could potentially be a surrogate. However, donkey milk is particularly nutrient poor (even compared to horse milk), and production rates are even lower - making them of relatively little interest from a waste conversion perspective.

- **Camels**

Dromedaries, being better milk producers than bactrians, are considered here. Camel milk has a fairly typical nutritional profile except for one factor: vitamin C is highly elevated, 30 times greater than cow's milk. However, this benefit is of relatively little utility, as agriculture makes vitamin C easy to acquire. Camels can be milked for

[530] Patil, S., & Totey, S. (2003). Developmental failure of hybrid embryos generated by in vitro fertilization of water buffalo (Bubalus bubalis) oocyte with bovine spermatozoa. *Molecular Reproduction and Development, 64*(3), 360-368. doi:10.1002/mrd.10269
[531] (2015) Buffalo: Feeding. *Animal Husbandry*. TNAU Agritech Portal.
[532] Park, Y. W., Haenlein, G. F., & Wendorff, W. L. (2017). *Handbook of milk of non-bovine mammals*. Hoboken, NJ: John Wiley & Sons.
[533] Falabella Breed Information. Horse Breeds List. Retrieved from http://horsebreedslist.com/horse-breeds/49/falabella
[534] Porter, V. (2016) *Mason's World Encyclopedia of Livestock Breeds and Breeding*.

Kenyan herders milking a dromedary. Photo: ILRI

protracted lengths of time after calving. Camel milk is poor for cheesemaking.[535] Their large size makes them impractical to transport, although they can be backbred from the much smaller new-world camelids (llama, alpaca, guanaco, vicuña). An adult Vicuña averages only 35-65 kg, vs. 450-540 kg for a dromedary.[536] The cama, a camel-llama hybrid, is smaller than either camels or llamas, at 50-70 kg. Camels consume particularly poor-quality forms of forage (including thorny and salty plants), and have low feed requirements; in times of shortage they can survive for months on as little as 2 kg dry matter per day.[537]

- **Alpacas**

Photo: Christophe Meneboeuf

Alpacas are the second smallest camelid (after the wild vicuña). Alpaca milk has a very high protein concentration - both in comparison to other camelids, and in general.[538] New World camelids are only rarely used for milk production (being more popular for wool), but the available data suggests good conversion rates.[539] [540] “Dwarf” breeds are only slightly smaller than “full size” breeds, < 55kg vs. 70kg.[541]

- **Reindeer**

Milking reindeer, Tsaata Village. Photo: François-Olivier Dommergues

Reindeer milk (popular among arctic peoples) is exceptionally rich, three times higher in protein vs. cow’s milk, five times higher in fat, and easy to process. However, lactation rates are very low, rendering it difficult to justify the animal's moderate size.[542] Females of the the smallest subspecies, the Svalbard reindeer, reach around 53-70 kg at maturity.[543] Moose milk is similar to reindeer milk, although not as rich, and not as extensively utilized.

In summary, goats seem an easy choice to start out dairy production, offering good feed conversion and outstanding production levels relative to their low body mass. They eat a diverse diet, and nigerian dwarfs are popular as pets. However, B12 production is low, and if bucks are to be raised, odour would dictate locating livestock pens well away from crew areas. Sheep by contrast yield large amounts of B12, but yields are lower, and the optimal

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[535] Barłowska et al 2011.
[536] Kindersley, Dorling (2005). *Animal The Definitive Visual Guide to the World’s Wildlife*. pp. 236–237. ISBN 0-7894-7764-5.
[537] Yagil, R. (1982). *Camels and Camel Milk*. Food and Agricultural Organization of the United Nations. ISBN 92-5-101169-9
[538] Parraguez, V.H., Thénot, M., Latorre, E., Ferrando, G, Raggi, L.A. (2003) Milk Composition in Alpaca (Lama Pacos): Comparative Study in Two Regions of Chile. *Arch. Zootec*. 52: 431-439
[539] Leyva, V., Markas, J. (1991) Involucion de la glandula mamaria en alpacas y efecto sobre el peso corporal y produccion de fibra. *Turrialba*. 41:59-63.
[540] Vaughan, J. *Feeding Alpacas to Maximize Their Reproductive Potential*. CRIA Genesis.
[541] *Miniature Alpaca*. Tanglewood Foundation. Retrieved from http://www.tanglewoodfoundation.org/miniature-alpacas.html
[542] Park, Y. W., Haenlein, G. F., & Wendorff, W. L. (2017). *Handbook of milk of non-bovine mammals*. Hoboken, NJ: John Wiley & Sons.
[543] Pedersen, Å. Ø. *Svalbard reindeer (Rangifer tarandus platyrhynchus)*. Norwegian Polar Institute.

shipping method requires backbreeding or the creation of new miniature dairy breeds. Many other species have points to argue in their favour, although some such as yaks and donkeys would be difficult to justify.

As processing of many dairy products involves aging under controlled temperature and humidity conditions, the refrigeration system in the kitchen must allow for both temperature and humidity control, ideally with multiple, individually-adjusted compartments. Cheesemaking requires small amounts of rennet and/or other products; these can be provided from Earth, or harvested; rennet can be produced either from carcases or via microbial culture. Without rennet, simple cheeses can be produced from almost any acid, including citric acid (ex. paneer), tartaric acid (ex. mascarpone), and vinegar (ex. ricotta).

Meat

Regardless of crew actions, meat is inherently generated by the process of raising animals, in that if not slaughtered they will eventually die a natural death and thus be a potential source of meat. If the crew is not opposed to slaughter, this can at times be the nutrition-optimal solution, such as when an animal's productivity has declined and more efficient feed conversion can be achieved by their replacement with a younger animal. And of course, given sufficient space and feed, animals can be raised with the specific intent of maximizing growth for slaughter. It falls on the crew to decide what they are comfortable with.

In the first two cases, however, it can be demonstrated that the amount of meat produced is very small. We will look at how much meat will be produced per crew member if livestock experience a linear increase in mass up to maturity and produce eggs or milk for 30% of their natural lifespan.

Type	# to produce 250 kcal/day egg or milk per crew (mature and immature)	Days to first production	Production days	Total living animal mass (kg)	Meat, g/day per crew
Chicken	5.4	140	877	5.5	5.4
Duck	3.6	147	1096	7.2	5.8
Goose	2.2	259	2191	6.8	2.8
Quail	23.5	49	274	3.3	10
Turkey	10.6	196	329	91	174
Goat	0.54	360	1096	16	11
Sheep	0.52	458	1205	22	14
Cow	0.12	793	1972	30	11
Water Buffalo	0.07	839	2739	32	8.9

- *Edible carcass mass taken at 50% of live animal mass*

As can be seen, with the exception of turkeys, the production of sizeable amounts of milk and eggs yields only small amounts of meat, even with slaughter. The reason for the exception in the case of turkeys is due to their nature of very poor producers of eggs, and thus requiring large amounts of animal mass (and correspondingly large feed consumption).

If more meat is desired from traditional sources, it must be specifically raised as such. However, it quickly becomes apparent that significantly greater amounts of feed and space will be required, even if the process (breeds, feeding) is optimized for meat rather than dairy or eggs. Contrarily, lab-grown meat is rapidly reaching maturity, and startups are seeking to scale up for consumer sales.[544] Lab-grown meat is efficiently produced and provides no moral qualms. However, its feedstocks must be carefully controlled, rather than being a way to convert agricultural waste.

Aquaculture

Tanks loaded with water can be heavy, but when empty, fibre-reinforced tanks need not be. Aquaculture can be fed by several means, including algae / aquatic plant growth, agricultural waste, and in some cases animal waste. The latter is a common, albeit controversial practice in tilapia farming in China, and can provide for a portion of their diet at the cost of contamination and odour concerns.[545]

Aquatic phototrophs tend to have high photosynthetic efficiency.[546] Fish production can be in the same tankage as algae, yielding a low fish density. At 75g/m²/day algae growth (accounting for elevated light and easily boosted CO_2), and with mature tilapia consuming 4% of their body mass per day, growing ~3g/day (450g body mass),[547] each square meter of clear-bottomed fish pond produces 12.5 grams of meat per day. In-situ production requires inaccessible areas for algae/plants to shelter to prevent overgrazing.

High density tilapia farming in California. Photo: Torti Tude

Conversely, fish can be raised in a setup separating high density fish farming from algae cultivation. The latter has been investigated for use on Mars.[548] The net mass of fish production in either algae-based system is limited primarily by the amount of light falling on the water. High density systems, while preventing overgrazing and being more convenient, require more careful environmental control to ensure proper oxygenation and removal of

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[544] Hafner, J. (2017, March 16). Lab-grown chicken strips, made from animal cells, debuted by startup. *USA Today*.
[545] Brown, C. L., Yang, T., Fitzsimmons, K., & Bolivar, R. B. (2014). The Value of Pig Manure as a Source of Nutrients for Semi-Intensive Culture of Nile Tilapia in Ponds (A Review). *Agricultural Sciences, 05*(12), 1182-1193. doi:10.4236/as.2014.512128
[546] Dismukes, G. C., Carrieri, D., Bennette, N., Ananyev, G. M., & Posewitz, M. C. (2008). Aquatic phototrophs: efficient alternatives to land-based crops for biofuels. *Current Opinion in Biotechnology, 19*(3), 235-240. doi:10.1016/j.copbio.2008.05.007
[547] Lim, C. (2008). *Tilapia: biology, culture, and nutrition*. New York: Food Products Press.
[548] Muller, M. S., Bauer, C. F.: *Oxygen Consumption of Tilapia and Preliminary Mass Flows through a Prototype Closed Aquaculture System*. NASA-TM-111882

NASA / ARC tilapia aquacultire experiment

wastes, as well as a method of supplying algae from their growth pond. Aeration is generally not required for low density cultivation.

Collection of certain algae (notably laver, also chlorella), even without the raising of fish, can provide a vegan source of B12. This requires filtering, drying, and depending on the species of algae potentially further processing to render it edible or extract the B12 as a supplement.[549]

Algae/water plant ponds and low-density fish ponds can be used for swimming, so long as animal waste is not used in the process. Algae ponds can provide enrichment and potentially nutrition for waterfowl such as ducks and geese, although access to water is in no way a requirement.

Edible sea lettice sometimes coats beaches. Photo: Thesupermat

As a general rule, aquatic species of interest cannot be transported as cryopreserved eggs or embryos (sperm cryopreservation is not a problem). There are exceptions - for example, salmonid eggs have been successfully cryopreserved,[550] but these are predominantly carnivorous species and thus inefficient for production. Despite much work, egg cryopreservation has not been achieved with common farmed vegetarian species such as tilapia.[551] However, most aquatic species demonstrate a useful property, in that when environmental conditions are poor, rather than dying, they exhibit little to no growth. This enables shipment of young in tiny volumes without significant growth during transit.

Tilapia fingerlings. Photo: Goldentilapia.com LLC

As an example, we look at the case of tilapia. Red tilapia fingerlings grow from 1 gram to 225 grams at 28°C, but simply by reducing the temperature to 22°C they reach only around 30 grams in the same timeperiod. Rate of growth also depends strongly on feeding. Just to reach 1 gram size in ideal conditions takes approximately 4 weeks for tilapia - far longer in suboptimal conditions. Even in some real-world growth tests not designed to minimize growth, the 4-week size

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549 Watanabe, F., Yabuta, Y., Bito, T., & Teng, F. (2014). Vitamin B12-Containing Plant Food Sources for Vegetarians. *Nutrients, 6*(5), 1861-1873. doi:10.3390/nu6051861

550 Rall, W. F. (1993). Advances in the Cryopreservation of Embryos and Prospects for Application to the Conservation of Salmonid Fishes. *Genetic Conservation of Salmonid Fishes,* 137-158. doi:10.1007/978-1-4615-2866-1_10

551 Poleo, G. A., Godke, R. R., & Tiersch, T. R. (2005). Intracytoplasmic Sperm Injection Using Cryopreserved, Fixed, and Freeze-dried Sperm in Eggs of Nile Tilapia. *Marine Biotechnology, 7*(2), 104-111. doi:10.1007/s10126-004-0162-5

can be as little as 100mg. Eggs are hatched 650-1350 per liter in small systems. In short, keeping significant numbers of tilapia small during a long transit should be readily achievable by the use of diet restriction and temperature reduction.[552]

We will not go into an exhaustive list of species for aquaculture (including fish, shellfish, crustaceans, etc), only to note that all species utilized should be efficient grazers and/or detritivores. Species already well established for aquaculture should be used such that the details concerning their rearing are well understood. For example, with tilapia, it is important that either all fish in the primary tank be males, or that harvesting is done before the fish reach maturity; otherwise, they will breed in the primary tank, which has the effect of creating many small fish that eat disproportionately much compared to their body mass but stand no chance of reaching adulthood. A secondary hatching/fingerling tank setup - ideally that which they were transported to the habitat in - is required for breeding.

Apiculture

Generally unthinkable from the perspective of an early-phase Mars habitat, the large sizes of a Landis habitat allow for both sufficient agricultural capacity to sustain a small hive of honeybees as well as sufficient space to separate the crew from the hive.

Transport to Venus may at first appear to be an issue, but the seasonal cycle of beehives suits well for transportation. Honeybees stop foraging at low temperatures. When outdoor temperatures have dropped sufficiently, the queen stops laying and the hive population reduces to minimize resource consumption. During this period they form up into a ball known as the winter cluster, which slowly moves across the comb, eating their honey reserves (generally around 20kg for a typical hive in a typical winter). Hives can also be fed with sugar water and protein supplements during periods where the temperature is high enough to allow bees to leave the hive. As soon as temperatures rise sufficiently, the queen begins laying a new generation of workers to rapidly expand the hive for the spring.[553] [554]

In short, a sealed box containing a climate controlled hive needs little to no maintenance in transit. Bees are hygienic animals, keeping their hive clean of all debris and potential sources of contamination - including removing bees that die inside. Indeed, bees have already been flown aboard the Space Shuttle, even demonstrating the ability to produce honeycomb in weightlessness.[555]

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[552] Santos, V. B., Mareco, E. A., & Silva, M. D. (2013). Growth curves of Nile tilapia (Oreochromis niloticus) strains cultivated at different temperatures. *Acta Scientiarum. Animal Sciences, 35*(3). doi:10.4025/actascianimsci.v35i3.19443
[553] Routh, J. (2012) Spring Feeding of Honey Bees. British Beekeepers Association.
[554] Seeley, T. D., & Visscher, P. K. (1985). Survival of honeybees in cold climates: the critical timing of colony growth and reproduction. *Ecological Entomology, 10*(1), 81-88. doi:10.1111/j.1365-2311.1985.tb00537.x
[555] Poskevich, D. (1989) A comparison of honeycomb structures built by *Apis millifera* (SE82_17). In: Jackson JT, Christie NW, comps.*Shuttle Student Involvement Program (SSIP) Final Reports of Experiments Flown*. Houston TX: National Aeronautics and Space Administration, Lyndon B. Johnson Space Center; 1989 Oct. JSC 24005.

Rates of annual honey production in semitropical environments vary widely; however, the Australian average is 75 kg.[556] Open sources of water must be made available, as bees collect water to drink and thermoregulate.

It is an open question as to how honeybees would navigate inside a 3d environment without a distinct “ground”, including dealing with changes of habitat pitch and with no distinct sun disc. Bee navigation is a complex topic involving both sun angles (which their brains automatically adjust for the passage of time when the sun is not visible) and vision. Their navigational ability appears to be hindered in the absence of ultraviolet light.[557] Bees convey positions to each other via waggle dancing on the comb, where upwards movement corresponds to the current sun position and the distance corresponds to the distance from the hive; bees choose to listen or ignore it based on their individual level of success at finding food, and can dispute a waggle with a 380hz buzz.[558] A bee navigating to a particular location flies a direct “beeline” to its approximate location, then begins a random search looking for the pollen/nectar source.

Honeybee pollinating an avocado flower. Photo: Andrew Mandemaker

In short, while their random-search behavior at destinations may provide some ability to compensate, bee navigational systems are not designed to convey three dimensional information and are premised around the presence of some form of ground and sun disc. If testing reveals difficulty in finding food resources, light cues could be mimicked with LED lights on the envelope that move based on the time of day. Additionally, solar cells on the lower envelope might be interpreted as some form of ground. However, experimentation will be required.

Bees do have a degree of learning ability. While often researched in terms of ability to learn what colours and shapes provide the best food resources,[559] of greater applicability is their ability to learn to recover from circadian rhythm disruptions.[560] This might assist in adapting to longer day lengths.

The area which a single hive can pollinate varies greatly based on race, colony strength, food availability, and other conditions - one study found ranges varying from 45 to 5983 meters.[561] Colony strength is important; a wide range of fungal, bacterial, viral diseases and macroscopic parasites infest bees and hives, including nosema, varroa and tracheal

[556] Gibbs, D. M. H. Muirhead, I. F. (1998) The economic value and environmental impact of the Australian beekeeping industry.
[557] Cockell, C. S., & Andrady, A. L. (1999). The Martian and extraterrestrial UV radiation environment—1. Biological and closed-loop ecosystem considerations. *Acta Astronautica, 44*(1), 53-62. doi:10.1016/s0094-5765(98)00186-6
[558] Nieh, J. C. (2010). A Negative Feedback Signal That Is Triggered by Peril Curbs Honey Bee Recruitment. *Current Biology, 20*(4), 310-315. doi:10.1016/j.cub.2009.12.060
[559] Jones, P. L., & Agrawal, A. A. (2017). Learning in Insect Pollinators and Herbivores. *Annual Review of Entomology, 62*(1), 53-71. doi:10.1146/annurev-ento-031616-034903
[560] Ludin, N. M., Cheeseman, J. F., Merry, A. F., Millar, C. D., & Warman, G. R. (2016). The effects of the general anaesthetic isoflurane on the honey bee (Apis mellifera) circadian clock. *Chronobiology International, 33*(1), 128-133. doi:10.3109/07420528.2015.1113987
[561] Abou-Shaara, H. F. (2014) The foraging behaviour of honey bees, Apis mellifera: a review. *Veterinarni Medicina*, 59, 2014 (1): 1–10

mites, american and small hive beetle, wax moth, european foulbrood, stonebrood, chalkbrood, deformed wing, sacbrood, acute bee paralysis, and numerous others. Keepers generally must open up hives multiple times a year to inspect for and treat diseases and parasites, as well as to monitor the queen. The ability to send, as much as is possible, a completely sterile and pest free stock would be of great advantage to local apiculture.

Electric tomato pollinator. Photo: Sucatool

Prototype pollination drone.
Photo: Eijiro Miyako

While flowers intended specifically for providing bees large amounts of pollen and nectar could be grown (additionally providing for a nice living environment), and honey is a desirable product, the pollination service provided by bees for agricultural crops is arguably the most valuable benefit they bring. Plant needs for pollination range from no benefit, to improved yields, to pollination being essential for fruit set. Pollination can be done by hand, and there exist tools to simplify it; however, this is a high labour task. More recently, a prototype drone-based pollination system has been developed, using an ionic gel to transfer pollen.[562]

[562] Chechetka, S. A., Yu, Y., Tange, M., & Miyako, E. (2017). Materially Engineered Artificial Pollinators. *Chem, 2*(2), 224-239. doi:10.1016/j.chempr.2017.01.008

8. Mineral Resources and Economics

While it can be desirable to operate initially using only resources available from the atmosphere, the ground below provides a wide variety of resources, both locally useful and potentially valuable for export. However, the hostile surface environment requires careful consideration.

Surface access

No solid surface in the solar system better conjures up images of Hell than Venus - a planet whose highest point, Skadi Mons is named after a Norse giantess whose very name means "damage". The 45 bar / 380°C (just below the melting point of zinc) environment there at 10.7 km is tame compared to the planetary mean of 95.6 bar / 467°C.[563] Multiple volcanoes show signs of recent activity,[564] while Ganiki Chasma was observed giving off infrared flashes indicative of ongoing volcanic eruption.[565] Only a handful of landers have landed on Venus's surface, and returned us only a small amount of data. How accessible can such a location be?

Venera 8 surface image. Photo processed by Don P. Mitchell.

The answer is, "surprisingly accessible" - in a broad sense.

Let us look at the Venera landers. Based around a roughly spherical titanium pressure shell on the outside, they were then lined with thermal insulation, followed by a "heat accumulator". This was simply a phase-change material which can store a great deal of heat before it continues its change in temperature - in this case, lithium nitrate trihydrate, which melts at 30°C. As for the cooling system, there was none. Simple thermal inertia allowed the landers to survive for over two hours using 1970s insulation technology.[566] This is not a limit; the larger the size of the lander, the longer the possible survival times, due to the greater the ratio of thermal mass to surface area and thicker insulation. The dense atmosphere makes gentle landing easy - Venera 7, a heavy metal sphere in near free fall after its parachute failed, hit the ground at only 17 m/s (38 mph) and continued operating.[567]

While the interior of a lander is relatively easy to keep at a comfortable temperature for a few hours, much more challenging are any external moving parts or pieces of sensitive scientific equipment. By the time of Venera 13 and 14 in 1981, however, the USSR had solved these problems - lubricants which tolerate high heat, motors whose magnets have high curie temperatures, etc.[568] Motors designed for extraction of smoke in fire emergencies

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[563] Fegley, B., Jr. (2016). *Practical Chemical Thermodynamics for Geoscientists*. Academic Press.
[564] Shalygin, E., Basilevsky, A., Markiewicz, W., Titov, D., Kreslavsky, M., & Roatsch, T. (2012). Search for ongoing volcanic activity on Venus: Case study of Maat Mons, Sapas Mons and Ozza Mons volcanoes. *Planetary and Space Science, 73*(1), 294-301. doi:10.1016/j.pss.2012.08.018
[565] Shalygin, E. V., Markiewicz, W. J., Basilevsky, A. T., Titov, D. V., Ignatiev, N. I., & Head, J. W. (2015). Active volcanism on Venus in the Ganiki Chasma rift zone. *Geophysical Research Letters, 42*(12), 4762-4769. doi:10.1002/2015gl064088
[566] Mitchell, D. P. (2004) *Venera: The Soviet Exploration of Venus*.
[567] Mitchell, D. P. (2004) *Venera: The Soviet Exploration of Venus*.
[568] Mitchell 2004.

tend to be optimal for use in Venus environments.[569] Magnetic actuators and induction motors can provide for penetration-free connections between the inside and the outside. Optical transparency is provided by fused quartz or high temperature glasses such as Vycor, which are widely used in scientific research. Alloys compatible with the surface's anhydrous acids and sulfur dioxide are well understood.

Getting back off the surface may likewise sound exceedingly difficult, but this too is well understood conceptually (although at relatively low TRL). There are two primary techniques. The first is phase-change balloons, similar to the technique used for buoyancy control and discussed previously. A liquid, such as ammonia, is condensed and stored in a pressure vessel. This helps provide thermal inertia for the lander, while its pressure steadily builds. When it is time to leave, the ammonia is allowed to flash to vapour inside a heat-tolerant balloon, such as a PBO/PIBO, carbon fibre, and/or metal-based fabrics. The balloon is either allowed to grow vertically, or a secondary balloon is deployed, to allow for greater inflation volume as it rises over the course of 1-2 hours. At altitude, the lander and habitat head for rendezvous, having been separated by many hundreds of kilometers by the zonal winds (“overshooting" the altitude can help a lander catch up by putting it into faster zonal winds). After docking, offloading, and recharging, any non-condensed phase-change liquid is re-chilled and its balloon is retracted / repacked. The lander drops off toward its next destination, landing approximately 45 minutes later.

In a future situation with multiple habitats, redocking with the same habitat is no longer necessary; 10-20 habitats at the same latitude could each pick up the lander launched by the habitat ahead of them, thus significantly increasing throughput.

0.8m diameter bellows. Image: NASA / JPL-Caltech

An alternative to the phase change balloon is the bellows balloon, also discussed previously. A metal bellows is expanded or contracted by a winch or actuator, changing its volume and thus its density. Due to the high pressures at the surface, a very small bellows has the capability for very large changes. A bellows balloon is envisioned in the VME and VISE mission concepts, and Venus-compatible bellows have already been created and tested in the lab.[570] [571] Due to the limited size of a bellows, however, a secondary balloon would be necessary to reach habitat altitudes.

Long-term operation at the surface is difficult, although surprisingly possible. Power can be provided by solar triple junction cells (albeit only at 8.7 W/m²),[572] RTGs (albeit with

[569] Bar-Cohen, Y., Bao, X., Badescu, M., Sherrit, S., Lee, H. J., Zacny, K., . . . Mumm, E. (2015). Drilling and Sample Transfer Mechanisms for Potential Missions to Venus. *Inner Solar System,* 163-187. doi:10.1007/978-3-319-19569-8_8

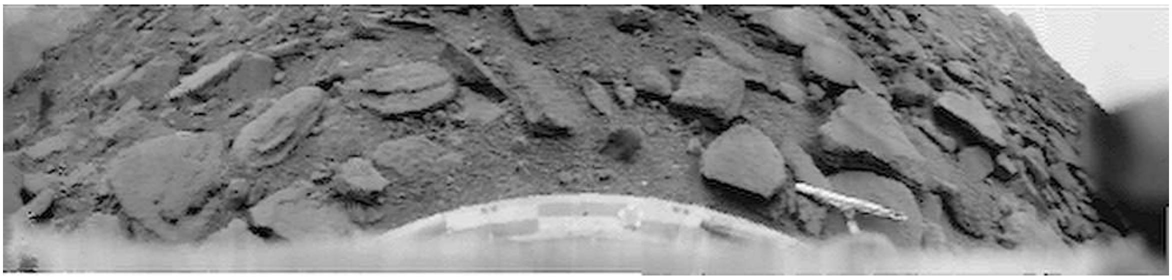
[570] Kerzhanovich, V., Hall, J., Yavrouian, A., Cutts, J. (2006) Dual Balloon Concept For Lifting Payloads From The Surface Of Venus. Jet Propulsion Laboratory, California Institute of Technology. Fourth International Planetary Probe Workshop. Pasadena, CA, USA, June 27-30, 2006

[571] Amato, M., & Williams, D. (2015). Accessing the Venus Lower Atmosphere and Surface- from Venera and Pioneer Venus to VISE and VITaL. *Inner Solar System,*71-100. doi:10.1007/978-3-319-19569-8_4

[572] Landis, G. A., & Haag, E. (2013). Analysis of Solar Cell Efficiency for Venus Atmosphere and Surface Missions. *11th International Energy Conversion Engineering Conference*. doi:10.2514/6.2013-4028.

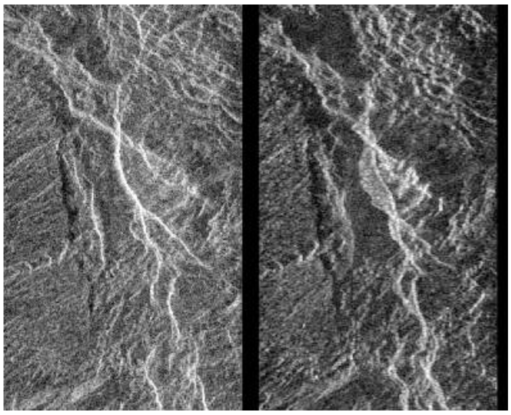
cooling challenges),[573] or wind. The latter been the most proposed, including Venera-D's proposal of a surface wind turbine and “vetrolet” kite, and Zephyr, which proposed to use a sail for locomotion.[574] A particularly curious proposal is AREE, a NIAC design study for an electronics-free wind-powered walking rover.[575] Venus's surface winds are mild, usually only around 1 m/s, but because of the high density still contain significant amounts of energy.

As far as recovering material from the surface, a variety of methods have been researched for the purpose of scientific sample returns, including drills, hammers, ultrasonic bores, thermal spalling, thermal melting, and cutting blades.[576] One might add explosives to the list, in an environment where in-situ production of nitric acid is available. All of these options, however - studied for taking very small volumes of scientific samples - are only necessary where there is unbroken rock.



Venera 9 , close view. Photo processed by Don P. Mitchell.

Venus's atmospheric density, about 67kg/m³, is about halfway between that of water and air on Earth on a logarithmic scale. Surface dredging - using the same fan as is used for propulsion - suggests a means for rapid collection of bulk loose material.



Landslides, like this on Aphrodite Terra, periodically expose fresh material. Image: NASA / JPL.

While robotic access is clearly the critical path for resource collection, the question inevitably turns to humans. As for any destination in space, there are many reasons always put forth for sending humans out on missions. They can fix things. They can repair things. They can operate faster. They can make serendipitous discoveries. There is some merit to each of all of them.

Do any of these justify the cost of developing systems to put humans on the surface? This is highly unlikely.

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[573] Landis, G. A., & Mellott, K. C. (2007). Venus surface power and cooling systems. *Acta Astronautica, 61*(11-12), 995-1001. doi:10.1016/j.actaastro.2006.12.031
[574] Badescu, V., & Zacny, K. (2015). *Inner solar system: prospective energy and material resources*. Cham: Springer.
[575] Sauder, J. (6 April 2007) *Automaton Rover for Extreme Environments (AREE)*. NASA / JPL.
[576] Bar-Cohen, Y., Bao, X., Badescu, M., Sherrit, S., Lee, H. J., Zacny, K., . . . Mumm, E. (2015). Drilling and Sample Transfer Mechanisms for Potential Missions to Venus. *Inner Solar System,* 163-187. doi:10.1007/978-3-319-19569-8_8

However, there is a much simpler point to make, which is simply that people will want to go there. And when people are paying the great cost to make an interplanetary journey, the relatively small incremental cost of developing the capability to place people on the surface becomes increasingly justified, if not outright obvious.

Maxwell Montes rises steeply over the surrounding terrain - Venus's Mount Everest. On its slopes, snows or frosts of some conductive or semiconductive material such as iron pyrite, bismuthinite or galena covers the ground.[577] The deep Diana Chasma (~15°S, ~155E, -2.9km altitude) is a a 100 km wide / 900 km long canyon featuring a 7 km deep dropoff from its surrounding cliffs; Venus's rocks are much harder than Earth's due to a lack of water, allowing for more dramatic landscapes.[578] Venus even has the longest river channel in the solar system (Baltis Vallis), 7000 km long and 20-100m deep, carved by an unknown substance - most likely an exotic low-temperature lava such as oily-black natrocarbonatite.[579] At these low altitudes, when the night falls, the ground may glow a dim crimson. While Mars is often compared to Earth's deserts, Venus has no comparison. It's a whole world down there, nearly as large as Earth and sculpted by processes totally alien to our experience.

The lava glow from Ol Doinyo Lengai, Earth's only active carbonatite volcano, visible only after sunset. The fast-flowing 500-600°C lava is only slightly hotter than the surface temperature at lower altitudes on Venus.
Photo: Marco Fulle - www.stromboli.net

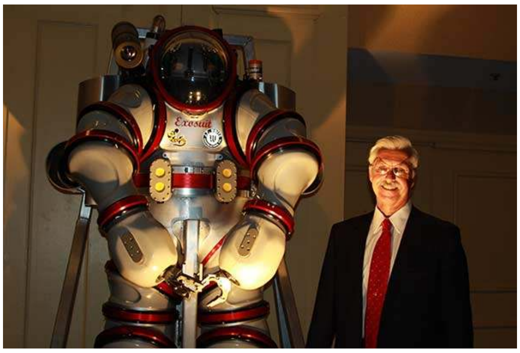
Climbing Mount Everest is only accessible to the fit, costs $30-$100k per attempt[580] (compared to the $100k that SpaceX predicts that their ITS launch system will eventually provide round-trip tickets to Mars for)[581] and kills half a percent of the people who attempt it. 1000 people try annually.[582] What candle does Everest hold to the surface of Venus? It's safe to say that eventually - even if the timeframes for achieving such launch price reductions are more delayed than proponents would prefer - there will be interplanetary tourism.

Clearly, if one can deliver landers to the surface, they could deliver humans to the surface in a "submersible" style vehicle. But that is not the personal experience that adventure seekers desire. Traditional space suits cannot function in such conditions, but there is one kind that can: hard-shell suits. Used today for deep-sea diving, NASA originally developed hard suits for the Apollo programme; progress proceeded faster than on the competing soft suit programme, but the latter eventually won out due to weight.

[577] Radar-Reflective Minerals Tested Under Venus Near-Surface Conditions (2014) Radar-Reflective Minerals Tested Under Venus Near-Surface Conditions. *American Geophysical Union*, Fall Meeting 2014, abstract #P21B-3913
[578] Nimmo, F., & Mckenzie, D. (1998). Volcanism And Tectonics On Venus. *Annual Review of Earth and Planetary Sciences, 26*(1), 23-51. doi:10.1146/annurev.earth.26.1.23
[579] Komatsu, G., Waltham, D., & Bray, V. J. (2014). Canali (Venus). *Encyclopedia of Planetary Landforms,* 1-8. doi:10.1007/978-1-4614-9213-9_36-1
[580] Hansmann, H (2003, 1 May) *How Much Does It Cost to Climb Everest?* Outside.
[581] Musk, E (2016). *Making Humans a Multiplanetary Species*. 67th International Astronautical Congress, Guadalajara.
[582] Jenkins, M. (2013, June) *Maxed Out on Everest*. National Geographic.

NASA continued work on hard suits, culminating in the AX-5 in 1988.[583] While easily superior to soft suits in enabling a full range of motion, they were never able to overcome the weight disadvantage. Today, hard shell suits see use in the form of atmospheric diving suits for deep underwater repair and recovery, such as the Newtsuit, Exosuit and WASP.

NASA AX-3 hard-shell pressure suit. Photo: NASA



Exosuit, an atmospheric diving suit with a crush pressure 2/3rds that of Venus's surface. Photo: Nuytco Research, Ltd.

A Venus hard suit, like an unmanned lander, would need the same outer layers: pressure shell and insulation. Inside, a heat accumulator like with Venera could be used, or contrarily, a heat pump. In Landis et al (2011), a 216W Stirling Duplex heat pump is assessed to be sufficient to maintain a 1m sphere at 250°C;[584] one to two additional stages could reduce this to body temperature.

The pressure shell, insulation, and thermal management will, of course, make the suit quite heavy. However, there is a simple workaround to the problem, desirable regardless of the suit mass: the aforementioned bellows balloon. And as with an unmanned probe, with just a small bellows balloon, a person in such a suit could fly. With small wings, they could soar and glide as well, with dive speeds up to or exceeding Venera 7's descent speed of 17 m/s (attempting to fly with small wings is not recommended on Mount Everest).

Some aspects of the sources of revenue for a Venus colony have already been briefly addressed, such as sales of deuterium and the potential for tourism. We will briefly cover several others here, after first addressing the surface composition.

Surface resources

A brief summary of our knowledge of Venus's surface would be: "not much". However, the little that we do know can give some clues as to what elements of value might be recoverable from it. First, we list the surface mineral types detected by the various landers and some concentrations of incompatible elements therein (boldfaced samples analyzed with XRF):[585] [586]

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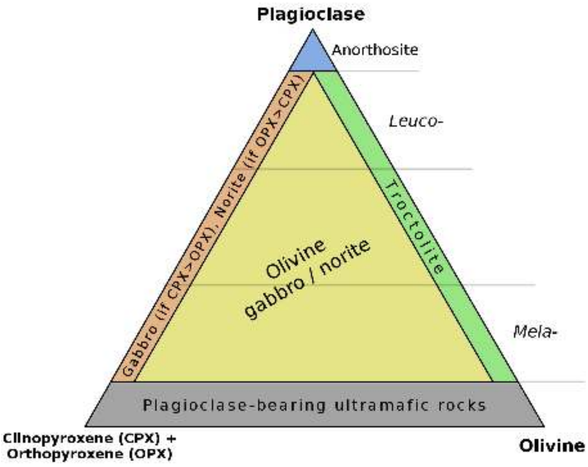
[583] Benson, E. A. (n.d.). *Investigation of a Cable-driven Parallel Mechanism for Pressure Suit Arm and Motion Assistance*. University of Maryland.
[584] Landis, G. A., Dyson, R., McGuire, M., Oleson, S., Schmidt, G., Grantier, J., ... McCurdy, D. (2011) Human Telerobotic Exploration of Venus: A Flexible Path Design Study. *49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition*, Aerospace Sciences Meetings. doi:10.2514/6.2011-335
[585] Abdrakhimov, A.M., Basilevsky, A.T. (2002) Geology of the Venera and Vega Landing-Site Regions. *Solar System Research*. 36: 136. doi:10.1023/A:1015222316518

[586] Kargel, J. (1993). The Volcanology of Venera and VEGA Landing Sites and the Geochemistry of Venus. *Icarus, 103*(2), 253-275. doi:10.1006/icar.1993.1069

Lander	Description	U (ppm)	Th (ppm)	K (ppm)
Venera 8	Uncertain; initially thought granitic because of the high rate of incompatible elements, but Venera 13 found the same from samples that were apparently basalt.	2.2	6.5	40000
Venera 9	Tholeiitic basalt / enriched MORB.	0.60	3.65	4700
Venera 10	Tholeiitic basalt / normal or enriched MORB. Hard, decrystallized, highly weathered.	0.46	0.7	3000
Venera 13	**Leucitic basalt / weakly differentiated melanocratic alkaline gabbroid**	-	-	33000
Venera 14	**Tholeiitic basalt / MORB**	-	-	1700
Vega 1	Tholeiitic basalt / normal MORB	0.64	1.5	4500
Vega 2	**Anorthosite-norite-troctolite**[587]	0.68	2.0	4000

Incompatible elements are elements that fit poorly within the crystal structure of rock. They are the first elements to enter the melt phase of a solution and the last phase to leave it; as a consequence, they help tell of the history of the magma that formed the rock. Examples of incompatible elements are potassium, rubidium, cesium, strontium, barium, zirconium, niobium, hafnium, rare earth elements, thorium, uranium, and tantalum.



Classification of gabbroic rock.

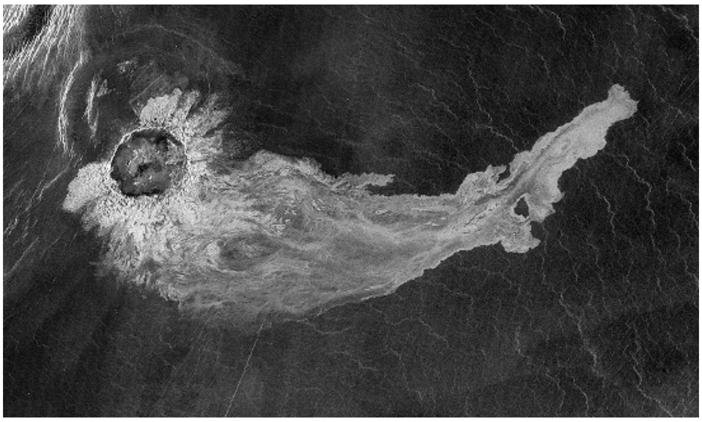
As a consequence of their histories, different types of rocks tend to have different levels of incompatible elements. Basalts (low-silica) are normally low in incompatible elements - particularly mid-ocean ridge basalts (MORB); contrarily, rhyolites (high silica) and granite are high in them. To give an example of typical values from basalts from the Earth and the moon:

Body	Sample	U (ppm)	Th (ppm)	K (ppm)
Earth	N-type MORB	0.047	0.12	600
Earth	E-type MORB	0.18	0.60	2100
Earth	OIB	1.02	4.20	12000
Moon	Low-Ti olivine 12002	0.22	0.75	415
Moon	Low-Ti olivine 15545	0.13	0.43	300
Moon	Low-Ti pigeonite 12064	0.22	0.84	580
Moon	Low-Ti pigeonite 15597	0.14	0.53	500
Moon	High-Ti, low K 70125	0.13	0.34	415
Moon	High-Ti, high K 10049	0.81	4.03	3000
Moon	Low-Ti, aluminuous 14035	0.59	2.1	830

[587] Surkov, Y. A., Moskaleva, L. P., Scheglov, O. P., Dudin, A. D., Kharyukova, V. P. (1986) VEGA-2 Lander Analysis of Rock Composition in Northern Aphrodite Terra. *Soviet Astronomy Letters*, vol. 12, Jan.-Feb. 1986, p. 28-31.

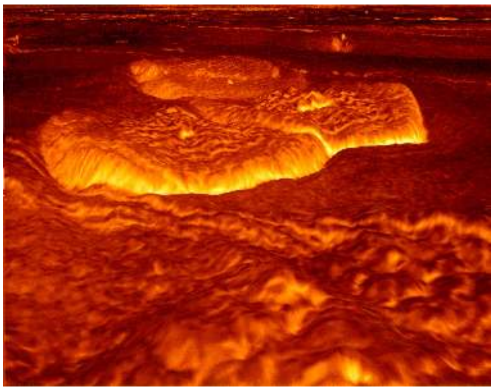
The peculiarly high values on Venus suggest the presence of highly evolved, well-differentiated basalts; the reason for these enrichments are not well understood. Concerning specific minerals suggested by the landers: anorthosite, while common on the moon, is rare on Earth; while different anorthosites share extreme plagioclase enrichment and depletion in incompatible elements, their various parent rocks and fractionation processes are still a topic of dispute.[588] Troctolite is similar to anorthosite except for with significant olivine enrichment instead of plagioclase - olivine being one of the first minerals to settle to the bottom during differentiation. Leucitic basalts, enriched in a high excess of potassium, are very rare on Earth. Indeed, only 0.1% of Earth upper crust is comprised of rocks as rich in potassium but as mafic as the Venera 8 and 13 samples.[589]

Surface features suggest the same story of slow differentiation processes. Large bolide impacts are not particularly common on Venus, but they create abnormal amounts of low-viscosity melt, which seems to persist for great lengths of time and often even overflow the craters of the impacts that created them. This is likely in no small part due to the high surface temperature environment.[590]



Addams Crater, with overflowing lava field. Image: NASA

Even in places where rhyolite seems to exist, it seems to be a consequences of secondary differentiation. Venus's pancake domes bear many similarities to Earth rhyolite domes (albeit abnormally smooth on radar echoes); if so, given the acidic environment they form in, they too would likely be due to secondary differentiation of basalts, akin to rhyolite volcanism in Iceland.[591]



Left: 3d reconstruction of Venusian pancake domes. Image: NASA.
Right: Panum Crater, California - rhyolite dome with tuff ring. Photo: USGS.

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588 Ashwal, L. D. (2012). *Anorthosites*. Springer-Verlag Berlin An.
589 Kargel, J. (1993). The Volcanology of Venera and VEGA Landing Sites and the Geochemistry of Venus. *Icarus, 103*(2), 253-275. doi:10.1006/icar.1993.1069
590 Dong, C. E. (2015) *Analysis and Comparison of Physical Properties and Morphology of Impact Melt Flows on Venus and the Moon to Determine Atmospheric Controls*. *Standard Theses*. 24.
591 Taylor, S. R., & McLennan, S. M. (2010). *Planetary crusts: their composition, origin and evolution*. Cambridge: Cambridge University Press.

A final factor to note is the theorized natrocarbonatite volcanism on Venus as an explanation for apparent river canyons like Baltis Vallis, as well as a number of other surface features. Carbonatites - low-temperature lavas which look like oil, flow like water and oxidize to bright white - are rare on Earth, with only one active carbonatite volcano in existence. These lavas are - again - highly differentiated and rich in incompatible elements.[592]

Natrocarbonatite stream.
Photo: Marco Fulle - www.stromboli.net

In short, it seems that if you're looking for magma differentiation and diversity different from Earth, Venus is the place to look.

Slow magmatic differentiation and layered mafic intrusions (LMIs) are associated with valuable mineralization. In such deposits on Earth, gabbros are frequently associated with economically important deposits of chromium, nickel, cobalt, gold, silver, platinum, copper and titanium, although this depends on the parent rock.[593] As a highly enriched end member, anorthosite is frequently found with the most valuable deposits in LMIs - bands of chromite (~100km long, <1.5m thick), the "Merensky type" platinum-group deposits, vanadium-rich magnetite layers, copper, gold, tin and others.[594] Highly incompatible element-rich lavas like carbonatites are widely associated with valuable deposits of phosphorus, niobium, tantalum, uranium, thorium, copper, iron, titanium, vanadium, barium, fluorine, and zirconium. As an example, South Africa's rich Palabora complex has produced valuable quantities of copper, cobalt, zirconium, hafnium, gold, silver, nickel, and platinum. It is rare among carbonatites for *not* containing significant deposits of niobium and rare earths.[595]

Long-lasting bolide melt pools are likewise associated with very valuable mineral deposits. For example, the Sudbury Basin represents one of the world's largest known impact craters; the result has been one of the world's largest mining centers, producing massive quantities of nickel, copper, platinum, palladium and gold.[596]

Differentiation of magmas is one of the major means to concentrating minerals. Additional keys to concentrating minerals and the creation of ore bodies are weathering and transport.

- Fluids selectively dissolve minerals soluble in them and carry them until they are no longer soluble, leaving them behind as precipitates

[592] Ionov, D. (1998). Trace Element Composition of Mantle-derived Carbonates and Coexisting Phasesin Peridotite Xenoliths from Alkali Basalts. *Journal of Petrology,39*(11-12), 1931-1941. doi:10.1093/petroj/39.11-12.1931
[593] Kumar, M. M., Krishna, G. V., Reddy, S. V., Kumar, R. A., & Ratnakar, J. (2016). The Boggulakonda Gabbros, Prakasam District, Andhra Pradesh, India: A Rich Source of Building Material. *IOSR Journal of Mechanical and Civil Engineering, 16*(053), 84-89. doi:10.9790/1684-16053018489
[594] Ashwal, L. D. (2012). *Anorthosites*. Springer-Verlag Berlin An.
[595] Heinrich, E. (1970). *The Palabora Carbonatitic Complex - A Unique Copper Deposit.*
[596] Ames, D. E., Davidson, A., & Wodicka, N. (2008). Geology of the giant Sudbury polymetallic mining camp, Ontario, Canada. *Economic Geology*, *103*(5), 1057-1077.

- Physical transport my fluids relocates minerals from one location to another until the environmental conditions (speed, turbulence) can no longer keep the minerals aloft. This tends to create areas that are eroded and areas in which deposits collect, while depositing denser minerals in different locations than lighter ones.

- Chemical and biologic processes selectively alter certain minerals while leaving others unaltered, changing their abilities to be dissolved and/or eroded/transported.

On Earth, surface fluid flows include water, air, and solid flows such as glaciers and tectonic alteration, while pressurized water and magma alter minerals under the ground. Earth's atmosphere is a very effective means of transport and chemically attacks minerals with oxygen, but is a poor solvent. Liquid water, underground and on the surface, is an excellent solvent, and readily varies in pH and dissolved minerals. This allowing for chemical weathering and deposition, in addition to physical weathering and transport by waves and rivers. Glaciers expose deeper rocks to the surface while tectonic forces compress and transport minerals to different environments. Frost, salt crystal growth and plants break up rocks. Magmatic intrusions heat surrounding rocks allowing for leaching and mineral alteration.

The "iron hat" of a gossan ore deposit on Thompson Island. Photo: John Scott, Thunder Bay Geological Services, Thunder Bay, Ontario.

A key to many of these processes is changes in environment. Minerals dissolved in hot deep waters would be retained in those waters if the environmental conditions remained constant. But as these mineral rich waters seep to the surface, the temperatures and pressures drop, precipitating out chert, gypsum, and other hydrothermal minerals.The greater the number of differing stages that act on a deposit, the more enriched it can become in various minerals. For example, the old gold mining phrase "*Gold wears an iron cap*" refers to gossan deposits, where sulfuric acid (formed from the action of water and oxygen on pyrite) heavily eats away at the rocks, leaving resistant minerals such as quartz (heavily stained red/brown/yellow by dissolved iron), and the gold contained therein.[597] Subsequent processes can further concentrate it - for example, alluvial and bench deposits occur when frost, glaciation and other means break up the deposit, allowing water to transport it, where gold settles out when the flow rate drops.[598]

At a first glance, this may appear to be a negative for Venus - and every other body in the solar system apart from Earth. While Venus has ample tectonic deformation and volcanism, it has no biologic activity, no liquid water, no ice, and no glaciers. However, if one is looking for minerals different than those found commonly on Earth, they're not looking for a second Earth; they're looking for a planet that has its own *different*, but still powerful

[597] Kelly, W. C.. Gossan. *Encyclopedia of Earth Science Mineralogy,* 194-195. doi:10.1007/0-387-30720-6_55
[598] (1994) *Extraction and Beneficiation of Ores and Minerals, Volume 6: Gold Placers*. U.S. Environmental Protection Agency. EPA 530-R-94

processes of dissolution, physical transport and chemical weathering. And Venus takes some of these to extremes.

Unlike Earth's atmosphere, which only "dissolves" water and small amounts of other compounds, Venus's dense, hot, acidic atmosphere is expected (and in some cases has been detected) to dissolve a staggeringly broad array of compounds, precipitating them out at different altitudes (see *Species of interest*). Some of the elements considered likely to undergo such precipitation include tellurium and indium compounds, each worth hundreds of dollars per kilogram and occasionally spiking higher. High altitude "frosts" are particularly appealing targets for sampling.

As discussed previously, liquids (likely low temperature magmas) have carved an extensive network of river canyons (*canali*) via thermal erosion. This phenomenon has only small-scale examples known on Earth, including examples with carbonatite lavas.[599] The amount of thermal erosion needed to carve a river channel larger than the Amazon River is a transport process entirely alien to our experience.

Elastomer o-ring dissolving in supercritical CO_2. Photo: Martyn Poliakoff

Volcanic features appear to be much more abundant on Venus than Earth, with more than a hundred supermassive (100-1000 km diameter) volcanoes, as well as orders of magnitude more smaller volcanoes scattered around the planet. Perhaps one of the most unusual fluid possibilities is the suggestion in Bolmotov (2014) that Venus's atmosphere might at times in the past have collapsed into a supercritical fluid foam.[600] Supercritical CO_2 is commonly used as a solvent on Earth. In magma, supercritical carbon dioxide, along with water, is a major contributor to mineral mobility and lode formation.[601] [602] In lava flows, by Henry's law the equilibrium CO_2 level is many orders of magnitude higher than on Earth, increasing mineral mobility at shallow depths.

Lower levels of water would appear to be a hindrance, but it has been argued that the continued presence of water vapour in Venus's atmosphere implies that the mantle is not fully devolatilized. Not only would water assist in differentiation and reduction of viscosity at depth, the water could even persist at up to 1% concentration in surface melts, due to Venus's high atmospheric pressure.[603] Such water would not persist once cooled; Venus's rugged landscapes strongly suggest a hard, water-degassed crust.

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[599] Kerr, R. C. (2001). Thermal erosion by laminar lava flows. *Journal of Geophysical Research: Solid Earth, 106*(B11), 26453-26465. doi:10.1029/2001jb000227
[600] Bolmatov, Dima, et al. Structural evolution of supercritical CO2 across the Frenkel line. *The journal of physical chemistry letters* 5.16 (2014): 2785-2790.
[601] Kokh, M. A., Akinfiev, N. N., Pokrovski, G. S., Salvi, S., & Guillaume, D. (2017). The role of carbon dioxide in the transport and fractionation of metals by geological fluids. *Geochimica et Cosmochimica Acta*, *197*, 433-466.
[602] Lowenstern, J. B. (2001). Carbon dioxide in magmas and implications for hydrothermal systems. *Mineralium Deposita*, *36*(6), 490-502.
[603] Elkins-Tanton, L. T., Smrekar, S. E., Hess, P. C., & Parmentier, E. M. (2007). Volcanism and volatile recycling on a one-plate planet: Applications to Venus. *Journal of Geophysical Research, 112*(E4). doi:10.1029/2006je002793

In addition to liquid transport, Venus's surface winds have been directly observed relocating dust from surface landers. While usually only blowing around a meter per second or less, the high density means that the atmosphere still has the ability to loft and transport particulate. Venus's lofted particulate is likely to be finer than Earth's, and conditions tend to form smaller dunes than elsewhere in the solar system due to the dense atmosphere. The characteristic dune length is ~20m on Earth, ~600m on Mars, but only ~10-20cm on Venus. Radar data suggests such "micro-dune" deposits in the southern hemisphere. Venus also has two fields of large dunes - Menat Undae and Al-Uzza Undae, the latter of which, at 67°N, would be well within range of a habitat designed for a nominal 70°N. Also detected by radar are thousands of wind streaks and features interpreted as yardangs.[604]

Yardangs in Kalout, Dasht-e-Lut. Photo: Thorsten

In short, Venus has most everything you would want to see in a planet if you were looking for mineral prospects - high temperatures, fluids eroding and transporting minerals into areas of different temperature and pressures, extensive intrusive volcanism, tectonic alteration, evidence favorable to heavy magma stratification, and so forth. While we have little data to say with any certainty at all what minerals of value *can* be found on Venus, all of the pieces together make it a compelling prospecting target.

To determine what might be worth transport to Earth, we will examine many of the most valuable naturally-occurring elements on the market (prices as of 11 January 2017). Where there is a significant difference in the price per kilogram between the mass weighted value of the element in its refined state and in its ore state, the value of the ore will be given.

Silver[605]	$540
Terbium[608]	$550
Beryllium[611]	$835
Lutetium[614]	$1.3k (oxide)
Ruthenium[617]	$1.3k
Xenon[620]	$2.3k

Rhenium[606]	$2.4k
Scandium[609]	$4.2k (oxide)
Thulium[612]	$6k (old data)
Cesium[615]	$13.2k
Osmium[618]	$13k

Iridium[607]	$23k
Palladium[610]	$24k
Rhodium[613]	$26k
Platinum[616]	$31k
Gold[619]	$38k

[604] Bourke, M. C., Lancaster, N., Fenton, L. K., Parteli, E. J., Zimbelman, J. R., & Radebaugh, J. (2010). Extraterrestrial dunes: An introduction to the special issue on planetary dune systems. *Geomorphology, 121*(1-2), 1-14. doi:10.1016/j.geomorph.2010.04.007
[605] *Gold Price*. Retrieved from http://goldprice.org/
[606] *Catalysts*. BASF. Retrieved from https://apps.catalysts.basf.com/apps/eibprices/mp/
[607] *Rare Metals Prices and Charts*. Quandl. Retrieved from https://www.quandl.com/collections/markets/rare-metals
[608] Mineral Prices. Retrieved from http://mineralprices.com/
[609] Mineral Prices. Retrieved from http://mineralprices.com/
[610] *Palladium Prices and Charts*. Quandl. Retrieved from https://www.quandl.com/collections/markets/palladium
[611] *SMM Ranking by Metal Price Increase.* Retrieved from https://news.metal.com/newscontent/100717662/SMM-Ranking-by-Metal-Price-Increase-(Weekly)20161230
[612] Hedrick, J. B. (1998) *Rare-Earth Metals*. USGS. Retrieved from https://minerals.usgs.gov/minerals/pubs/commodity/rare_earths/740798.pdf
[613] *Rare Metals Prices and Charts*. Quandl. Retrieved from https://www.quandl.com/collections/markets/rare-metals
[614] *Lutetium oxide price worldwide from 2010 to 2025 (in U.S. dollars per kilogram)*. Statista. Retrieved from https://www.statista.com/statistics/450175/global-reo-lutetium-oxide-price-forecast/
[615] Anguolo, M.A. (2012) *Cesium*. USGS. Retrieved from https://minerals.usgs.gov/minerals/pubs/commodity/cesium/mcs-2012-cesiu.pdf
[616] *Rare Metals Prices and Charts*. Quandl. Retrieved from https://www.quandl.com/collections/markets/rare-metals
[617] *Rare Metals Prices and Charts*. Quandl. Retrieved from https://www.quandl.com/collections/markets/rare-metals
[618] *Live Osmium Prices*. Tax-Free Gold. Retrieved from https://taxfreegold.co.uk/osmiumpricesusdollars.html
[619] *Gold Price*. Retrieved from http://goldprice.org/
[620] *Xenon Gas*. AliBaba (various suppliers). Retrieved from https://www.alibaba.com/showroom/xenon-gas.html

A note of caution must be given on these mineral prices. While some of these are traded in large quantities, like gold and platinum, others, like scandium and cesium are traded in small quantities, and thus may be subject to high price fluctuations. This can however go both ways; depressed prices of certain elements can skyrocket when new products suddenly increase the demand for them (rare earth elements have proven particularly prone to this). High volume commodities, however, are easier to plan for.

Export of elements at values over $10k, and particularly high demand elements like gold and platinum at over $30k, is potentially quite justifiable as launch costs continue to decline, so long as access to Venus orbit can be proven to be reliable, without significant use of expendable hardware. In the long term, a much broader range of elemental exports may further prove economic.

Tempering this, however, is the difference between local and remote production costs. Due to Venus's lack of industrial infrastructure and our adaptation to life on Earth, our home planet always begins with a major advantage in production costs. Every fluid, every spare part, every crew consumable imported to Venus comes at a huge expense. In the long run, however, it is essentially unavoidable that this will be overcome, as local costs on Venus drop, while Earth resources must be recovered from ever more challenging sources. On Venus, resources are extracted from concentrated, never-before mined surface deposits and - in some cases - even the air itself.

In short, mining for the purpose of extracting valuable elements for export shows significant promise in the long term. In the short to mid term, however, it is likely to face difficulties of shipping costs and local production costs.

Gemstones

In contrast to valuable elements, gemstones can offer far greater value density. We will examine the potential using prices from Gemval[621] and omitting the most commercially desirable stones (diamond, emerald, opal, ruby, sapphire, spinel and tanzanite).

Low quality gems are typically worth ½ to 1 orders of magnitude less than top quality gems. For the least valuable listed gemstone (quartz), top quality prices are $1.56/ct for less desirable varieties of quartz at 1ct size. On the other side of the spectrum, top grades of paraïba tourmaline sell for $17259.43/ct at 3ct size - that is, $86m/kg. Clearly, gems pose a potential export at even high payload return prices.

Paraïba tourmaline. Photo: Don Guennie

Fine paraïba tourmaline is hardly the only expensive entry on the list. Top quality benitoite ranges from $8-21m/kg. Sunstone, $0.7-5.5m/kg. Common tourmaline, $0.8-14m/kg. Taaffeite, $11-37m/kg. Aquamarine, $0.4-3.3m/kg. Axinite, $0.3-3.3m/kg. Rhodochrosite, $1.0-3.6m/kg. Demantoid garnet, $3-32m/kg. Pezzotaite, $3.5-14m/kg. Tsavorite garnet, $0.7-12m/kg. Colour change garnet, $1.1-14m/kg. Chrysoberyl, $1.0-7.1m/kg. And so forth, over numerous gem species.

[621] *Reference Value of Gems*. Gemval. Retrieved from http://gemval.com/;prices are as of 11 January 2017.

This list hardly counts as the most expensive gem species overall.[622] [623] High quality alexandrite, diamond, serendibite, grandidierite, musgravite and jadeite regularly sell for $10-20k/ct ($50-100m/kg). Painite can sell for $50-60k/ct ($100-120m/kg). Exceptional diamonds are almost unbounded. The Pink Star Diamond, at 59.6 carats, sold in 2017 for $71.2m, a whopping $6B/kg. Red diamonds, of which only 35 are known, likewise sell at around $5B per kilogram.

The Pink Star Diamond, sold for around 70% of the price of a 54.4-tonne payload Falcon Heavy rocket launch.
Photo: Diamond History Girl

What makes the most valuable gems valuable is their rarity and how exotic they are. Yet it is not at all unrealistic that there may be gemstones that exist on Venus that simply do not exist on Earth, due to the dramatic difference in the environmental conditions. The potential price per kilogram of quality cut "Venusite" is, again, practically boundless.

Clearly, even with near-term small-scale return prices and extreme local production costs, gemstones can prove economic for export. Furthermore, a Venus habitat comes with a far greater degree of mobility as well in comparison to a lunar or Mars habitat, improving search propects. Such an economic possibility comes with critical caveats, of course: that such gem-bearing pegmatites or other deposits exist, can be found, and can be reasonably recovered.

How prone is Venus to generating valuable gemstones? Clearly, when it comes to some types, "not likely". Opal, for example, is a hydrated amorphous form of silica; it is incompatible with Venus's hot, desiccating environment. Many minerals that are not directly hydrated still form in hydrothermal veins or otherwise due to the action of liquid water. For the majority of minerals of interest, however, the keys to their formation are generally some combination of slow cooling, heavy differentiation, unusual fractionalization processes, and so forth. Venus appears quite promising in these regards.

Should further surface exploration provide strong signs of indicator minerals, targeted exploration could potentially yield a relatively fast means to shift Venus from a negative to a positive trade deficit.

Decorative / collectible stone

While gemstones requires exploration and research, a far simpler means for near-term trade is no more complicated than ordinary rock.

Martian meteorites - far from pristine, and of no use other than as collectors items - frequently sell for $1m/kg or more. The most valuable, Black Beauty, is estimated at a value of $10m/kg.[624] Values of lunar samples vary widely, from $330k for 1.8kg in 2012[625] to three

[622] Nace, T. (2015, 2 Nov) *12 Most Expensive Gemstones In The World*. Forbes
[623] *10 Really Expensive Gemstones: From Tanzanite To Pink Star Diamond.* Finances Online.
[624] Sutherland, S. (2014, 2 Dec.) *What does it take for a rock to be worth $10,000 a gram? Being from space is a good start.* The Weather Network.

grams from Russia's Luna 16 sold for $442.5k ($147.5m/kg).[626] Interestingly, while origin matters, it matters in the opposite manner as one would expect: samples returned by space agencies are worth far more than those which arrive as impactors. The number of known meteorites on Earth to have come from Venus is zero.

Meeting the demand of collectors is an interesting market, but one which can be readily saturated with imports. However, it can be expanded into the exotic decorative / semi precious stone market, which is far larger. When your average mineral baron, tech billionaire or royal figure is looking for a new countertop for their yacht, there's no question that "*My countertop is made of the finest tuscan marble*" does not have the same ring as "*My countertop comes from the slopes of a Venusian volcano.*"

While even relatively mundane minerals have some potential for use in this fashion, the more attractive and durable they are, the greater the value and market size. And again, in this regard, Venus appears to deliver. Venus's rocks appear to be hard and slowly cooled. The Vega 2 and Venera 13 samples are gabbroids. Gabbro, sold as "black granite", is a strong mineral with large, distinct crystal growths throughout it. Occasionally gabbro is found in orbicular forms, each orb being a crystallization center.

Polished troctolite. Exhibit GLAHM 134797; ©The Hunterian, University of Glasgow

Orbicular gabbro from Dehesa, San Diego County. Photo: Eurico Zimbres

Volodarsk-Volhynsky anorthosite, Ukraine. Photo: James St. John

Carbonatite from Jacupiranga Estado de São Paulo. Photo: Eurico Zimbres

Norite. Photo: Denis Finnin, American Museum of Natural History.

625 (2002, 15 Oct.) [*Moon Rock Brings $330,000 To Lead $1,066,000+ Meteorite Event At Heritage Auctions*]. Heritage Auctions.

626 Ulivi, P., & Harland, D. M. (2004). [*Lunar exploration: human pioneers and robotic surveyors*]. London: Springer-Verlag.

Troctolite is an olivine (peridot)-rich, a somewhat speckled, feldspar-rich gabbroic rock. Sometimes anorthosite minerals express labradorescence (a bluish iridescence) due to the presence of the feldspar mineral labradorite; labradorite-rich samples are sold as gemstones under the name spectrolite.


Labradorite, UCL collections. Photo: Mary Hinkley

It remains an open question as to what degree rocks on Venus will be weathered / altered and to what depth. For example, while anorthosite is abundant on the moon, the lunar highland samples are generally breccias;[627] heavy bombardment shatters the lunar surface and the fragments slowly cement back together. Venus is well shielded from bombardment against all but large impactors, but has a hot, acidic atmosphere. Venera imagery shows varying levels of weathering between sites. It's also worth noting that with the high levels of tectonic deformation on Venus, a wide range of metamorphic species can be expected in addition to the discussed igneous species.

Returns of any Venus rocks will present a ready market beginning in the short term after a colony is established. The greater the magnitude of exports, the lower the value per kilogram - but significant value will always remain. Cutting and polishing of mineral samples to the rough desired form before export will maximize the value per kilogram by eliminating waste material that would be otherwise need to be eliminated on the Earth end. Waste from the process can be fed into various production streams that call for abrasives or minerals desirable for smelting.

Agricultural products

Kopi Luwak coffee sells for $350 per kilogram - and Hacienda La Esmeralda for $770.[628] The most expensive cheeses sell for nearly $1300 per kilogram.[629] The most expensive wines sell for thousands to hundreds of thousands of dollars per bottle.[630] The most expensive teas can sell for over a million dollars per kilogram, over thirty times their weight in gold.[631]

What is it that causes people to pay so much for some agricultural products? As with the luxury market in general, it's the combination of rarity and desirability. Indeed, in many cases claims of the rarity are artificially inflated - for example, Kopi Luwak is believed to be produced in quantity far exceeding the supposed 500 kilograms per year.[632] The reputation, however, combined with the supposed rarity, inflates its price.

[627] Ashwal, L. D. (2012). *Anorthosites*. Springer-Verlag Berlin An.
[628] Top 10 Most Expensive Coffee In The World: Luwak Coffee Is Not The No. 1. Finances Online.
[629] Semigram, R. (2016, 8 April) *15 of the World's Most Expensive Cheeses*. Mental Floss.
[630] *Top 10 Most Expensive Red Wines In The World: Cabernet Sauvignon Tops The List*. Finances Online.
[631] Sutcliffe, T. (2016, 26 April) *The drink that costs more than gold*. BBC News.
[632] Kwok, Y. (2013, 2 Oct) *The World's Most Expensive Coffee Is a Cruel Cynical Scam.* TIME.

Reputations get inflated by supposed differences in products - however tenuously connected to quality. Kopi Luwak passes through the digestive system of a civet. Pule is one of the world's few donkey cheeses. Every expensive wine has a whole history explaining its unique provenance. Da Hong Pao tea comes from a few trees cultivated since ancient times. The story, plus its rarity, builds its price.

Which brings us back to Venus. Rarity is enforced - payload limitations and transport costs ensure that only small amounts of agricultural products will ever arrive at Earth. The environment has numerous differences that can give every product its own qualitative differences - unusual day lengths, low air pressures, different atmospheric gas mixtures, characteristic water mineral concentrations, different gravities, and so forth. And the very concept of food coming from another planet gives it its own exotic story.

In short, all of the pieces are present for agricultural exports (which can survive the journey) commanding very high prices on Earth - indeed, potentially enough to justify the export costs and turn a profit in small quantities.

Indirect export of energy

Iceland is the world's 11th largest aluminum producer, but ranks #173 in terms of population. Little aluminum is used domestically. Nor are there any economic aluminum deposits in the country. Ore is shipped to Iceland, and finished aluminum shipped out, simply for one reason: electricity is cheap in Iceland, and aluminum refining is an electricity-intensive process. Iceland is, in effect, exporting energy.[633]

While there are no prospects of exporting a product as cheap as aluminum from Venus, the same general concept remains: energy can be exported indirectly. And as mentioned previously, Venus has massive potential sources of both wind and solar energy compared to Earth. In the early days, high local production and labour costs will make effective energy costs far cheaper on Earth; however, in the long term, Venus has the potential to experience cheaper energy costs than Earth, and perhaps significantly so. How can it be exported?

● Manufactured isotopes

Some of the most value-dense substances that exist are various isotopes - with even greater mass density than the rarest gemstones. The global medical radioisotope market is expected to reach $8B in 2017 and is rapidly growing.[634] Even the most commonly produced medical radioisotope, 99Mo, is worth $46B/kg.[635] Per-kilogram shipping costs are essentially irrelevant when it comes to such value densities.

There are several hundred isotopes in-demand for various medical, industrial and research applications. Different isotopes are manufactured by different processes. Some are

[633] Chu, H. (2011, 26 Mar). Iceland divided over aluminum's role in its future. *LA Times*.
[634] (2016, 28 Dec) *Radioisotopes in Medicine*. World Nuclear Association.
[635] (2009) *Molybdenum-99/Technetium-99m Production Costs*. NCBI.

best produced in nuclear fission, and have little applicability to Venus Some are separated from naturally occurring minerals. An additional class is most easily produced by bombarding targets with high-energy particles from accelerators; these would be the local focus.

While some desirable isotopes are stable, most in demand are radioisotopes, which have limited lifetimes, often in the range of a few days to several months. The aforementioned 99Mo, for example, has a half-life of 2.7489 days - far too short for transit back to Earth with low energy trajectories. In most cases, Venus would need to produce parent isotopes which produce the desired isotope by decay; this which would significantly reduce the range of radioisotopes of interest. However, utilizing high energy returns opens up significantly more options, with returns possible in months or even weeks. This raises the cost per kilogram of returns dramatically, but said cost per kilogram is essentially irrelevant given their extreme value density. A single gram’s return may pay for a heavy-lift rocket launch on Earth.

One potentially interesting radioisotope for production is 22Na, which can be produced (alongside 26Al) by bombarding water-cooled magnesium targets with deuterium.[636] As a cold positron source, it has been suggested for use in an antimatter-initiated fusion rocket, yielding a specific impulse of over 100 thousand seconds. Startup Positron Dynamics hopes to demonstrate such a thruster by 2019.[637] More down to Earth, it has recently gained interest as a PET scanning isotope (see *Medicine*)

Perhaps the ultimate form of storage of energy for propulsion via particle accelerators is the creation of antimatter for direct antimatter annihilation engines. However, as technology is as of yet not advanced for antimatter propulsion to be practical, this does not bear extensive consideration.

While energy costs may make up the vast majority of some types of accelerator operation, there still remains the dependency in that the cost of building the accelerator locally must be affordable. This is to say, as much of the mass as possible should be from local production. The exact balance of economic factors depends on the difference between local and Earth energy prices and the ratio of capital to energy costs.

[636] Rightmire, R. A., Kohman, T. P., & Allen, A. J. (1957). Production of carrier-free aluminum-26 and sodium-22. *The International Journal of Applied Radiation and Isotopes, 2*(3-4), 274-279. doi:10.1016/0020-708x(57)90271-5
[637] (2016, 24 Oct) Positron Dynamics near term work to proving out antimatter catalyzed deuterium fusion propulsion with over 100,000 ISP. Next Big Future.

- ## High energy research

If accelerators useful for isotope production become cheaper to operate on Venus than on Earth, then it becomes likely also cheaper to conduct high-energy physics research on Venus using the same accelerators. Particle accelerators are also useful for many types of medical research (such as X-ray synchrotron light sources for investigating protein structures)[638] and chemistry.

ORNL Spallation Neutron Source. Photo: DOE

- ## Computation

Data processing demand continues to grow. While power consumption isn't as extreme relative to capital costs as that of operating enrichment facilities or some particle accelerator applications, they still make up around half of the costs of operating a datacenter.[639] While this sort of difference cannot readily justify the expense of sending entire compute clusters of Venus, it could prove economic should the ability to locally produce casing, cooling, etc be established; lightweight, complicated components such as CPUs and GPUs could be economically imported.

Applications to be run on Venus cannot be highly bandwidth or latency restricted, with an exception for cases in which the operators/users can reside locally.

- ## Electronics

Conversely, the same lightness that makes complicated electronics a potentially viable import makes them a potentially viable export. To pick an example valid as of 11 Jan 2017, the lowest retail price for a 128MB MicroSD card on Amazon.com is $40. At a weight of 0.4 grams, this is represents an energy density of $100k/kg. Samsung's announced 256MB MicroSD card has a launch price of $249.99, or $625k/kg.[640] While retail prices are higher than wholesale, there clearly exists the potential for electronics exports even at high launch costs. High density integrated circuits such as are used in CPUs and GPUs can represent even higher value density (although

An finished silicon wafer ready for dicing, worth two orders of magnitude more than its weight in gold. Photo: Seb

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[638] Experimental Techniques at Light-Source Beamlines. DOE

[639] Koomey, J. G., Belady, C., Patterson, M., Santos, A., Lange, K-D. (2009) Assessing Trends Over Time In Performance, Costs, And Energy Use for Servers. Lawrence Berkeley National Laboratory, Stanford University, Microsoft Corporation, Intel Corporation, Hewlett-Packard Corporation

[640] (2016) Samsung Electronics Introduces the EVO Plus 256GB MicroSD Card, with the Highest Capacity in its Class. Samsung Newsroom.

whole CPU/GPU masses, dominated by casing and heat management mass, are far less value dense).

The primary constraint, thus, is not launch costs, but local production costs; it would need to be demonstrated that local production costs could actually be kept lower than on Earth, in addition to accounting for the shipping cost. Consequently, these possibilities are largely long term and unlikely to prove economic in the short to mid-term.

Science

Today, Earth pays for the costs of all scientific research conducted by and for humanity. In the short to mid-term, Earth would continue to be expected to pay for research conducted on Venus, which would by most logically be conducted based from any habitats present. Such funding means covering the costs of both the people and hardware involved in the research.

However, there are also prospects for science not pertaining to Venus being located on Venus. Of particular note are systems in which physical separation is critical, such as astronomical interferometry (interplanetary radio telescope array, interplanetary gravitational wave observatory, etc). While technically such systems could be located at any point in space, only physical bodies offer the possibility of local production of the bulk their mass, and the advantages of Venus in this regard (both in terms of material resource production and supporting human labour) have been discussed.

Note that scientific hardware does not need to be located within the middle cloud layer; it can be located higher, with the caveat that the higher it is to be lofted, the larger the envelope must be per unit lift.

Services

Increasingly, many jobs today are outsourced, with people telecommuting from great distances to do the same job. Programming, design, research, engineering, and so forth - any work which does not require a person to be co-located with physical facilities or partake in regular travel, and which is tolerant of some communications latency. The same applies to a Venus habitat: Earth could literally outsource jobs to Venus.

For this to be a net positive economic activity, the value of the work of an individual would need to exceed the value of their personal consumables sent from Earth, as well as what they consume indirectly by virtue of the needs of the colony as a whole. This can be more easily viewed by considering a colony as a whole: if for a colony of 200 it takes the labour of 100 people to provide for all needs and maintenance, and 100 people can handle “outsourced” services, then for the colony to be operating in the black the trade deficit on physical goods must be less than the value of the labour for the outsourced services. In the above example, if the average individual conducted a job worth $70k per year, yielding $7m revenue, and launch costs to the habitat from Earth were $10k/kg, then to run in the black the colony could import no more than 700kg - roughly one small-payload rocket per year. This would mean an average of 3.5 kg of high-value-density objects imported from Earth per colonist per year.

Any physical exports from the colony would lower the trade deficit and thus increase the amount of annual imports without requiring operating at a loss.

VISA fees

A relatively simple means is available to ensure that every colonist has the means to support themselves is VISA fees. Under such a scheme:

- All immigrants, whether permanent or temporary, are required to purchase a round ticket, not simply a one-way ticket.
- In addition to ticket costs, they must downpay the cost of their share of consumables from Earth, as well as the cost of hiring someone to do their share of the colony's labour on the assumption that they do not work. This would need to cover the time between when they arrive and the next return launch window.
- If they have not by the time of that launch window downpaid their living expenses for the subsequent launch window, they must return on the next flight.
- Parents are responsible for the costs of their minor children, whether born on Earth or on Venus.
- A small percentage fee needs to be tacked on to account for unseen costs to the colony.
- Everyone who works locally is paid a salary for their work, roughly cancelling the downpaid cost of their share of the colony's labour (but not the cost of their imports). Those who don't work (people of means, tourists, etc) receive no local salary.
- If the colony has exports, they offset every residents' import costs.
- Local salaries are adjusted based on predicted labour availability and needs.

In short, the approach would resemble that of VISA applications in many places on Earth, where applicants must prove the ability to sustain themselves during their residence period. The primary difference is that on Venus the primary expenses are communal rather than personal, and hence the "proven assets" must go into a communal fund.

Such a system should be inherently balancing and responsive to the needs of individuals and the colony. It would allow people who normally wouldn't have the means to sustain themselves to do so by holding a job. In turn, local labour would support tourists and those who have the means to pay to live there without working. During labour shortages, "advances" paid on local salaries to prospective workers could fund ticket subsidies, allowing those who have no other means to travel to the planet to immigrate. This, again, has analogues on Earth.

Distribution of labour

It is common to hear, when offworld colonies are discussed, “what will people there actually do?” There appears to be a common perception that whenever people live offworld there will be mechanical systems conducting all labour.

This is - quite unfortunately - not a realistic hope. As with on Earth, and likewise on the International Space Station, robotic systems are limited in their capabilities. The problem: 1) labour throughput, 2) ability to handle diverse/complex tasks, and 3) development costs are three mutually exclusive aspects when it comes to robotics. Furthermore, the cost for developing a habitat is high; money will not be in excess to allocate to automation where automation is not essential. To put it another way: the last thing that money would be put towards would be expensive systems to allow residents to sit around doing nothing all day. Even relative “simple” systems such robots that roll along hydroponic conduits to assist in harvesting or other agricultural tasks, are unlikely to be present in an early colony, when the money could instead be dedicated toward development of better ISRU systems that reduce the annual cost of resupplying the colony.

Let us look at some of the types of work that would be necessary in an early-stage colony and a possible distribution of labour to support it.

- **Cooking**: Likely to be only part-time work for an initial colony.
- **Food processing**: Raw agricultural products can require significant amounts of processing. Grains need to be threshed, winnowed and ground. Nuts must be shelled. Pastas and breads need to be made, and a yeast culture nurtured. Dairy products need to be individually made - cheeses, butters, etc. Various food products need to be dried. Vinegar needs to be fermented. The complete list is quite long. In an early-phase colony, the chef is a natural match for this work.
- **Primitive skills**: Many things typically done by hand in earlier societies would again be hand work, including manufacture of soaps and hair products from fats and hydroxides, manufacture of rough paper from plant fibre slurries, sewing, and so forth. Some of these products are best made in a kitchen environment, and could again go to the chef. Others may be more suited to other crew members.

Homemade paper from 8 varieties of Kansas plants. Local paper would be primarily for sanitary needs. Photo: Lawrence Farmers’ Market

- **Medicine, veterinary medicine, and dentistry**: A single individual would be expected to perform all of these tasks until the population grows significantly, and in the early phases it would not be a full-time job. Others people may be required to assist in procedures at times.

- **Chemist**: A chemist will be required to assist with numerous tasks, including medicine production, scientific research, and manufacture.

- **Research**: Significant scientific research would be expected to be conducted in various fields concerning the local environment; if you have a manned platform offworld, you will use it to its full extent so long as it's crewed.

- **Maintenance:** Things break; everything must be designed to be repaired or replaced. One or more people should be trained in repairing the diverse array of systems onboard. In particular...

- **Chemical engineering:** An individual will be needed to operate, expand, and optimize the numerous ISRU systems onboard.

- **Machinists:** Initially only a part-time position; as manufacturing capabilities expand, so will the needs for people with skills in welding, cutting, CNC / printing operation, and so forth. The number of people working in manufacturing will drastically expand when working on constructing new habitats.

- **Agriculture:** The large area of plants needed to maintain a colony will mean dedicating at least one, probably multiple people to the task. This number will be expected to grow linearly with the population, up to the point that the population size is sufficient to justify the investment into automated equipment to assist in planting, inspection for disease, maintenance and harvesting. Beyond farming tasks, monitoring of plant health, optimization of nutrient solutions, tracking of food yields, and testing harvests for nutritional content represent additional workload.

- **Livestock**: Maintaining livestock and fish production, if present, would initially be only part-time in an early colony, and the job will not exist at all until such livestock / fish production has commenced.

- **Janitorial**: Beyond the simple need to keep common areas tidy (and empty the toilet for cation recovery), removing dust and debris that accumulates around the envelope will involve a significant amount of time. This involves moving about on rigid framework elements and/or ropes, making it somewhat more glamorous than janitorial work on Earth.

- **Assembly:** Initially only in low demand (beyond the installation of new systems), a very large amount of labour will be needed for the assembly of new habitats and expansion of existing ones.

Additional labour over time - regardless of scaleup - will involve caretaking, both of children, the infirm and the elderly.

9. Other Considerations

Scientific Mission

It can be well argued in general that if one's only goal is scientific research, that offworld human habitation is not worth the expense in the short to mid term. The standard argument is that one could launch an order of magnitude more robotic missions relative to the cost of a single manned mission - launched to diverse locations, with diverse sets of hardware. The argument continues that humans are ultimately limited in their science-gathering ability by the equipment that they arrive with, just like robots, except that integrated equipment on robots is lighter than that designed for human hands. That the main thing humans bring to the table is reduced latency, but when you can only afford robotic missions roughly annually either way, it doesn't matter whether their mission is accomplished in days or months. That while humans may be able to repair some (but not all) types of system failures, this is countered many times over by the fragility of humans.

DAVINCI probe descent.
Artwork: NASA/GSFC

And all of these things are, at least in the short term, true. However, Venus presents an unusual case. Because at Venus, latency *does matter.*

Unlike most solid bodies in the solar system, the surface of Venus is very hostile, and the amount of time that probes can spend there - unless extensive measures are taken - is limited. For a Mars probe, it's just fine - even beneficial - for a probe to sit idle, charging its batteries or processing samples. On Venus's surface, sitting around waiting for commands is highly problematic. A probe may land on yet another piece of tholeitic basalt, just centimeters from a granite outcrop or other feature representing an exciting new find; however, as it can't afford to wait for human input, it will dutifully sample from the basalt because time is limited. With real-time control, interesting locations can be targeted as they come into view. A surface probe can be controlled, driven or flown to whatever appears interesting en route. With only a few hours time at the surface, low-latency communications allows for vastly more science to be conducted.

Low latency does not require the presence of humans in the middle cloud environment; humans in orbit could accomplish the same feat.[641] [642] But humans need to be at Venus either way. And only in the cloud environment is there the potential to self-sustain, or at least reduce the consumables from Earth - as well as conduct in-situ atmospheric science.

[641] Schmidt, G., Landis, G. A., Oleson, S. HERRO Missions to Mars and Venus using Telerobotic Surface Exploration from Orbit, *AIAA SPACE 2011 Conference & Exposition, AIAA SPACE Forum*. doi:10.2514/6.2011-7343
[642] Landis, G. A., Dyson, R., McGuire, M., Oleson, S., Schmidt, G., Grantier, J., ... McCurdy, D. (2011) Human Telerobotic Exploration of Venus: A Flexible Path Design Study. *49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition*, Aerospace Sciences Meetings. doi:10.2514/6.2011-335

A Venus probe, unless bandwidth is to be limited, requires a relay to communicate with Earth. Again, this does not need to be within the atmosphere - although this would reduce the required gain on the lander, making it simpler and lighter. A manned habitat can provide this capability for an unlimited amount of time, while largely self-sustaining. Hostile environments for landers also imply greater maintenance needs than are typical elsewhere in the solar system. Maintenance can only realistically be done within Venus's cloud environment.

In short, regardless of the balance of the humans-versus-robots debate, if there is any location in which the balance would favour humans, it's Venus.

It is somewhat difficult to lay out the scientific mission, as that will depend largely on what is discovered between now and the commencement of operations at the habitat. It may be tempting to view this as meaning "there will be less to study", but in practice, just the opposite is true. When you have relatively unknown bodies with very basic questions unanswered, cracking the surface of those questions tends to open up a whole range of even greater questions.

We will, however, examine some of the Venus topics open today and hardware that could be used to help investigate them. First, we list the VEXAG goals for Venus. Investigations that should be advanced before final design / construction of a habitat will be marked in red; investigations that are important for manned habitation but not required before completion of design/construction will be marked in yellow; and investigations of only indirect applicability to human habitation will be marked in blue.

- **I. Understand atmospheric formation, evolution, and climate history on Venus**
  - *A. How did the atmosphere of Venus form and evolve?*
    - 1. Measure the relative abundances of Ne, O isotopes, bulk Xe, Kr, and other noble gases to determine if Venus and Earth formed from the same mix of solar nebular ingredients, and to determine if large, cold comets played a substantial role in delivering volatiles.
    - 2. Measure the isotopes of noble gases (especially Xe and Kr), D/H, 15N/14N, and current O and H escape rates to determine the amount and timeline of the loss of the original atmosphere during the last stage of formation and the current loss to space.
  - *B. What is the nature of the radiative and dynamical energy balance on Venus that defines the current climate? Specifically, what processes control the atmospheric super-rotation and the atmospheric greenhouse?*
    - 1. Characterize and understand the atmospheric super-rotation and global circulation, including solar-anti-solar circulation above ~90 km and planetary-scale waves, by measuring the zonal and meridional wind structure and energy transport from the equator to polar latitudes and over time-of-day from the surface to ~120 km altitude. Use global circulation models to comprehensively connect observations acquired over different epochs, altitudes, and latitudinal regions.

        - 2. Determine the atmospheric radiative balance and the atmospheric temperature profile over latitude and time-of-day, from the surface to ~140 km altitude, in order to characterize the deposition of solar energy in the cloud layers and re-radiation from below, including the role of the widespread UV absorber(s).
        - 3. Characterize small-scale vertical motions in order to determine the roles of convection and local (e.g., gravity) waves in the vertical transport of heat and mass and their role in global circulation.
    - *C. What are the morphology, chemical makeup and variability of the Venus clouds, what are their roles in the atmospheric dynamical and radiative energy balance, and what is their impact on the Venus climate? Does the habitable zone in the clouds harbor life?*
        - 1. Characterize the dynamic meteorology and chemistry of the cloud layer through correlated measurements of formation and dissipation processes over all times-of-day and a range of latitudes. Analyze cloud aerosols, including their particle sizes, number/mass densities, bulk composition, and vertical motions. Study the abundances of their primary parent gaseous species, such as SO_2, H_2O, and H_2SO_4, as well as minor cloud constituents, such as Sn and aqueous cloud chemical products.
        - 2. Determine the composition, and the production and loss mechanisms, of “Greenhouse” aerosols and gases, including sulfur cycle-generated species and UV absorbers, and their roles in the cloud-level radiative balance.
        - 3. Characterize lightning/electrical discharge strength, frequency, and variation with time of day and latitude. Determine the role of lightning in creating trace gas species and aerosols.
        - 4. Characterize biologically-relevant cloud and gas chemistry, including 13C/12C and complex organic molecules.
- **II. Determine the evolution of the surface and interior of Venus**
    - *A. How is Venus releasing its heat now and how is this related to resurfacing and outgassing? Has the style of tectonism or resurfacing varied with time? Specifically, did Venus ever experience a transition in tectonic style from mobile lid tectonics to stagnant lid tectonics?*
        - 1. Through high-resolution imaging and topography, characterize the stratigraphy and deformation of surface units in order to learn the sequence of events in Venusian geologic history. This includes assessing any evolution in volcanic and tectonic styles and analyzing any evidence of significant past horizontal surface displacement.
        - 2. Measure radiogenic 4 He, 40Ar, and Xe isotopic mixing ratios in the atmosphere to determine the mean rate of interior outgassing over Venus’s history.
        - 3. Combine geophysical measurements with surface observations to characterize the structure, dynamics, and history of the interior of Venus and its effects on surface geology. Relevant geophysical approaches include, but are not limited to, gravity, electromagnetics,

heat flow, rotational dynamics, remnant magnetization, and seismology.
        - 4. Determine contemporary rates of volcanic and tectonic activity through observations of current and recent activity, such as evaluating thermal and chemical signatures, repeat-image analysis, ground deformation studies, and observations of outgassing.
        - 5. Determine absolute ages for rocks at locations that are key to understanding the planet's geologic history.
    - *B. How did Venus differentiate and evolve over time? Is the crust nearly all basalt, or are there significant volumes of more differentiated (silica-rich) crust?*
        - 1. Determine elemental composition, mineralogy, and petrography of surface samples at key geologic sites, such as the highlands tesserae, in order to understand the compositional diversity and origin of the crust.
        - 2. Determine compositional information for rocks at large scales using remote sensing to gain a regional picture of geochemical processes.
        - 3. Determine the structure of the crust, as it varies both spatially and with depth, through high-resolution geophysical measurements (e.g., topography and gravity, seismology), in order to constrain estimates of crustal volume and lithospheric structure and processes.
        - 4. Determine the size and state of the core and mantle structure (e.g., via geodesy or seismology) to place constraints on early differentiation processes and thermal evolution history.
        - 5. Evaluate the radiogenic heat-producing element content of the crust to better constrain bulk composition, differentiation and thermal evolution.
        - 6. Characterize subsurface layering and geologic contacts to depths up to several kilometers to enhance understanding of crustal processes.
- **III. Understand the nature of interior-surface-atmosphere interactions over time, including whether liquid water was ever present.**
    - *A. Did Venus ever have surface or interior liquid water, and what role has the greenhouse effect had on climate through Venus' history?*
        - 1. Determine the isotopic ratio of D/H in the atmosphere to place constraints on the history of water. Determine isotopic ratios of $^{15}N/^{14}N$, $^{17}O/^{16}O$, $^{18}O/^{16}O$, $^{34}S/^{32}S$, and $^{13}C/^{12}C$ in the atmosphere to constrain models of paleochemical disequilibria.
        - 2. Identify and characterize any areas that reflect formation in a geological or climatological environment significantly different from present day. Determine the role, if any, of water in the formation of highlands tesserae.
        - 3. Search for evidence of hydrous minerals, of water-deposited sediments, and of greenhouse gases trapped in surface rocks in order to understand changes in planetary water budget and atmospheric composition over time.

- *B. How have the interior, surface, and atmosphere interacted as a coupled climate system over time?*
    - 1. Characterize elemental composition and isotopic ratios of noble gases in the Venus atmosphere and in solid samples, especially Xe, Kr, ^{40}Ar, ^{36}Ar, Ne, ^{4}He, and ^{3}He, to constrain the sources and sinks that are driving evolution of the atmosphere, including outgassing from surface/interior.
    - 2. Understand chemical and physical processes that influence rock weathering on Venus in order to determine contemporary rates and identify products from past climate conditions. At large scales, determine the causes and spatial extent (horizontal and vertical) of weathering regimes such as the high-elevation lowering of microwave emissivity. At local scales, evaluate the characteristics of weathering rinds and compare to unweathered rocks.
    - 3. Determine the abundances and altitude profiles of reactive atmospheric species (OCS, H_2S, SO_2, SO_3, H_2SO_4, S_n, HCl, HF, ClO_2 and Cl_2), greenhouse gases, H_2O, and other condensables, in order to characterize sources of chemical disequilibrium in the atmosphere and to understand influences on the current climate.
    - 4. Determine the current rate of sulfur outgassing from the surface and characterize the atmospheric/surface sulfur cycle through measurements of the isotopic ratios of D/H, $^{15}N/^{14}N$, $^{17}O/^{16}O$ $^{18}O/^{16}O$, $^{34}S/^{32}S$ $^{13}C/^{12}C$ in solid samples and atmospheric measurements of SO_2, H_2O_2, OCS, CO, $^{34}S/^{32}S$ and sulfuric acid aerosols (H_2SO_4).

Beyond broad mission goals listed above, a number of specific phenomena of applicability bear investigation:

- **Precipitation**: Initially interpreted as no precipitation, a later analysis of Vega data argued that both balloons experienced significant precipitation during their time in the middle cloud layer.[643] Understanding the existence, varieties, nature, and distribution of any such precipitation form(s), and correlating it to satellite data to enable long-term study and development of an improved predictive model, is critical to habitat safety and ISRU capabilities.

- **Minor atmospheric species**: Understanding minor atmospheric species in the middle cloud layer, and less importantly in other layers, is important to developing ISRU systems and determining production rates. Particular curiosities from a scientific perspective include the nature of the upper atmospheric UV absorber and determining what happened to Venus's mercury inventory.

- **Surface aerosols**: Photometric observations from the Venera 13 and 14 landers detected a layer of absorbers at 1-2 km altitude at both landing sites, alternatively

[643] Dorrington, G. E. (2013). Preliminary evidence for drizzle in the middle cloud layer of Venus. *Advances in Space Research, 52*(3), 505-511. doi:10.1016/j.asr.2013.03.026

speculated as sand/dust lofted by surface winds, volcanic ash, and metallic / semiconducting condensates similar to those suspected at higher altitudes.[644]

While this in no means intended to be exhaustive, examples of scientific equipment available to the habitat, lander(s), or inside the laboratory can include:

Hardware	Used on	Purpose
Phased-array radar	Habitat	Detailed mapping of the surface, including changing surface features. Discussed under *Radar and communications*.
RF lightning detectors	Habitat	Multiple, separated around the envelope for limited triangulation.
Visible / UV spectrometer	Habitat	Observe variations in spectral absorption to determine changes in atmospheric species
Near-IR spectrometer	Habitat	Detection of active volcanism / thermal anomalies.
Fluxgate magnetometer	Habitat, lander	Probe the internal dynamics of the planet.
Nephelometer	Habitat, lander	Determine the density of fogs in different atmospheric layers.
Meteorological package	Habitat	Measure temperature, pressure, windspeed, precipitation.
Visible camera	Habitat, lander	Observe real-time/high resolution images of meteorological and surface phenomena.
Gamma ray spectrometer (GRS)	Lander	Identify subsurface compounds via detection of gamma radiation emitted via passive activation by cosmic radiation.
Mid-IR spectrometer	Lander	High resolution mid-IR mapping from <16km
Corner reflector	Lander/dropped	Multiple, left on the surface at various points to measure surface deformation
Seismograph	Lander, optionally dropped	Detect tectonic and volcanic activity
Surface meteorological package	Lander, optionally dropped	Measure temperature, pressure, windspeed, aerosol deposition.
TDL spectrometer	Laboratory	Detection of trace species in gaseous samples.
Mass spectrometer	Laboratory	Determine isotopic signature of atmospheric, surface samples
Attenuated total reflectance spectrometer (ATRS)	Laboratory	Identifying compounds in solid and liquid samples.
Microbalance	Laboratory	In addition to weighing samples, measure the local gravitational field for detecting local gravitational anomalies.
Gas chromatograph	Laboratory	Identification of vaporizable, non-ionic compounds.
X-ray fluorescence (XRF)	Laboratory	Elemental and chemical analysis of recovered surface samples.

A complete list of laboratory equipment is beyond the scope of this assessment, as is further analysis of habitat and lander communications system needs.

[644] Grieger, B., Ignatiev, N. I., Hoekzema, N. M., & Keller, H. U. (2004). Indication of a near surface cloud layer on Venus from reanalysis of Venera 13/14 spectrophotometer data. Proceedings of the International Workshop Planetary Probe Atmospheric Entry and Descent Trajectory Analysis and Science, 6-9 October 2003, Lisbon, Portugal. ISBN 92-9092-855-7,

In-transit

Beyond ensuring that the envelope is sufficiently vacuum-compatible and can survive the transit without degradation or problems with deployment, the space environment must also be accounted for.

While holes from micrometeoroid punctures on their own would not be a serious threat due to the low habitat overpressure, the folded nature of the envelope when packed means that every impact will cause numerous perforations, yielding a cumulative effect over the course of the transit. Thermal management in-transit is an additional need; sunlight is much more intense in space than in the middle cloud layer, and there is no convective cooling.

We will investigate a common thermal / minor impact shielding scenario. First we must determine the risk of micrometeorids en route to Venus. Based on the calculations in Motoyashiki et al (2008)[645] for the Akatsuki Venus probe for a thruster of projected area 0.06m², we will scale the cumulative probabilities by a 1000x projected area increase. This yields an expected value of 1000 impacts at E >= 0.005J, 100 at E >= 0.13J, and 10 at E >= 1.6J.

Complete shielding from all impacts is impractical due to the packed size; some degree of pinholes must be accepted. However, to the degree that the thermal management system can also double as standoff fragmentation layer(s) for minor impacts, this would be advantageous.

Another concern with any packed fabric in space is vacuum welding. Generally thought of as a concern for metals, polymer layers can also become joined in the absence of an atmosphere. Maintaining a small amount of residual gas between layers can prevent this.[646]

Other details, such as in-transit communications, control, guidance, propulsion, et cetera are beyond the scope of this book.

[645] Motoyashiki, Y., Hasegawa, S., Okudaira, K., & Sato, E. (2008). Micrometeoroid impact on ceramic thin components for interplanetary probe. *International Journal of Impact Engineering*, 35(12), 1666-1671. doi:10.1016/j.ijimpeng.2008.07.051
[646] Griebel, H. (2011). *Reaching high altitudes on Mars with an inflatable hypersonic drag balloon (Ballute)*. Wiesbaden: Vieweg Teubner Verlag.

Entertainment

Human beings require time to relax - a lesson which NASA learned the hard way with the fourth Skylab crew in 1973, when stress from overworked crew members ended up coming to a head in a series of adversarial conversations with ground control:

> *"We need more time to rest. We need a schedule that is not so packed. We don't want to exercise after a meal. We need to get things under control."*[647]

Often erroneously described as a "mutiny" by the press after the crew inadvertently left their radios off for an orbit, the event nonetheless left its mark on future planning. Humans in space are, when it comes down to it, still human. In a scenario of long-term habitation of another worlds, the recreational needs of the crew should be seen as similar to those we are already used to on Earth.

Many entertainment options can be seen as individual personal hobbies, wherein mass requirements are low and there is little hardware involved that can be effectively shared among the crew. For example, if an individual enjoys knitting, and there is a means aboard for producing yarns (industrial-scale, simple mechanical, or hand-spun), there is no reason to object.

Matrix 54" 7-in-1 convertible gaming table
Image: Amazon.com

As laptops or tablets should be seen as standard equipment in lieu of paper, e-books, videos and games can be shared from the habitat's central server. Multiplayer games can be played across the local wireless network. Lightweight, potentially hanging chairs and couches in the common area can provide a gathering area around a large screen for social TV, movie and gaming activities.

Also in the common area, a multipurpose convertible gaming table would allow for table games such as pool, table tennis, air hockey, magnetic boards (printed on or displayed via a screen) for games such as checkers / chess, go, and so forth, as well as as providing a flat surface for playing cards and small-group common dining. All loose pieces must be able to be secured (magnetic or otherwise) to account for habitat rolling in severe turbulence, habitat acceleration during ascent vehicle launches, and so forth.

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[647] Hitt, D., Garriott, O. K., & Kerwin, J. (2008). Homesteading space: the Skylab story. Lincoln, NE: University of Nebraska Press.

Balls for ball games would be acceptable for use within locations in which they 1) are large enough to not be at risk of falling through safety netting, and 2) for use only in games where they cannot reach velocities that could pose a safety hazard.

Some activities, however, are likely to stem naturally from the unique environment that such a habitat provides. For example, given a habitat dozens or even hundreds of meters in height, with the crew located at the top, with safety netting below, it might prove difficult to *stop* crew members from using that feature recreationally, such as indoor skydiving, bungee jumping, rope swings, etc. The abundance of plants also provides opportunity for hobby gardening, including plants of lesser utility to the crew (such as flowers, topiary, etc). The potential inclusion of low-density aquaculture environments might allow for swimming.

Slacklining, zip lining, and a full range of circus rope / net activities are possible within the cavernous interior.
Image: Will McPherson

Particularly for a habitat in which "space tourism" has shown potential, the external environment provides numerous "extreme sports" possibilities. Even in a scenario where no manned vehicle for surface access has been developed, kilometer-long “bungee” jumps from beneath the habitat would provide no shortage of thrills. With a watercooled suit, rapid controlled descents could be extended to several kilometers beneath the habitat, potentially through gaps in the cloud layer, allowing for a helmet-mounted IR camera to see the surface in optical windows.

As discussed under "Surface Access", with the availability of hard-shell atmospheric diving suits, a descent to the surface would provide a most extraordinary experience for occupants - first a ½ to 1 hour skydive, followed by controlled flight around the landmarks of a very alien planet, with each dive being to explore an area that no human has ever set eyes on before.

While such activities represent the extreme end of entertainment, basic entertainment activities, however, represent an imposition of very little mass - only requiring proper budgeting of crew workloads to ensure sufficient time off.

Medicine

Some aspects of medical care have already been discussed, such as the possibility of colocating medical facilities with the common area until a habitat is large enough to justify a dedicated medical area, and the use of the same laboratory facilities that conduct atmospheric and surface analysis to perform sample analysis and batch medication synthesis. However, medical care involves much more than generalities. Much of this section will be based on issues discussed in Barrat and Pool (2008).[648]

On the International Space Station, medical care focuses around local treatment of minor conditions, but stabilization for evacuation to Earth for major conditions. Indeed, there is no requirement for a physician to be on board, and the CMO has only 80 hours of medical training. On Venus, evacuation to Earth can take many months even if an available return vehicle is present in orbit at an appropriate launch window; this renders evacuation only suitable for treatment of chronic conditions. Telemedical consultations are available, but realtime control of remote systems for surgical procedures is not possible due to communications delays. In short, the crew must be qualified to treat serious conditions, and have the hardware needed to do so.

Ultrasound examination in the International Space Station's Columbus Laboratory. Photo: NASA

Many organizations on Earth have experience operating medical facilities in remote areas that can experience infrequent, unpredictable restocking, and can contribute knowledge. Surgical needs, in particular, are of concern. The most common cause of evacuation from patrol submarines (in addition to psychiatric events) is suspected appendicitis, a so-called minor surgical condition. A 6-person crew can be expected experience a minor surgical event once every 3-6 years.

Based on the dimensions of the medical facility planned for Space Station Freedom and inflating that by 50%, we arrive at around 30m² of floor space. By contrast, a 4.4m common area core with 4.3m foldout leaves to expand its floor area (13m total diameter) equates to 133m². A core with 2.1m foldout leaves (8.5m diameter) equates to a floor area of 57m². Rollable floor designs can be half a dozen or more meters wide (stored vertically inside the launch vehicle fairing) and effectively unlimited length without the need for leaves. In short, the floor area requirements can be readily met - and in the large-leaf or rollable floor scenarios, potentially left permanently dedicated to medical purposes.

Considering the equipment intended for Freedom, in addition to the medical hardware used variously on Skylab, Shuttle, MIR and ISS, proposed hardware for future missions, and expanding it as required for longer-term care with no quick access to Earth facilities, we come up with the following categories of small hardware needs (not intended to be exhaustive):

- **General medicine**: Blood pressure cuff, stethoscope, speculas, neurological exam instruments, thermometers, magnifying glass, sterile gloves, masks, sheeting, sterile clothing, tubex injectors, reusable syringes (multiple types)

[648] Barratt, M. R., & Pool, S. L. (2008). *Principles of clinical medicine for space flight*. New York, NY: Springer.

- **Ophthalmology**: Eye pads, eye shield, fox shield, ophthalmoscope with spare bulb, visual acuity card, intraocular lens implants, iris scissors, spatulum, fluorescein strips

- **Otorhinolaryngology**: Otoscope w/reusable speculas and spare bulb, aural extraction equipment, aural probe, aural speculum, mouth/throat/laryngeal mirrors, laryngoscope, nasal light guide, ophthalmic extraction equipment, ophthalmic loop, ophthalmic spatula, slit lamp, laryngoscope, tracheostomy equipment, tongue depressors, nasogastric tube, myringotomy knife, ear curettes

- **Dental**: Cutters, drills (mechanical and hand-operated), carver file, cement spatula, excavator, extractors, forceps, fuse, nozzle, plugger, pulp extractors, scraper, smoother, tweezers, speculum, scalpel, tooth probe, dental syringe, scalers and curettes, toothache kits (eugenol, cotton pellets, tweezers), fillings, articulating paper.

- **Urology**: Urinary catheters, nozzles, leg bag, therapeutic ultrasound

- **Other fields**: Pelvic exam kit

- **Intravenous**: Administration sets (powered and unpowered), flowmeter, infusion device, venous catheters, cannula, pressure infuser, three-way valves, D5W solution, infusion set

- **Surgical, post-surgical care, and rehabilitation**: Head-mounted lights, endoscope and laparoscope plus accessories, surgical masks, sterile drapes, towels, tissue forceps (various), scalpels, lancets, retractors, hemostats, probes, needle holder, needle driver, oro- and nasopharyngeal airways, intubation bulb, suction and tubing, respiratory support system, end-tidal CO2 detector, air temperature monitor, chest drain, hemoglobin meter / oximeter, sutures / needles, surgical lubricant, hand grip dynamometer, digital spirometer.

- **Wounds / fluid management**: Tissue adhesives, tapes (varied), gauze and absorbent cotton products / packings (widely varied), cloth bandages, adhesive bandages (varied), butterfly closures ("Steri-Strips"), benzoin swabs, tourniquet, plastic spatula (ointment), petroleum jelly, splints (varied)

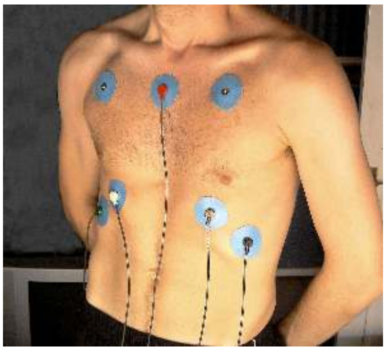
- **Pathology and analysis**: Culture dishes/discs and media (including sensitivity discs), swabs, streakers, loop holders, specific gravity refractometer, slide stainers (with slides and reagents), slide dispenser, oxidase strips, hemolysis applicators, hemacheck assembly, urine test strips, hCG test, portable clinical blood analyzer and accessories (including control solutions), microscope and accessories, immersion oil, capillary bulbs & tubes, finger lancets, culture incubator.

- **Samples and waste**: Hazard identification labels, bags (chemical resistant, red bio-wipe, ziploc), absorbent wipes, vials / containers (ex: urine sample), waste canisters

- **Health, safety and monitoring**: Total organic carbon analyzer (water), ion-selective electrode assembly (water), microbial air sampler, gas monitors (fixed and portable), temperature monitors, radiation monitors

The most diverse diagnostic imaging tool currently employed in space is sonography, with a range of applications including abdominal, gynecological, thoracic, muscle and tendon, vascular, small parts, and heart (echocardiography). But others should be noted:

- **Electrography**: Comprising a broad array of medical systems that work by similar means (electrocardiography, electroencephalography, electromyography, etc), electrography represents another imaging modality with comparably lightweight hardware.



Holter electrodes for EKG.

- **X-ray scanner**: While no full X-ray imaging system has been deployed to space, a small DXA experiment for measuring mouse bone loss has been prepared.[649] X-rays are used in a variety of modalities, among them direct imaging, fluoroscopy (real-time imaging), and angiography (x-ray after injection of a contrast agent). Multipurpose X-ray systems exist, are not particularly large, and most of the volume is housing and supports that could potentially be produced locally.[650]

- **Magnetic Resonance Imaging**: Generally thought of as very large, heavy devices, a miniature TRASE MRI system has been developed for space applications.[651] Such an device sized for arms and legs would weigh under 50 kg, while one sized for the whole body would weigh around 700 kg; by contrast, MRI systems on Earth often mass around 10 tonnes.

- **Positron Emission Tomography**: While it would be desirable to make use of PET imaging; however, traditional PET imaging involves the use of sizeable particle accelerators to create short-lived radioisotopes (such as fluorine-18) which are then used to manufacture tracer compounds (such as 18-fluorodeoxyglucose). The short half-lives involved are measured in minutes, prevent importing such compounds from Earth. However, an alternative approach in development involving the use of radiolabeled nanoparticles allows the use of long-lived positron sources (such as 22Na) by ensuring that they do not persist in the body.[652]

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[649] Shi, J., Lee, S., Uyeda, M., Tanjaya, J., Kim, J. K., Pan, H. C., . . . Soo, C. (2016). Guidelines for Dual Energy X-Ray Absorptiometry Analysis of Trabecular Bone-Rich Regions in Mice: Improved Precision, Accuracy, and Sensitivity for Assessing Longitudinal Bone Changes. *Tissue Engineering Part C: Methods*, 22(5), 451-463. doi:10.1089/ten.tec.2015.0383
[650] *Radiography systems*. Medical Expo. Retrieved from http://www.medicalexpo.com/medical-manufacturer/radiography-system-3034.html
[651] Sarty, G.E., Sharp, J., Tomanek, B., Turek, K., Obenaus, A., Scott, ... Pierson, R.A. (2012) *A Magnetic Resonance Imager for the International Space Station*. 63rd International Astronautical Congress, Naples, Italy. IAC-12-A1.3.13
[652] Faraj, A. A., Alotaibi, B., Shaik, A. P., Shamma, K., Jammaz, I. A., & Gerl, J. (2015). Sodium-22-radiolabeled silica nanoparticles as new radiotracer for biomedical applications: in vivo positron emission tomography imaging, biodistribution, and biocompatibility. *International Journal of Nanomedicine,* 6293. doi:10.2147/ijn.s93523

Concerning radioisotopes, a number of sealed-source brachytherapy (radiation therapy) isotopes have sufficiently long half-lives for import to be viable, including 137Cs (*30.17y*), 60Co (*5.26y*), 106Ru (*1.02y*), and to a lesser extent 192Ir (*73.8d*) and 125I (*59.6d*). The unsealed brachytherapy isotope 89Sr (*50.57d*), used for palliative bone pain treatment, could also be potentially imported.[653] In terms of local usage of accelerators for production of radioisotopes, plasma wakefield devices are a promising avenue toward achieving high energies with small systems.[654]

At a minimum for medical facilities, a common table (such as a multipurpose gaming table or meeting table) can be repurposed for exams and surgery with the use of sterile plastic sheeting. Sterilization of large objects (including sheeting) in addition to smaller objects (such as gloves and medical instruments) should be taken into account in choosing an autoclave for the laboratory. A procedure for testing for pinholes should be in place.

Antiseptics, both for sterilization of surfaces and topical treatment of patients, are important, and a desired target for local production. While antiseptics such as iodine, brilliant green tincture and benzalkonium chloride are not well suited to simple local production, ethyl alcohol has been used since time immemorial, and hydrogen peroxide can be generated from water by simple electrolysis.[655] Some antiseptics (and other medical products) come in the form of coatings on applicator sticks, such as silver nitrate; these would ideally be handled in a reusable manner where the coating can be reapplied from a bulk solution.

Due to the presence of an autoclave for sterilization, safe syringe reuse is possible. While not typically performed, needle reuse is also possible, with caution; for example, while earlier studies of diabetics demonstrated little problem with needle reuse ranging from 4-200 injections, with only occasional redness as a side effect,[656] more modern studies have associated it with lipohypertrophy.[657] Handling of used needles presents a safety risk; proper procedures or hardware (such as self-retracting needles[658]), as well as needles designed to maintain sharpness (or resharpenable / self-sharpening) should be investigated. It should be noted that even single-use needles represents only a small import mass.

Dealing with stockpiled blood and transfusions can be challenging in space, raising interest in alternative solutions. In particular, hemoglobin-based oxygen carriers (HBOC) have gained interest as an alternative to red blood cells, as they are broadly compatible, sterile and readily stockpiled - albeit at a higher risk of adverse clinical events in usage.[659]

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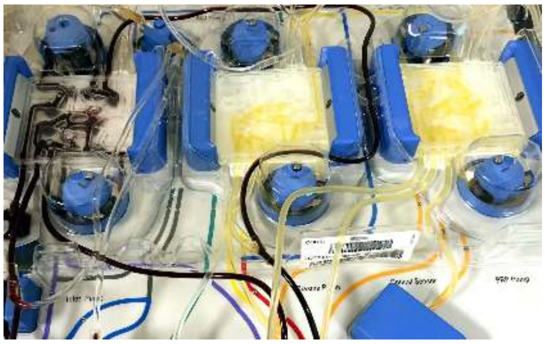
653 *Nuclear Wallet Cards*. Retrieved from http://www.nndc.bnl.gov/wallet/wc7.html
654 Litos, M., Adli, E., An, W., Clarke, C. I., Clayton, C. E., Corde, S., . . . Yocky, G. (2014). High-efficiency acceleration of an electron beam in a plasma wakefield accelerator. *Nature*, 515(7525), 92-95. doi:10.1038/nature13882
655 (2010) *Electrochemical Hydrogen Peroxide Generator*. Lyndon B. Johnson Space Center, Houston, Texas.
656 Chlup, R., Marŝálek, E., & Bruns, W. (1990). A Prospective Study of the Hazards of Multiple Use of Disposable Syringes and Needles in Intensified Insulin Therapy. *Diabetic Medicine*, 7(7), 624-627. doi:10.1111/j.1464-5491.1990.tb01461.x
657 Blanco, M., Hernández, M., Strauss, K., & Amaya, M. (2013). Prevalence and risk factors of lipohypertrophy in insulin-injecting patients with diabetes. *Diabetes & Metabolism*, 39(5), 445-453. doi:10.1016/j.diabet.2013.05.006
658 Van Dyke, L. R. (1999). *U.S. Patent No. US 6413236 B1*. Washington, DC: U.S. Patent and Trademark Office.
659 Weiskopf, R. B., & Silverman, T. A. (2013). Balancing potential risks and benefits of hemoglobin-based oxygen carriers. *Transfusion*. doi:10.1111/trf.12339

Where blood supplies are required, the crew would be expected to be willing to donate to restore any deficiencies. This would require that hardware for apheresis be on-hand, as well as additives to stabilize the blood such as sodium citrate and adenine. Glucose, usually added and also needed for parenteral feeding, is locally replenishable from starch, so long as imported stocks of alpha-amylase, glucoamylase and glucose isomerase are maintained. Hydrochloric acid and chloralkali-sourced caustic soda (also required) are available locally. The process is ideally performed with a dedicated system, but for small quantities can be done via batch synthesis. In the early phases, import of glucose is a simpler option.



Apheresis machine separating blood. Photo: NIAID

For any legitimate colony, obstetrics must be taken into account. Concerning neonatal care, a infant incubator (transport-style) might be desirable in the event of an unplanned pregnancy, and could be shipped in advance of planned pregnancy, to have on hand as needed. However, most of the capabilities of an incubator - blood pressure monitoring, oxygen hood, IV pump, pulse oximeter, etc - could likely be provided by existing equipment if care is taken to ensure their compatibility with neonates. The simplicity of bubble CPAP makes it an appealing means to deal with infant respiratory distress syndrome, in comparison to mechanical ventilation.

We do not go into a full breakdown of medications, and instead consider it premised on the full the WHO Model List of Essential Medicines[660] (supplemented as needed), which is too extensive to cover here. Only a small fraction medications would be available in forms ready for patient dosing; the remaining will be in concentrated forms for compounding. Compounding fillers can be widely varied, and should be selected based on local availability. Of the WHO medication list, most items are very small; however, sizeable elements include the inhalation medicines (halothane, isoflurane, nitrous oxide and oxygen); blood and blood components (plasma, platelet concentrates, packed red blood cells and whole blood); and long-term parenteral feeding needs (glucose, potassium chloride, sodium chloride, water).

As a general rule, inhalation anesthesia is prohibited in space medicine, due to the confined spaces; even small gas leaks could prove highly hazardous to crews. This rule does not apply on Venus due to the extremely large enclosed volume. Easily producible inhalant anesthetics such as nitrous oxide should ideally be favoured over more difficult (but nonetheless potentially producible) anesthetics such as isoflurane and halothane. Tankage mass still must be accounted for.

Water sourced from dehumidification can be highly pure; so long collection and storage systems are designed to ensure a high level of sterility (such as a UV sterilizer built into each tank), it should be sufficient for IV needs. Sodium and potassium chloride are readily produced from fractional crystallization of the hydroponics system (already a

[660] (2015) *WHO Model Lists of Essential Medicines*. World Health Organization. Retrieved from http://www.who.int/medicines/publications/essentialmedicines/en/

requirement to ensure that the nutrient solution remains balanced). Production of glucose is described above.

It can be difficult to justify, from a mass and labour perspective, most local production of medication and medical supplies. However, if one retains sight of the long-term goal - the ability to survive and thrive independent of Earth - it makes sense to attempt to nurture nascent production as much as possible.

Foxglove, source of the heart medication Digoxin (Lanoxin). Photo: Jcart1534

It should be noted that some medications are relatively simple to produce. There are many recipes for capsicum waxes and oils for pain, making use of the anesthetic properties of the capsaicin from hot peppers. Throat lozenges are often pectin-based sweets containing a mild anesthetic or other soothing compound, such as steam-distilled eucalyptus or mint oil. And indeed, many modern medications for more serious conditions are simple extracts (or simple derivatives thereof) of plant compounds. Opium is produced from opium poppies. Digoxin, from foxglove. Atropine from belladonna. L-dopa from velvet bean. Ephedrine from ephedra species. The total list of plant-, fungal- and microbial-derived drugs would be prohibitively long. While simple tinctures of plants can frequently be hazardous due to varying levels of the active compounds, the presence of a broad suite of chemical analysis hardware for study of the local environment makes precise dosing quite achievable. Each medicinal plant grown locally serves a double purpose: preserving an additional piece of Earth's biodiversity offworld. Contrarily, microbe-produced drugs offer the potential of efficient production at very small scales.

Most concerns with space medicine have to do with the microgravity environment, which is large inapplicable to Venus habitation. An exception to this is recovery from any physical degeneration / radiation exposure in-transit. In particular, patients can be expected to have experienced some degree of muscle atrophy upon arrival, and will need a period to adjust. Early scheduling of physical activities, such as cargo offloading, should be planned around the capabilities of individuals taking into account their reduced muscle mass.

Travel to other planets is inherently self-quarantining; multi-month transits are longer than most disease incubation times. Plans should be in place on how to handle arriving spacecraft on which contagious disease outbreaks of note have occurred.

Concerning the Venus environment itself, any health consequences of exposure to the external environment, as described in *Chemical Environment and Resource Considerations*, must be well studied. Long-term workplace exposure to sulfuric acid fumes is associated with cancer and other adverse health effects, although this should not be of concern inside a properly developed habitat with proper atmospheric monitoring. Protracted skin exposure to the external environment can be expected to be associated with dermatitis, and short-term eye exposure would be expected to be associated with pain, redness, and blurred vision. Eye exposure to sulfuric acid, the most serious acute risk factor, is treated by flushing with water or saline solution for at least 20 minutes; hence, water or saline solution should be located immediately near airlocks in case of an accident. Decontamination is not required if the patient has only been exposed to mists. Significant inhalation of sulfuric acid (>5 mg/m³) is treated by a beclomethasone inhaler and humidified oxygen; IV steroids can also be of utility. Patients should be monitored for at least 24 hours.[661] Potentially a more significant threat is that of carbon dioxide poisoning. In addition to resuscitative measures if the patient has gone into cardiac arrest or respiratory failure, the primary objective is correction of hypoxaemia via monitoring with a pulse oximeter while administering oxygen.[662]

Medications typically measured in "drops" can be problematic in offworld environments, as droplet sizes can be affected by gravity. Venus's flight-altitude ~8.7 m/s^2 gravity is close to, but not identical to, Earth's 9.8 m/s^2; the average droplet size will tend to be slightly larger on Venus.

As is standard in space medicine, dosing of over-the-counter medications such as aspirin should be left to the discretion of crew members. As an emergency precaution, defibrillators, ambu bags and other emergency equipment should be accessible in multiple locations.

A difficult aspect to control is circadian rhythms. While extreme polar locations can experience roughly 24-hour days, other locations experience day-lengths ranging from a couple Earth days up to nearly a week. Unusual light cycles are, it should be noted, not abnormal on Earth; residents of high latitude locations experience little dimming (if any) during summer days and little light (if any) during winter nights, for months on end. Excess light is commonly addressed with blackout curtains around sleeping areas. Some individuals experience seasonal affective disorder, which is commonly treated by phototherapy, psychotherapy and/or medications;[663] however, as this is a condition related to prolonged periods of consistent lighting, not cycling between light and dark periods, its applicability is not direct. Further study is needed concerning the effects of 36-120 day photoperiods for protracted lengths of time. Mass and power constraints prohibit lighting the entire volume of the habitat at night, even to room-lighting levels; however, the areas within and immediately around living quarters can be kept well illuminated with LED lighting.

An advantage to the Venus environment is that people can be readily physically isolated from each other if need be, including for quarantine or to deal with antagonistic interpersonal issues between crew members. However, more serious issues that involve a risk of harm to self or others must be dealt with. As per NASA guidelines, short-term control of aggressive individuals can be handled through tape / binding of their limbs and tranquilizers.[664] However, unlike on the International Space Station, such individuals cannot

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[661] (2012) *Sulfuric Acid*. BASF Chemical Medical Emergency Medical Guidelines. Code E015-004.
[662] (2003, 18 March) *Managing hypoxia and hypercapnia*. Nursing Times
[663] (2014) Seasonal Affective Disorder (SAD). Mayo Clinic. Retrieved from http://www.mayoclinic.org/diseases-conditions/seasonal-affective-disorder/basics/definition/con-20021047
[664] (2001) *Behavioral - Acute Psychosis - Emergency. International Space Station Integrated Medical Group (IMG) Medical Checklist*. NASA. JSC-48522-E4.

be readily transported back to Earth. Consideration should be given toward the removal of all sharp / heavy objects from a bedroom and the ability to seal safety netting completely around it, with respect to the netting's durability against an individual determined to escape. Containment of problematic crew members during a return voyage is an issue left to the design of the interplanetary transfer stage, the design elements of which are not discussed in this book.

Radar and communications

Radar and communications involve multiple requirements:

- Communication with Earth
- Communication with surface probes
- Communication with orbital and incoming spacecraft
- High resolution surface scanning with radar
- Weather radar
- Communications with Earth must be tolerant of hardware failures
- Radar should not disrupt communications with Earth

The radar system most commonly used on spacecraft is synthetic aperture radar (SAR) and variants such as inverse synthetic aperture radar (ISAR) or interferometric synthetic aperture radar (InSAR). All make use of the spacecraft's motion between the emission of a radar pulse and the registration of its return in order to emulate the use of a larger aperture, and thus higher maximum achievable resolution. This immediately raises a challenge for a habitat-borne radar system, which moves moving at two orders of magnitude lower velocity than an orbital spacecraft yet flies only half an order of magnitude closer to the ground.

Instead, the optimal design in the case of a habitat is a phased-array radar. In a phased-array, multiple independent antennas function together to emulate a single larger antenna, with the emulated aperture proportional to the maximum distance between individual antennas. For most spacecraft and habitats, this separation would be relatively small; however, in the enormity of an inflated Venus habitat, these distances could be substantial. The maximum achievable resolution is governed by:

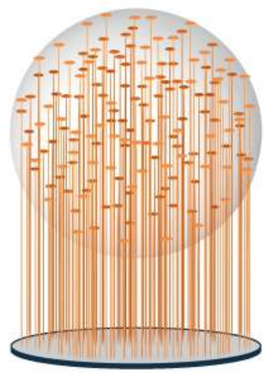
$$R_{target} = \lambda * R / B_n$$

Where:

- R_{target} is the resolution at the target
- λ is the wavelength
- R is the radar target distance
- B_n is the perpendicular baseline (distance between antennas perpendicular to the path of the beam)

For the band in question, we favor the judgement of the VERITAS team in their InSAR analysis, and begin by selecting X-band - specifically, for space-based observations at 30°, they determine an optimal 3.8cm wavelength.[665] We then adjust for the difference between the middle cloud and orbital environments. Taking into account having the habitat being located partway through the atmosphere's radar-absorption cross section, the availability of abundant low-mass-penalty power provided by the habitat's inflatable solar power system, and an easier-to-justify greater antenna mass for a manned mission versus an unmanned one, we consider allowing a 20x increase in acceptable atmospheric attenuation to be be a pessimistic assumption. As atmospheric attenuation rises quadratically relative to the frequency, this yields a further drop in the wavelength to 0.85cm. This puts us in Ka band (35.3 GHz).

Entering that into the above equation, and assuming a baseline of 300 meters from an altitude of 55km with an assumed angle of 30 degrees to the perpendicular (a path length of 63.5km), we arrive at a maximum resolution of 1.8 meters (without considering enhancement techniques such as combining multiple looks). By contrast, the VERITAS proposal aimed to map Venus at 15 meters per pixel, and the best current mapping of Venus (Magellan) does not exceed 101m.[666] The lower altitude would also yield significantly improved height accuracy.



Crow's Nest phased-array antenna; elements are distributed throughout the volume such that their side lobes do not interfere. Image: Christian Wolff

In short, even if an unmanned radar mapping probe such as VERITAS is utilized between now and the time of habitat deployment, and even if the habitat's radar system is for various reasons not as as precise as the above figures suggest, an atmospheric habitat still offers the potential for dramatic improvement in the ability to resolve fine surface features. In addition, the long-term observation from a permanent habitat presents the opportunity to monitor for changes in the terrain, such as tectonic shifts, mass wasting, volcanic processes, and alterations in surface reflectivity.

A phased-array antenna provides additional benefits as well:

- The ability to take part in multiple simultaneous independent radar and communications tasks, with capacity for each task allocated as needed.
- Rapid digital steering of the beam
- Graceful degradation in the event of hardware failures

Like with SAR, a phased array radar can function in backscatter, altimetry, and emissivity measurement modes. A disadvantage is that geometric precision is critical to controlling phased array timing. Given that the habitat structure will flex, all antennas must

[665] Hensley, S., Smrekar, S., Nunes, D., Seu., R., Lombardo, P., et al. (2016) Single Pass X-band Radar Interferometry for Topographic Mapping of Venus. 47th Lunar and Planetary Science Conference.
[666] Grayzeck, E. (1997). "Magellan: Mission Plan". NASA / JPL.

have the means to precisely calculate their distance relative to each other multiple times per second.

K-band is not commonly used for weather radar on Earth due to high absorption, although it does provide some limited range. X-band is commonly used for portable, low-gain, short-range weather radar systems on Earth, generally around 250km range in good weather but under 50km range in the rain. Longer-range weather radar generally uses C or S band. Higher frequency radars allow for the detection of smaller particles[667] - of significant scientific on interest on Venus. S-band, having been used for previous radar observations of Venus, would allow for more direct data comparisons. Additionally, the ability to handle multiple frequencies increases the variety of radio science experiments that can be conducted. In short, the ability to operate in a range of different bands is worth further consideration.

Concerning Earth and spacecraft communications, precise pointing is required. While “steering” is one of the advantages of phased-array systems, the habitat must know its current position over Venus’s surface. While timing between sunrise and sunset could yield approximate locations, radar and/or IR observations of the surface would yield much greater precision.

As noted under *Infrared rejection*, low-E coatings tend to significantly hinder radio transmissions - but this can be worked around by printing them out as a non-continuous layer. Carbon fibre, if used as a reinforcing fabric, needs to ensure that it does not provide significant attenuation for the radio system. This is likely to be more of a concern for loose-fill CF than for cable reinforcement - the former being a relatively poor choice on its own due to light absorption.

Without an orbital relay, communications blackout would occur for approximately half of each atmospheric superrotation period (“day”). This can be addressed by utilization of one or more communications relay satellites.

Orbital hardware

In order to maintain nighttime communications, at least one relay satellite would be required. This is not so much of an imposition as an opportunity; having satellite observations of the local environment to correlate with conditions observed by the craft would be of tremendous utility in enhancing models of Venus's atmosphere, as well as in providing weather forecasts to the habitat.

For a single-satellite scenario, an approximately geostationary orbit (with respect to the superrotation rate in the habitat environment rather than the surface) would seem the logical choice. For a 48-hour circulation (VeRa zonal wind speed estimates), this would be a circular orbit at 56582km with zero inclination - high enough to keep occultation of Earth by Venus relatively rare. In the future, three such satellites could provide global coverage to

[667] (2000) *Radar Bands*. Everything Weather / Weather Edge.

Venus outside the far polar regions as well as prevent communications blackouts. Contrarily, there are a wide range of inclined elliptical orbits which can provide coverage in a multi-satellite environment while allowing for low-altitude passes.

Beyond communications / observation satellites, an early-phase habitat requires no further orbital hardware. In the longer term, however, a number of options are worth consideration.

A space station would allow outbound crews to amass in orbit to await an incoming transfer vehicle. This is unlikely to be of great utility early on; as discussed in *Getting There and Back*, the lift of a habitat is primarily used for propellant mass, which in turn cannot be rapidly regenerated over short timescales. Hence a single habitat cannot rapidly re-launch its ascent vehicle to send more crew to a station. However, for a colonized Venus with multiple habitats, crews could be amassed from different habitats. Additionally, for larger future habitats with much higher propellant production rates, relaunch rates could be much higher, allowing the habitat to make multiple launches in a relatively short period of time.

From a long-term view, a propellant depot would greatly increase the delivery and return capacity of incoming transfer stages. The propellant type would need to be compatible with the transfer stage, either implying a transfer stage which can burn low-hydrogen fuels, or very large-scale processing of mists in-situ.

A spacecraft in orbit around Venus, like Earth, will slowly decay over time; this occurs at higher altitudes than on Earth. For a satellite with a 138 kg/m^2 ballistic coefficient, over the course of two years, it would lose around 195 m/s at 200km, 50m/s at 225km, 10m/s at 250km, and 1 m/s at 300km.[668]

Preliminary steps

Studies and prototypes

- **Design studies**: Created integrated model combining structural design, FEA, radiative and convective balance, power production, climate control / humidity, propulsion, buoyancy calculations, and planetary models (VenusGRAM / etc). Optimize the model over desired mission parameters.

- **Humans / human models**: Followup studies on long-term reduced pressure effects. Follow-up studies on the effects of long days and coping strategies. Better quantification of acceptable levels of gas permeation. Studies on crew abilities to perform tasks in simulated habitat environments (envelope cleaning, harvesting, etc while on trusses, ropes, etc). EVA suit development / selection.

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[668] Lockwood, M. K., Paulson, J. W., Kontinos, D. A., Chen, Y.K., Laub, B., Olejniczak, J., ... (2006). *Systems Analysis for a Venus Aerocapture Mission*. NASA STI Program, NASA/TM-2006-214291

- **Agriculture**: Followup studies on long day lengths and strategies to minimize harmful effects. Plant selection and breeding / engineering to maximize production in long day / low pressure environments. Self-contained mushroom cultivation system prototype. Hydroponics and aeroponics prototypes tested in simulated conditions. Seed germination rates under various storage, temperature and atmospheric conditions. Waste incineration, cation recovery and fractional crystalization system prototype.

- **Animal husbandry**: Studies on livestock adaptation to Venus habitat conditions. Breed optimization for small transport size and backbreeding effectiveness without sacrificing production or feed conversion. Studies on the effectiveness of various agricultural waste diets. Functional prototype pens and all livestock management hardware, both for habitat and transit environments.

- **Aquaculture**: Follow-up studies on adapting current systems to a Venus habitat environment, optimally for simultaneous culture of multiple species. Studies on the minimization of species size during transport. Full-size prototypes tested through all stages of operation, using locally available feedstocks. Consideration of the ability to use the aquaculture facilities for recreational bathing.

- **Apiculture**: Investigation of bee navigational ability in a Venus habitat (requires prototype habitat). Investigation into bee adaptability to Venus-like day lengths, pressures and gas mixtures. Prototype transport hive and demonstration of survivability through transport conditions.

- **Testing**: Development of environment to simulate Venus's middle cloud environment (chemical mixture, temperature, light, etc). Development of environment to test surface probes. Existing facilities may be used as appropriate.

- **Materials**: Develop flight-intent system for extruding envelope gores. Include all additives and surface treatments (plasma, coatings, etc). Incorporate optional solar printing. Prototype flooring. Prototype solar "tents". Ensure adaptability to all types of required polymer sheeting. Develop flight-intent gel spinning and rope braiding system; demonstrate for all required fibres. If loose-fill fibre is to be utilized, prototype a fibre chopping system. Acquire or develop a miniature loom capable of producing all necessary weaves. Prototype a system for doing all necessary fibre and fabric treatments (such as PAN carbonization). Analysis of the usage of carbon nanotube wiring and capability for local production. Development / adaptation of structural element extrusion systems.

- **Habitat propulsion and In-Situ Resource Utilization**: Feasibility study of alternative means of propulsion. Investigation into ionic liquids optimized for scrubbing. Prototype scrubber / propulsion system, incrementally enhanced with recovery, boiling / catalytic decomposition, distillation, and inert gas recovery / distillation. Incremental prototyping of propellant feedstock synthesis systems. For any cryogenic compounds, prototyping of flight-capable cryogenic storage systems.

- **Envelope**: Accelerated aging of envelopes for long-term survivability, transparency, permeation, electrical and mechanical properties. Demonstration of secure joining of gores and in-situ repairs. Development and demonstration of and pinhole detection and repair systems. Development and testing of safety systems (netting, etc).

- **Entry systems**: Detailed reentry heating analysis study, in conjunction with habitat and ascent vehicle design studies. Envelope testing in simulated entry conditions.

- **Transfer stages**: Full design studies for the habitat and crew transfer stages.

- **Ascent vehicle**: Low-hydrogen propellant studies with engine prototyping. Nuclear-thermal concept study for Venus conditions, including capability for hover while docking. Automated envelope repacking testbed.

- **Laboratory / shelter / bathroom**: Design, prototyping, deployment and human usage studies for a combination laboratory / shelter containing a bathroom with a desiccating toilet. Selection and adaptation of all necessary laboratory equipment to support local scientific, medical, and industrial needs.

- **Common area / medical**: Design, prototyping, deployment and human usage studies for a common area, optionally integrated with medical facilities.

- **Kitchen / food storage / processing**: Design, prototyping, deployment and human usage studies for the facilities for handling food. Prototyping or adaptation of lightweight food processing systems. Creation of lightweight / collapsible refrigeration, oven, range and microwave systems. Integrated wastewater handling system study.

- **Bedrooms**: Design, prototyping, deployment and human usage studies for lightweight bedrooms, including water collection / handling and power systems.

- **Shower**: Design / prototyping (or acquisition / adaptation) of a grey water recycling shower system with integrated solar tent and water collection.

- **Climate control and dehumidification**: Prototyping of lightweight climate control and dehumidification systems, optionally involving structural elements as radiators.

- **Radar / communications**: Development of prototype crow’s nest phased-array radar and communications system with continuous adjustment for flexing of the habitat’s structure. Integration with a wireless LAN.

- **Medicine**: Continuation of current programmes for the development of lightweight medical systems. Increased emphasis on in-situ produced medical consumables where possible. Investigations on medication compounding with locally-available fillers. Development of a common surgical theatre.

- **Entertainment**: Development of lightweight multipurpose gaming systems and other entertainment activities.

- **Scientific payloads**: Continuation and expansion of programmes to develop systems useful for meeting VEXAG goals.

- **Surface systems**: Continuation of the development of high temperature systems for use on Venus's surface, with a focus on phase-change and bellows balloons that can raise samples to high altitudes. Prototype dredging system.

Missions

- **Entry testbed(s)**: A programme must test entry and inflation prototypes on Earth to advance the TRL for use on Venus missions (both full scale and smaller-scale preliminary missions).

- **In-situ test mission**: A balloon probe (ideally as part of a broader scientific mission) must operate in the target environment for a significant length of time (90-day minimum baseline), testing basic technologies such as envelope materials, solar power generation, etc., as well as fully quantifying the atmospheric properties of the operating environment (chemical, wind, etc).

- **Mini-habitat in-situ testbed**: A miniature (e.g. 1/10th scale) unmanned version of the habitat should be deployed on Venus, performing all of the same basic functions as the full-scale manned habitat.

- **Heliox testbed**: A mid- to full-scale version of the habitat launched on Earth and inflated with heliox, a breathable lighter-than-air mixture of helium and oxygen commonly used for deep-sea diving. This would enable testing all aspects of long-term habitation in a floating habitat within Earth's troposphere - even atmospheric scrubbing (albeit with the recovery of different species).

- **Communications relay(s)**: Before any launch of humans, there should be at least one satellite present which can function as a communications relay during the period that Earth is occluded from Venus. As in the case of Mars, such satellites will generally serve other scientific purposes as well as relaying communications.

- **Surface probes**: While not necessary for an initial habitat, probes which can repeatedly access the surface (bellows / phase-change balloons) are both of significant utility to the habitat (ISRU, science), as well as being useful on their own without a habitat being present.

Mass budget

For the below sample mass budget, we will consider a habitat with a CyMet/MON ascent vehicle (nuclear would be smaller) with a surface area of 60614m² and a volume of 881217m³, entering to 60kPa/30°C, before rising to 50kPa/20°C. The initial lift (aka, without ISRU-produced lifting gases) is 9 tonnes less than the initial habitat mass, premised on the concept that propulsive lift, a L/D ratio or the rate of production of lifting gases would be sufficient to make up such a small difference.

Name	Arrival (kg)	Pre-crew ISRU (kg)	Crew arrival (kg)	Eventual (kg)	Notes
Envelope					
Fabric	10910	0	0	1091	Assumed base fabric mass of 180g/m²; small expansions over time assumed.
Retained entry systems	1147	0	0	0	2% of total entry mass added for entry-related hardware which is not jettisoned.
Reinforcement / walkways / hydroponics channels	2728	0	0	273	Reinforcement, walkways and hydroponics / aeroponics allocated at 25% of fabric mass
Empennage	1364	0	0	0	Empennage allocated at 10% of (fabric + reinforcement) mass
Primary support cables	241	0	0	24.5	Cables carrying the entire habitat mass (incl ascent vehicle) across it's height at average angle of 30 degrees with tensile strength of 5GPa, density 1,85g/cm³, and safety margin of 400%. Allocated for 1) accessing remote areas, and 2) hanging structural mass (including within individual rooms)
Horizontal transfer cables	61.9	0	0	0	Horizontal cables (9600m), as per above, for carrying up to 500kg to inaccessible locations.
Sheaves	347	0	0	0	1158x sheaves (300g each) on the horizontal transfer cables
Catenary curtain mass	40.1	0	0	4.1	10m catenaries, calculated the same as primary support cables.
Ballonet fabric	6061	0	0	606	100g/m² ballonet fabric at the same area as the outer envelope
Phase-change envelope	303	0	0	30.3	100g/m² phase change envelope fabric at 5% the outer envelope area (spread along the surface to maximize heat exchange)
Safety netting	1704	0	0	170	193 g/m² carbon fibre safety netting (designed for 300kg falling 20m decelerated over 5m) over 8812 m² (40% of the maximal habitat horizontal cross section)
Precip / condensation collection	873	0	0	0	8% of the base envelope mass
Solar cells (w/o substrate)	1488	0	0	149	0.1kg/m² solar cell mass (on top of the base envelope mass) generating a peak 2.5MW at a peak 560W/m² (14881m²)
Long-distance HV wiring	114	0	57.1	0	Average wire diameter of 2,5mm (~10 AWG), 1730m (4x height + 4x width + 2x length), 50% overhead, copper pessimistically assumed. An additional 50%

					assumed to arrive later.
Lighting, cameras, sensors	74.4	0	74.4	0	Average of 1kg per 2000m² surface plus 1kg per 20000m³ volume, with the same amount arriving later.
Ballonet fans / enclosures	182	0	0	90.9	3g of ballonet fan system mass per cubic meter of ballonet area
Airlocks	25	0	0	25	Flexible plastic plus vacuuming system. Fixed value assumed.
Vents	546	0	0	0	5% of the base envelope mass
Total	**27269**	**0**	**0**	**2348**	
With 10% margin:	*29995*	*0*	*0*	*2582*	
Fuel cell stacks					Nighttime power storage = 23.06GJ 18.45 GJ recoverable
Stack	214	0	0	0	0.5g/cm², 0.8W/cm², 80% efficiency, 137kW max
Cl2 envelope	94.8	0	0	0	7086kg Cl2 max (7213m³ including 50% leeway), 130g/m²
H2 envelopes	239	0	0	0	204kg H2 for the fuel cell but 6xed for initial H2 surplus (28850m³), 130g/m²
HCl envelopes	301	0	0	0	7291kg Cl2 max (14425m³ including 50% leeway), 130g/m², doubled due to cascade subdivision
Cl2	886	6200	0	0	1/8th delivered initially, 7/8ths produced in-situ. Requires slower initial night flight speeds / night scrubbing.
H2	1227	0	0	0	6x max requirement shipped initially (from decomposed hydrazine), for extra lift and initial water production.
HCl	0	0	0	0	Produced at night from H2 + Cl2, does not need to be accounted for separately
Cl2 condenser	13.1	0	0	0	200 times the max chlorine storage rate (65.6 g/s)
H2 compressors	1.1	0	0	0	Calculated from curve fit of MH compressors for the storage rate (1.89g/s)
HCl plumbing	8.6	0	0	0	100g/m x 86m
H2 plumbing	0.3	0	0	0	100g/m x 3m (handled internally, no long connections)
Depleted H2 plumbing	8.3	0	0	0	100g/m x 83m (less cascade plumbing than HCl, otherwise similar constraints)
D2 plumbing	8.3	0	0	0	100g/m x 83m (like above)
Cl2 plumbing	8.6	0	0	0	100g/m x 86m (like HCl)
Wiring / sensors	26.2	0	0	0	10% of stack, plumbing, and condenser/compressor mass
Total	2984	**6200**	**0**	**0**	
With 10% margin:	3282	*6820*	*0*	*0*	
Phase-change hardware					
Initial NH3/H2O mixture	1000	0	0	0	Arbitrary figure; actual amount controlled by desired passive flight stability.
NH3/H2O tank	27.5	0	0	0	Curve fit based on contents, pressure, temperature, etc.
NH3/H2O supply plumbing	8.3	0	0	0	100g/m x 83m
Total	**1036**	**0**	**0**	**0**	
With 10% margin:	*1139*	*0*	*0*	*0*	
Industrial / gondola					
Floor (two levels)	81.7	0	0	0	2kg/m² fold-out composite flooring * 40.8m²

Envelope	36	0	0	0	Assumed to be separated from the habitat (e.g. on empennage elements or hanging below) and require its own envelope (same material, 200m²)
Envelope structural	9	0	0	0	25% of envelope mass
Envelope filtration / climate	5	0	0	0	Requires its own miniature atmospheric regulation system.
Spotlight	10	0	0	0	Powerful light for visual recognition by / illumination of incoming or hanging vehicles.
Docking lighting	5	0	0	0	Multiple smaller lights to assist in docking and offloading
Interior lighting	0.5	0	0	0	LED lighting
Chemical tankage	100	0	0	900	Arbitrary values (detailed industrial systems design TBD). Hardware needed to produce ammonia, water, and nitrates sent initially, but not propellant (as there's no place to store propellant until the crew arrives in an ascent vehicle)
Plumbing	10	0	0	100	|
Wiring, breaker box	10	0	0	0	|
Primary distillation unit	200	0	0	0	|
Haber unit	200	0	0	0	|
Ostwald unit	200	0	0	0	|
Sabatier unit	0	0	200	0	|
MON unit	0	0	200	0	|
Cyanogen unit	0	0	200	0	|
Dehydrogenation units	0	0	0	200	|
Hydrocarbon distillation	0	0	0	200	|
Solid oxide fuel cell	0	0	0	0	|
Ethylene unit	0	0	0	0	|
Hydrogen cyanide unit	0	0	200	0	|
Caustic unit	0	0	0	0	|
Fischer-Tropsch unit	0	0	0	200	|
Methanol unit	0	0	0	200	|
Acetylene unit	0	0	0	200	|
Ethylene oxide unit	0	0	0	200	|
Organochlorine units	0	0	0	200	|
Cyclar unit	0	0	0	200	|
Naphtalene unit	0	0	0	200	|
Acetic acid unit	0	0	0	200	|
Glycol unit	0	0	0	200	|
Ammoxidation unit	0	0	0	200	|
Chlorofluorocarbon units	0	0	0	200	|
Other chemical units	0	0	100	800	|
Gel spinning	0	0	0	50	|
Film extrusion / blowing	0	0	0	200	|
Film printing (solar, coatings)	0	0	0	100	|
Extrusion	0	0	0	150	|
Cable braiding	0	0	0	50	|
Textile weaving	0	0	0	80	\ /

Safety netting / rails	7	0	0	0	Arbitrary.
Total	**867**	**0**	**900**	**5030**	
With 10% margin:	*954*	*0*	*990*	*5533*	
Propulsion					
Propellor(s)	60	0	0	0	Assumed 2x 4.2m diameter props with mass 1.7 * d^2
Motor(s)	60	0	0	0	90kW max prop power, 1500W/kg motor power
Cowlings	60	0	0	0	Assumed equal to prop mass.
Total	**180**	**0**	**0**	**0**	
With 10% margin:	*198*	*0*	*0*	*0*	
Scrubber					
Duct	95	0	0	0	4.2m diameter, 60m long, 120g/m^2
Collapsible trusses	38	0	0	0	40% of duct mass
ESPs (x3)	83.1	0	0	0	3x, 2kg/m^2
Spray assembly	50.9	0	0	0	70x spray nozzles (227g each) plus 5kg of plumbing per nozzle.
Spray feed	550	0	0	0	40m, PEX, 3x safety factor, 4m height change, 7.5m/s flow speed, 24 mPas kinematic viscosity, 3 bar feed pressure, 1 bar pressure drop
IL tank	110	0	0	0	20% the mass of the feed line (most of the ionic liquid remains in the feed line, the tank acts as a surplus reservoir)
IL	3000	0	0	0	As discussed under In-Situ Resource Utilization, the scrubbing system has not been optimized.
IL pump	800	0	0	0	Based on an existing system with similar flow and head (https://product-selection.grundfos.com/product-detail.product-detail.html?lang=ENU&productnumber=96162123&productrange=gps&qcid=221514724), lightened by 60%
Demisters and return feeds	249	0	0	0	Assumed 3x the mass of the ESPs.
SO3 conditioning and feeds	20	0	0	0	Arbitrary values (detailed industrial systems design TBD).
Recovery boiler	300	0	0	0	/ \
Recovery heat exchanger	300	0	0	0	|
Decomposition feed	30	0	0	0	|
Decomposition boiler	30	0	0	0	|
Water stripper	10	0	0	0	|
O2 stripper	10	0	0	0	|
Decomposition heat exchangers	30	0	0	0	|
Decomposition outbound plumbing	20	0	0	0	|
Wiring	20	0	0	0	\ /
Total	**4976**	**0**	**0**	**0**	
With 10% margin:	*5474*	*0*	*0*	*0*	
Ascent/docking-related					
Propellant feed lines	500	0	0	0	Assumed 200m lines; 2x 1kg/m, 1x 0,5kg/m.
Launch winch & cabling	1486	0	0	0	As discussed under Docking, ascent and descent, plus

					a 20% margin.
Secondary winches and cabling	149	0	0	594	Miscellaneous purposes; assumed at 10% of the primary launch winch, plus more arriving later to assist in construction / expansion.
Drone	50	0	0	0	Large tethered docking drone, and all associated hardware.
Other docking hardware	200	0	0	0	Miscellaneous.
Total	**2384**	**0**	**0**	**594**	
With 10% margin:	*2623*	*0*	*0*	*654*	
Bedrooms					
Floor	0	0	5.5	0	0.4kg/m² composite floor, 13.9m² (embedded solar underside).
Bedframe	0	0	2	0	Composite frame, ideally cable suspended.
Mattress	0	0	4	0	Could be lighter (air mattress) or heavier (traditional), depending on the variety. Composite spring, carbon aerogel, or other means could yield particularly lightweight mattresses without sacrificing comfort.
Sheeting	0	0	1.5	0	Heavy duvet not required due to the climate. Durability should be emphasized.
Solar tent	0	0	11.6	0	300g/m²; 2.1m height; functions as walls and ceiling, with openable flap windows and door.
Surge battery	0	0	1.6	0	Buffer of 1.5kW for 10 minutes (hair dryer, etc), to reduce the external supply wiring's gauge.
Wiring / breaker box	0	0	1.5	0	Arbitrary.
Plumbing	0	0	1.5	0	Arbitrary. Includes either drainage feed to a nearby hydroponics channel (or mister) to eliminate grey water.
Dehumidifier / condenser	0	0	2	0	Mini water generator; each bedroom has its own supply.
Water tank	0	0	0.9	0	15l water tank
Water	0	0	0	15	15l of water.
Grey water processing	0	0	0.3	0	Simple filtration.
Sink	0	0	0.3	0	Small personal sink (composite).
Shelving	0	0	1	0	Composite shelving (ideally hanging).
Lighting	0	0	0.05	0	Small overhead LED lights.
Misc. furnishings	0	0	1.5	0	Arbitrary.
Gas mask	0	0	0.3	0	Every individual has their own gas mask and small oxygen tank.
Oxygen tank	0	0	2	0	See above.
Laptop	0	0	1	0	Every individual assumed to have their own personal laptop, connected to the common data and control server via wifi.
Indoor clothing	0	0	5	0	Arbitrary.
Atmospheric protection suit	0	0	4	0	Arbitrary. Designed for EVAs. Not a pressure suit.
Fan	0	0	1	0	Small ceiling / desk fan.
Climbing harness / ascender	0	0	10	0	Ability to ascend cables to inaccessible locations.
Personal possessions	0	0	25	0	Arbitrary.
Crew	0	0	65	0	Assumed average crew member mass.
Total per bedroom	**0**	**0**	**149**	**15**	Single bedroom, plus one crew member and all of their individual needs.

Total	**0**	**0**	**1486**	**150**	10x crew. Bedrooms can be joined up for families.
With 10% margin:	*0*	*0*	*1635*	*165*	
Workshop					
Floor (w/foldout leaves)	45.3	0	0	0	1.5kg/m² composite floor, 30.2m² including fold-out leaves (embedded solar underside).
Shelving / workbenches	3	0	0	0	0.5kg/m² composite shelving over 20% of the workshop area.
Solar tent	24.8	0	0	0	300g/m²; 3m height; functions as walls and ceiling; can be raised / lowered.
Lighting	0.25	0	0	0	Overhead LED lights.
Wiring, breaker box	6	0	0	1	Arbitrary.
Surplus materials (repairs, etc)	0	0	100	1000	|
Envelope maintenance hardware	0	0	20	0	|
Incinerator (w/plumbing)	40	0	0	0	|
Welder (MIG or TIG), gear	0	0	18	0	|
CO2 tubing from industrial	1.5	0	0	0	|
Hand tools	0	0	20	20	|
Screws, bolts, tape, adhesives, foam, etc	0	0	20	80	|
Storage containers	0	0	3	4	|
Drill, bits	0	0	3	5	|
Saw, blades	0	0	3	5	|
Power tool batteries, chargers	0	0	3	5	|
Vise	0	0	6	0	|
3d printer(s) / CNC	0	0	50	800	|
Printing raw material stocks	0	0	40	600	\ /
Safety tent	11.8	0	0	0	300g/m², 2.5m height; extra tent to protect from sparks, splatter, debris, etc.
Surge battery	8.3	0	0	0	Buffer of 8kW for 10 minutes (welding, sintering, 3d printing, etc), to reduce the external supply wiring's gauge.
Fan	2.5	0	0	0	Ceiling fan
Miscellaneous	10	0	20	50	Arbitrary.
Total	**154**	**0**	**306**	**2570**	
With 10% margin:	*169*	*0*	*337*	*2827*	
Kitchen					
Floor (w/foldout leaves)	30.2	0	0	0	1kg/m² composite floor, 30.2m² including fold-out leaves (embedded solar underside).
Solar tent	16.4	0	0	0	300g/m²; 3m height; functions as walls; can be raised / lowered.
Sink	2	0	0	0	Must be large enough to wash not just dishes, but also clothing, sheets, etc.
Lighting	0.25	0	0	0	Overhead LED lights.

Clothespins and line	1	0	0	0	Arbitrary.
Countertops	0.9	0	0	0	0.2kg/m² composite countertops over 1/7th of the kitchen area.
Walk-in fridge / freezer, collapsible	54	0	0	0	600g/m²; 3m height, 6m²; flexible aluminized bubble wrap and/or aerogel. Mass increased 50% for internal walls. Chiller assumed at 25kg.
Fridge/freezer shelving	4.8	0	0	0	0.2kg/m², 24m² shelving (4x refrigerator floor area).
4x oven x microwave, collapsible	10	0	0	0	Vertically stacked ovens/microwaves (high temperature collapsible insulation structure), for cooking, dehydrating, etc.
Food stockpiles (dry, liquid, frozen)	0	0	9150	4575	610 days of stockpiled 2000kcal/kg food for 3000kcal/day diets for a 10-person crew, plus an extra 50% stockpiled over time.
Large-scale hanging dry food storage	0	0	686	0	Assumed to be 5% of max food stockpile mass.
Large-scale hanging liquids storage	0	0	343	0	Assumed to be 50% of dry storage mass.
Kitchen shelving	18.1	0	0	0	0.15kg/m², 91m² (3x kitchen floor area)
Containers	0	0	3	3	Arbitrary.
Range	2.5	0	0	0	|
Mushroom cultivation	15	0	0	0	|
Mushroom compost	0	0	0	60	|
Wiring	5	0	0	0	|
Plumbing	3	0	0	0	|
Water in plumbing	0	10	0	0	|
Grey water filtration	0.6	0	0	0	|
Tablet (controls)	0.5	0	0	0	|
Thresher / winnower	0	0	12	0	|
Grain mill, mid-sized	0	0	6	0	|
Grinder, small	0	0	0.5	0	|
Press / extruder (pasta, puffed grain, etc)	0	0	3	0	|
Food processor / blender	0	0	1	0	|
Kneader / churn / conche	0	0	5	0	|
Cookware	0	0	25	10	|
Fan	0	0	2.5	0	\ /
Total	**164**	**10**	**10235**	**4648**	
With 10% margin:	*181*	*11*	*11258*	*5113*	
Common area					
Floor (w/foldout leaves)	15.1	0	0	0	0.5kg/m² composite floor, 30.2m² including fold-out leaves.
Shelving	4.5	0	0	0	0.15kg/m², 30.2m² (same as floor area)
Chairs	0	0	12.6	0	6x, 35% the weight of a bedroom bed
Couches	0	0	8.4	0	2x, 70% the weight of a bedroom bed
Television, brackets, cabling, speakers, etc.	0	0	9	0	Large, lightweight hanging flat screen (movies, games, etc)
Media / control / data cluster	0	0	6	0	Common set of lightweight computers for habitat control, data storage, internet caching, TV / movies / games, local computing, and other needs. Use of multiple

					systems provides redundancy and allows parts to be cannibalized from broken systems.
Solar tent	13.6	0	0	0	300g/m²; 2.5m height; functions as walls; can be raised / lowered.
Wiring	3.5	0	0	0	Arbitrary.
Plumbing (pass through)	1	0	0	0	Arbitrary.
Games, general entertainment	0	0	6	0	Any physical gaming equipment not part of a gaming table.
Convertible gaming table	0	0	15	0	Multipurpose table (pool, table tennis, glide hockey, foosball, poker, etc) which can double as a general meeting / dining table, or – with the addition of sterile plastic sheeting – a surgical table.
Medical / dental hardware	0	0	200	1000	Not broken down individually.
Medicine / disposables	0	0	40	120	Not broken down individually.
Room lighting	0.25	0	0	0	Overhead LED lights.
Surgical light	0	0	6	0	Ceiling-mounted articulating light over the table for medical / dental procedures.
Total	**38**	**0**	**303**	**1120**	
With 10% margin:	*41.8*	*0*	*333*	*1232*	
Shelter / laboratory + bathroom					
Floor / walls / ceiling / doors	222	0	0	0	4kg/m² composite structure, 4.2m² diameter, 2.1m height. Airtight and sufficiently robust to withstand a small pressure differential, so that vacuum-incompatible hardware can be stored inside, and crew safety in the event of envelope gas contamination.
Interior walls / doors	5	0	0	0	0.4kg/m² x 6m.
Lighting	0.15	0	0	0	Small overhead LED lights.
Shelving	2.1	0	0	0	0.15kg/m², 13.9m² (same as floor area)
External platform / railing	6.7	0	0	0	3% of the base structural mass of the shelter / laboratory.
Wiring / breaker box	5	0	0	0	Arbitrary.
Plumbing	5	0	0	0	|
Containers	0	0	1	0	|
Computers	0	0	4	0	|
External winch / bucket / cabling	20	0	0	0	|
Chairs	0	0	8.4	0	\ /
CO2 scrubbing system	10	0	0	0	An independent CO2 scrubbing system is required for the room to act as a shelter.
Oxygen dewar	29.4	0	0	0	Half the weight of the stored oxygen.
Oxygen liquefaction / dispensing	19.6	0	0	0	A third the weight of the stored oxygen.
Oxygen	0	58.8	0	0	Sufficient oxygen for 10 people breathing 0.84kg/day for a week.
Gas masks (x3)	0	0	0.9	0	Three personal gas masks present, to allow people to leave the shelter in the case of an emergency or to act as spares.
Individual oxygen tanks (x6)	0	0	12	0	Personal oxygen tanks, refillable within the shelter from stored oxygen.
Climbing harnesses / ascenders (x3)	0	0	30	0	Spares / for use in emergencies.

Toilet (washing, dessicating)	10	0	0	0	Arbitrary.
Sink	0.3	0	0	0	Arbitrary.
Misc. bathroom	0	0	5	0	Arbitrary.
Central core surge battery	9.4	0	0	0	Buffer of 6kW for 15 minutes for the upper central core (lab, common area, kitchen), to reduce the external supply wiring's gauge.
Fan	1	0	0	0	Small ceiling / desk fan.
Total	**344**	**58.8**	**61.3**	**0**	
With 10% margin:	*379*	*64.7*	*67.4*	*0*	
Atmosphere and water management					
Condenser / environmental control	4000	0	0	0	Arbitrary; see
Central core water tank	40	0	0	0	Composite water tank, 4% the mass of the stored water
Central core water	0	1000	0	0	1000l of water
Total	**4040**	**1000**	**0**	**0**	
With 10% margin:	*4444*	*1100*	*0*	*0*	
Shower					
Light	0	0	0.05	0	Small LED light.
Solar curtain	0	0	2.9	0	300g/m²; 2.1m height; shower assumed to be 2m²; no roof present.
Shower base (pumping, water recapture)	0	0	15	0	Based on existing water-recycling shower systems, somewhat lightened.
Dehumidifier / condenser	0	0	4	0	Small condenser to refill the tank
Water tank	0	0	1.8	0	Composite water tank, 6% the mass of the stored water
Water	0	0	0	30	30 liters of water.
Plumbing	0	0	1	0	Arbitrary.
Wiring	0	0	1	0	|
Towels / washcloths, drying line	0	0	5	0	|
Miscellaneous	0	0	4	0	\ /
Surge battery	0	0	4.7	0	Buffer of 3kW for 15 minutes, to reduce the external supply wiring's gauge.
Total	**0**	**0**	**39.5**	**30**	
With 10% margin:	*0*	*0*	*43.4*	*33*	
Agriculture, apiculture					
Nutrients	30	0	30	200	Individual agricultural fertilizer nutrients, shipped either as salts ready for dissolution, or to reduce shipping mass, metals or oxides / hydroxides to be reacted with acids to generate salts locally.
Fractional crystalization	20	0	0	0	Arbitrary
Solution tanks	60	0	0	0	Composite solution tanks, 6% of the mass of the stored solution.
Solution	0	1000	0	0	1000l of solution, generated with in-situ water.
Solution analysis & adjustment	10	0	0	0	Arbitrary.
Plumbing	10	0	0	0	/ \
Pumps	20	0	0	0	|

Flow management	10	0	0	0	|
Movable shading / lighting tent(s)	0	0	40	0	|
Gardening equipment	0	0	30	0	\ /
Seeds / plants	10	2500	50	5000	Any plants for which its desirable (and possible) to ship seeds pre-embedded in germination substrate in the hydroponics channels are shipped thusly; others arrive with the crew.
Beehive (empty)	0	0	30	0	A small hive arrives fully sealed, in hibernation mode; some blooming plants at arrival would allow for immediate opening of the hive.
Beehive (internal)	0	0	50	0	Bees, honey, etc.
Beekeeping equipment	0	0	12	0	Arbitrary.
Total	**170**	**3500**	**242**	**5250**	
With 10% margin:	*187*	*3850*	*266*	*5720*	
Aquaculture					
Pond(s)	0	0	0	800	Transparent, composite-reinforced tank - 8% of the water mass.
Water	0	0	0	10000	1m deep / 10m². Grown purely on algae, this yields 15g tilapia per person per day; this figure can be boosted via LED-boosted algae growth and feeding of agricultural and/or livestock wastes.
Algae shelter	0	0	0	6	600g per square meter.
Water quality management	0	0	0	7	700g per square meter
Fingerling / fry rearing	0	0	0	30	Arbitrary
Tools (nets, etc)	0	0	0	10	|
Wiring	0	0	0	1	|
Plumbing	0	0	0	2	\ /
Total	**0**	**0**	**0**	**10856**	
With 10% margin:	*0*	*0*	*0*	*11942*	
Livestock					
Floor	0	0	0	7.6	0.7kg/m² x 10.9m² (sum of dairy and egg areas, times 1.5 and plus 2 square meters to account for walkways). Goats assumed for dairy (aka, low floor impact)
Solar tent	0	0	0	11.2	300g/m²; 2.5m height; functions as walls and ceiling; can be raised / lowered.
Circumference waste trough	0	0	0	2.9	25% of floor mass plus 1kg
Dairy animal mass	0	0	0	125	Calculated for goats with 1/2 l per crew member per day.
Dairy pen	0	0	0	7.2	Containment, feeding, enrichment, etc – 1.5kg/m² x 4.8m² (pen area increased to 50% over the minimum)
Bird mass	0	0	0	12.6	Calculated for hens with 3 small eggs per crew member per day.
Enriched caging	0	0	0	4.5	Containment, feeding, enrichment, etc – 2kg/m² x 2.2m² (pen area increased to 50% over the minimum)
Stockpiled dairy feed	0	0	0	143	20 days feed stockpile
Stockpiled laying feed	0	0	0	22.9	20 days feed stockpile
Water in troughs	0	0	0	8.3	6% of animal mass

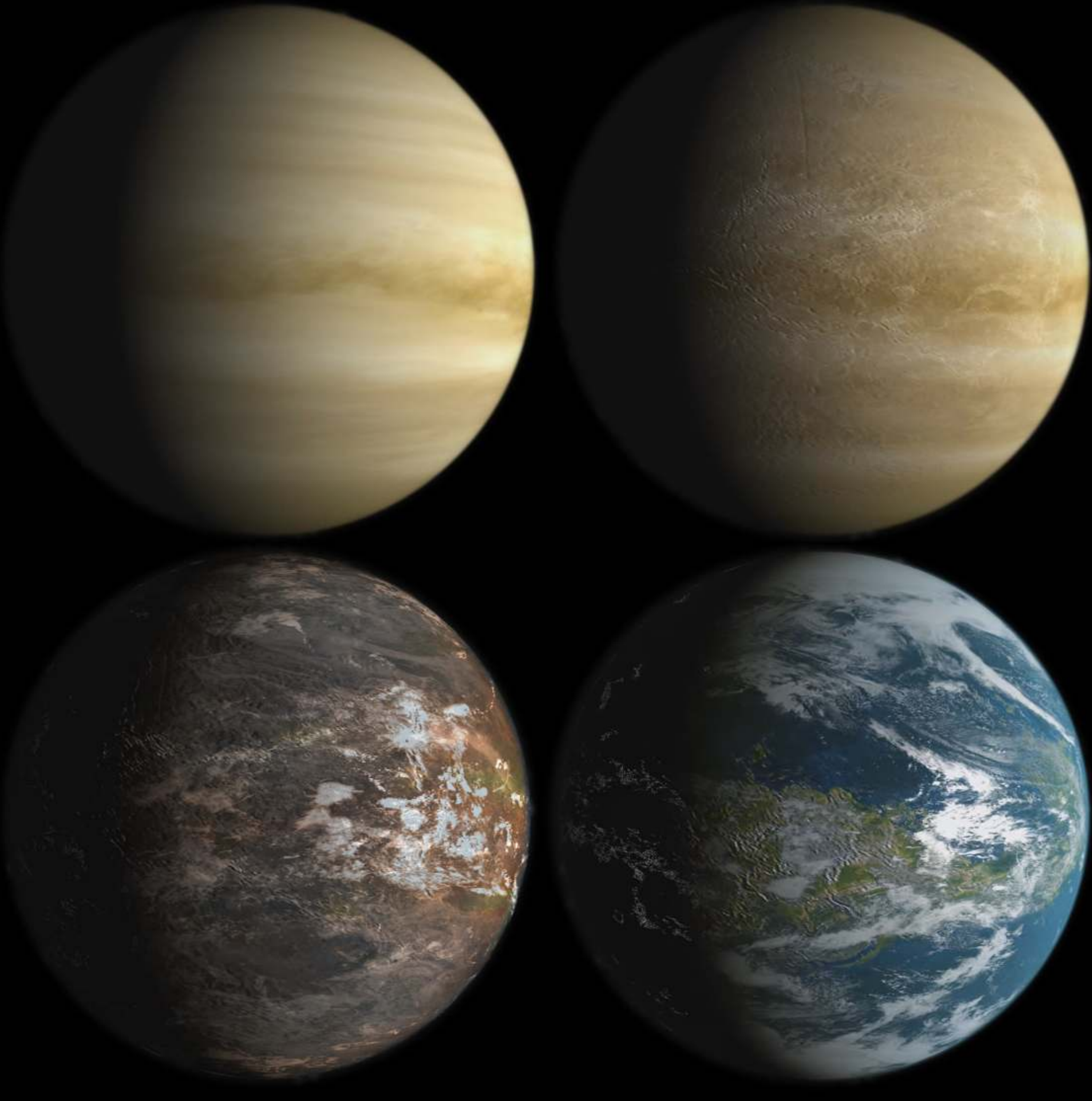
Dehumidifier / condenser	0	0	0	10	Midsized condenser.
Water tank	0	0	6	0	Composite water tank, 6% the mass of the stored water
Water in tank	0	0	0	100	100 liters of water.
Wiring / breaker box	0	0	0	3	Arbitrary
Plumbing	0	0	0	2	/ \
Lighting	0	0	0	0.15	|
Portable milking machine	0	0	0	20	|
Incubator	0	0	0	10	|
Buckets, containers, tools	0	0	0	20	|
Vetenary	0	0	0	50	\ /
Surge battery	0	0	0	1.6	Buffer of 1.5kW for 10 minutes, to reduce the external supply wiring's gauge.
Total	**0**	**0**	**6**	**562**	
With 10% margin:	*0*	*0*	*6.6*	*618*	
Communications / science					
Antennas	75	0	0	0	50x 1.5kg antennas (including relay / power)
Radio management system	10	0	0	0	Arbitrary.
Wifi / repeaters	15	0	0	0	|
Wiring	10	0	0	0	\ /
Nephelometers	2.3	0	0	0	Based on EVE instruments, with small increases.
Radiometers	2	0	0	0	|
XRF	0	0	1	0	|
MET	2.3	0	0	0	|
TDL spectrometers	0	0	1.7	0	|
Mass spectrometer	0	0	3.5	0	|
ATRS	0	0	2	0	\ /
Cameras (misc)	10	0	0	0	Arbitrary
Scale + microbalance	0	0	1	0	|
Autoclave	0	0	30	0	|
Robotic chem lab	0	0	0	300	|
Rock tools	0	0	20	0	|
Microscope(s) & accessories	0	0	10	0	|
Hot plate, stirrir	0	0	1	0	|
Miscellaneous lab equipment	0	0	40	40	|
Miscellaneous experiments	20	0	20	120	\ /
Total	**147**	**0**	**130**	**460**	
With 10% margin:	*161*	*0*	*143*	*506*	
In-transit (not retained)					
Cl2 supply tank(s)	29.8				Curve fit based on contents, pressure, temperature, etc.
Ammonia tank	340				5% of the ammonia mass.
Nitrogen fraction of	5600				Hydrogen fraction already accounted for under Fuel cell

ammonia					stacks. This nitrogen inflates the habitat portion of the envelope 1.1% full.
Hydrazine decomposition	100				Catalyst pack to break down and inject ammonia
N2/H2 separation	100				Separation membrane to strip nitrogen from the hydrogen envelope and inject it into the primary envelope.
Propellant and tankage	1218				2% of initial spacecraft mass, not counting transit hardware.
Propulsion	60.9				5% of propellant and tankage mass.
In-transit communications	10				Arbitrary.
Guidance	10				Arbitrary.
Shielding	305				0.5% of initial spacecraft mass, not counting transit hardware.
Disposed entry systems	1827				3% of initial spacecraft mass, not counting transit hardware.
Power subsystem	100				Arbitrary.
Miscellaneous	385				0.5% of initial spacecraft mass plus 5% of other in-transit mass.
Total	**10085**				
With 10% margin:	*11093*				

The retained habitat mass is 46500 kg, while including the disposed-of transfer hardware (but not the VTO boost stage) is 57350 kg. This puts it within the range of upcoming launch vehicles to LEO (SLS Block 1, Falcon Heavy, New Glenn), optionally with some components (such as liquids) added with a subsequent launch. The transfer stage could be launched separately and mated in orbit. Contrarily, a larger rocket such as SLS Block 2 or SpaceX ITS could launch it complete to LEO.

After deployment, an added 11.8 tonnes of mass is produced before the crew arrives. The first crew arrival brings 15.5 tonnes of payload, most of which could be sent instead with the habitat if so desired. An extra 37.1 tonnes is eventually added, 32% of which is represented by the aquaculture pond; if this mass is deemed excessive, aquaculture could be focused on more intensive means (feeding of waste rather than algae and/or LED-grown algae), at the cost of not providing a location for swimming, or avoided altogether. Including the aquaculture pond, the total habitat mass by the end is 121.7 tonnes, versus a total lift of 264.1 tonnes, leaving lift of up to 142.4 tonnes for the ascent vehicle. While a wide variety of cutbacks or design changes are possible to eliminate up to few dozen tonnes, it is unlikely that an ascent vehicle for such a habitat would be able to exceed around 170 tonnes wet mass.

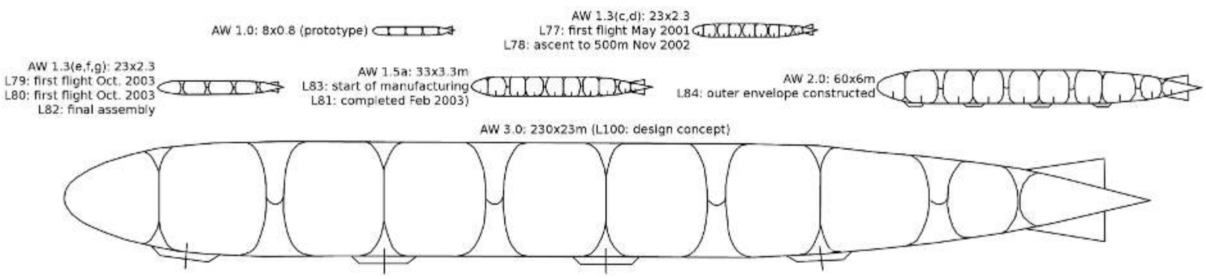
10. The Future of Venus



Expansion

The primary goal of long-term settlement of another world is that, once all local needs are accounted for, the settlement can be expanded, through any combination of enlargement and new settlement construction. This is no different on Venus. Once a habitat has reached the stage of stability and is achieving production of structural ISRU materials (envelope fabric, cabling, etc) in excess of local needs, focus should be moved towards new construction.

There are no shortage of ways in which a new habitat "could" be constructed - hanging from beneath the existing habitat, floating above it, to the side, and a variety of means for building within the habitat and "budded" off. Without casting judgement on any other possible means, we will focus on the latter, and in particular an airship variant known as the "airworm".



A variety of airworm designs from 2001 and 2003. Based on Kröplin et al (2006).[669]

The airworm (multisegmented airship / "steerable draft") concept was first proposed by Ferdinand von Zeppelin in 1890 with a commercialization attempt in 1909 by Theodor Zorn, but ultimately never implemented.[670] The idea was resurrected in 2001 by a University of Stuttgart spinoff named TAO (later renamed AirChain[671]) to commercialize a small-scale variant known as the Sanswire-TAO STS-111. This was subsequently developed into the “Argus One” UAV by its successor, World Surveillance Group. Their variant, however, utilized somewhat different design decisions to that needed for a habitat (the rear cells being used for holding only gaseous fuel, not for payload-bearing lift). The design was chosen as one of Time's best 50 inventions of 2010.[672]

[669] Kröplin, B., Epperlein, F., Kunze, A. (2006) *Mechanical aspects of flight in the lower stratosphere*. Shell Structures: Theory and Applications - Pietraszkiewicz & Szymczak. 2006 Taylor & Francis Group, London. ISBN 0 415 38390 0
[670] Bleibler, J. (2002): *Starrluftschiffprojekte in Deutschland 1908 bis 1914*, in: Meighörner, W. (Hrsg.): Luftschiffe die nie gebaut wurden, Friedrichshafen, S. 31.
[671] Lutz, T. *AirChain*. Institut für Aerodynamik und Gasdynamik, Universität Stuttgart.
[672] Luscombe, B. (2010, November 11). *The 50 Best Inventions of 2010* . Time.

Argus One. Photo: © World Surveillance Group

Contrary to appearances, the airworm concept was not designed to be a means to expand existing airships. Rather, it is an airship design from the ground up for achieving high mass efficiency in large nonrigid airships. As has been discussed previously, the greatest mass efficiency is achieved the closer an airship is to spherical. Contrarily, aerodynamics favours long, narrow shapes. Hence, the airworm combines the two: lift from nearly spherical envelopes, arranged in a line as lift cells, with lightweight, low overpressure interconnects between them. Each nearly-spherical envelope is built as a largely independent airship, with its own propulsion/steering, but all coordinate together for collective mobility.[673]

While not designed as such, the applicability of the airworm concept towards in-situ expansion can be clearly seen; the original habitat continues to function as normal, while new habitats are built with direct connection to the original. Each new habitat can be built bigger than the last, and - more to the point - it is actually desirable, from an aerodynamics perspective, to do so; aerodynamics favours tapering shapes. When it becomes desirable to have a human presence in multiple locations, portions of an airworm can disconnect their lift cells and their outer skin at an arbitrary point, and each segment remains fully functional as an airship on its own. Each segment can also be isolated from each other in the event of emergencies. Entire segments could be, for example, dedicated to industry, with little concern about contamination of adjacent segments in the event of an accident, simply by keeping the "door" closed. In the event of a severe explosion, it is unlikely that more than one or two segments would be damaged; the others would continue to provide lift.

In short, there is much appealing about the design. However, we must now examine issues that pertain specifically to the use of an airworm design as a Venus habitat expansion concept.

- **Envelope material**: Clearly, any envelope fabric exposed to the harsh external environment must be rated to tolerate it. This includes exterior portions of lift cells as well as the interconnecting fabric. But what about the inwards-facing portions of the lift envelope?

  Resistant coatings come at a cost - particularly fluoropolymer coatings, due to the relative rarity of fluorine compared to other atmospheric gases. They also tend to be heavy and with lower structural strength. While an initial habitat might have only

[673] Kröplin et al 2006.

one layer rather than distinct lift cells surrounded by an outer skin, it may be desirable for future lift cells to have their unexposed portions lack such coatings, with only the outer sheath protected. This would have a few implications:

- The void space between lift cells, while it must be buoyancy neutral (carbon dioxide) to serve the purpose of remaining low stress / lightweight, may not contain corrosive compounds, such as acidic mists.

- During separation, the inner envelope must never be directly exposed.

- **Moisture**: The CO_2-filled void space should ideally have slow dehumidification to recover moisture permeated into it from the habitable lift envelopes, particularly if the outer envelope is highly impermeable (e.g. PCTFE). High accumulation of water vapour permeation from the lift cells would not only be a waste of a valuable resource, but could also lead to condensation and precipitation, and thus potentially concentrated mass loadings of liquid water on the envelope. Other permeated gases are not of much concern; nitrogen and oxygen are easier to acquire, and don't pose any condensation risk.

- **Utilization**: While the void space cannot be economically utilized for lift (without imposing stress and thus mass requirements), it can nonetheless be utilized for solar power generation. The potential of the use of the void space for agriculture is worth investigating.

Any sort of basic “budding” process - whether a new habitat section or just a temporary lift envelope - follows roughly the same process. If there is no external envelope:

- This first involves creation of a reinforcing ring in the envelope. Any holes in an envelope are high-stress areas that requires cabling to bear the load. This cabling must be installed without damaging the envelope. Immediately inside the reinforcing ring, a heater wire should be installed, and inside that, a small retaining line attached to the envelope.

- Next, the temporary envelope(s) must be built indoors, and joined with the exterior envelope at the reinforcing ring. The temporary envelope should be securely affixed to the original habitat (catenaries and/or rigid reinforcement) with winches.

- Current is sent through the heater wire, melting off the section of the original envelope inside the reinforcing ring. Slowly letting off the brakes on the winches allows internal pressure to push out the new temporary lift envelope and inflate it. The ballonets inside the habitat simultaneously inflate to compensate for the loss of air.

- As new ISRU hardware production produces more fabric and cabling, ISRU O_2/N_2 production can produce more lifting gas to compensate. The severed section of envelope and heater wire can be retrieved through the airlock via the retaining line for reuse.

For cases where lift cells are separate from the external envelope, this depends on the habitat's design. A habitat designed from the beginning for airworm-style "budding" may already have inner "lift cells" surrounded by an outer "protective" envelope. In this case, the outer envelope can be expanded by budding (the details depending on the implementation), followed by budding off the new lift cell inside of it as described above. If the original habitat was not designed suchly, there may be no outer envelope connection between the first and second lift cells; the outer envelope would then begin at the second lift cell, and be available for each subsequent expansion. A habitat could also undergo "mitosis" down the center (albeit at greater difficulty), deploying an outer envelope at the same time it deploys two lift cell walls.

Expansion is a double-edged sword: it greatly increases local production capacity, but at the same time, by having more people's needs to meet and conducting more local production, it inflates the import requirements from Earth. Hence it is important to ensure that as a colony grows, it increases its ability to produce a broader range of local goods to help alleviate import needs. This includes utilization of both atmospheric and surface-dredging feedstocks.

From this point forward, there are no limits. We thus return to Landis (2003), who described the long-term potential as follows:

> *"For objects the size of cities, this represents an enormous amount of lifting power. A one-kilometer diameter spherical envelope will lift 700,000 tons (two Empire state buildings). A two-kilometer diameter envelope would lift 6 million tons. So, if the settlement is contained in an envelope containing oxygen and nitrogen the size of a modest city, the amount of mass which can be lifted will be, in fact, large enough that it could also hold the mass of a modest city. The result would be an environment as spacious as a typical city. "*

By the time that habitat diameters are measured in kilometers rather than dozens or hundreds of meters, you could loft whole redwood forests. Sculpted landscapes with soil and boulders atop a structural grid. You could, in effect, build an entire new surface over the planet - a surface 3.1 times as large as all the land area of Earth. This is, in effect, a form of terraforming.

But there are other forms as well.

Terraforming

The ultimate vision of many space colonization advocates is terraforming. The logo of the Mars Society, for example, features an image of Mars being transformed into an Earthlike planet with an astronaut standing in the foreground. When discussing their Mars plans, SpaceX frequently uses a series of images of Mars slowly transforming into another Earth. Indeed, terraforming is a nearly ubiquitous trope in science fiction.

The literature on the subject is extensive and we will not seek to recreate it all here, only to recap some of the major aspects. Making a planet Earthlike requires overcoming a number of obstacles. First, things which on Venus are far easier to deal with than Mars:

- **Gravity**

Earth's surface gravity is 9.81 m/s^2. Mars's is 3.71 m/s^2. Venus's is 8.87m/s^2. There is little reason to suspect that Venus's gravity would pose a problem for long-term human health, but it's uncertain as to whether Mars's would. Unfortunately, terraforming Mars's gravity is essentially an impossible task, as gravity is a consequence of mass, and apart from slamming Venus or Earth into Mars, or somehow extracting potential solid matter from the cores of gas/ice giants or the sun's plasma, there just is not that much solid matter in the solar system.

- **Insufficient nitrogen**

While some of Mars' nitrogen has been sequestered to soil as nitrates, most - as evidenced by its isotopic ratios - has been largely lost to space over its history. Initial levels of nitrogen on Mars were dozens to hundreds of times higher than they are today.[674] Nitrogen is a key element for all life. The quantity of nitrogen or ammonia ices that would have to be imported from the Kuiper belt to give Mars an Earthlike atmosphere is far beyond our means for the foreseeable future.

- **Biopreservation**

One of the primary arguments against terraforming Mars is fear that it could wipe out current or past life, or at least evidence of it. As concerns of life on Venus are much lower and the entire planet appears to have already been resurfaced, this is a much lesser concern (although some lines of evidence have been suggested as potential evidence of life).[675]

There are also problems which Venus must address that Mars does not:

- **Rotation**

Mars' day is 24h 37m, nearly the same as Earth's. Venus's surface however experiences a day length of 243 Earth days. Making Venus "Earthlike" requires remedying this situation.

- **Insufficient water**

Venus's average water inventory of 20ppm means that if Venus's carbon dioxide and most of its nitrogen were removed, it would be left with an atmosphere containing 0.18%

[674] Jakosky, B. M., Pepin, R. O., Johnson, R. E., & Fox, J. L. (1994). Mars atmospheric loss and isotopic fractionation by solar-wind-induced sputtering and photochemical escape. *Icarus*, *111*(2), 271-288.
[675] Landis, G. A. (2003). Astrobiology: the case for Venus. *Journal of the British Interplanetary Society*, vol. 56, p. 250-254

water vapour (dry air) over a largely water-degassed crust. In short, it would be a desert planet.

Lastly, there exist problems shared by both:

- **Magnetosphere**

Creating a planetary magnetosphere, whether internal or artificial, would be needed for Earthlike levels of radiation at the surface.

- **Atmospheric density**

Venus has too much of an atmosphere, with far too much CO_2 and somewhat of an excess of N_2; the pressure must be lowered to make it Earthlike. Mars, conversely, has too little of an atmosphere.

- **Radiative balance**

Mars and Venus need to ensure, after their atmospheres are adjusted, that the appropriate level of albedo/greenhouse effect is present to ensure Earthlike temperatures at the surface.

In short, we have five problems to solve for Venus.

Proposals

Carl Sagan made the first major proposal for depleting carbon dioxide from Venus's atmosphere in 1961, proposing the injection of photosynthetic bacteria into the atmosphere to sequester carbon.[676] Although the composition of the atmosphere wasn't well known at the time, today we know that while the upper atmosphere is quite hostile, there exists in it varying quantities of C, H, O, N, S, and probably significant amounts of P as well - the key elements of all life on Earth.

Unfortunately for his plan, the Venera programme revealed that Venus's atmosphere was far more massive than expected. Sagan later conceded that his proposal was unviable:

> "...the result would be a surface buried in hundreds of meters of fine graphite, and an atmosphere made of 64 bars of almost pure molecular oxygen. Whether we would first implode under the atmospheric pressure or spontaneously burst into flames in all that oxygen is open to question. However, long before so much oxygen could build up, the graphite would spontaneously burn back to CO_2, short-circuiting the process."[677]

[676] Sagan, C. (1961). The Planet Venus: Recent observations shed light on the atmosphere, surface, and possible biology of the nearest planet. *Science,133*(3456), 849-858. doi:10.1126/science.133.3456.849
[677] Sagan, C., & Druyan, A. (2011). *Pale Blue Dot.* S.I.: Ballantine Books.

Frequently suggested approaches to removing the atmosphere have involved bombardment. Unfortunately Pollack and Sagan calculated in 1994 that striking Venus with an object 700km in diameter (roughly 40% greater than Enceladus) at greater than 20 km/s would only remove less than a thousandth of the atmosphere - largely into Venus's orbit, where it could eventually be recaptured.[678] The violent impacts might instead indirectly increase Venus's atmosphere by inducing volcanic outgassing.

More realistic, but still far beyond our capability, involves bombarding Venus with material to sequester its atmosphere. Gillet proposed bombarding Venus with approximately 8e20kg calcium or 5e20kg magnesium.[679] By contrast, the mass of the entire asteroid belt is only 3e21kg in total. Perhaps more interesting is Birch's 1991 proposal to bombard Venus with 4e19kg of hydrogen (which is far more abundant) to convert its atmosphere to graphite and water via the Bosch reaction. Such a process would simultaneously generate seas covering 80% of Venus's surface. The possibility of hydrogen import through solar wind capture is yet to be studied, although due to the limited flux it would be a slow process. Other sea-generating proposals involve trajectory adjustments on comets or ejecting small moons from the outer planets onto a Venus-intercept trajectory, via encounters with larger moons of the same system.[680] The concept of extracting water from Venus's mantle (which is likely not completely degassed[681]) has also been discussed, although a realistic means to do so is lacking. Regardless of the means, if seas were formed, a portion of Venus's excess nitrogen would dissolve into them in accordance with Henry's Law.

A variety of concepts presented by Birch also call for freezing the carbon dioxide out of the atmosphere, by various means such as supermassive heat pipes and solar shades. This then requires shielding the frozen carbon dioxide on the surface, with expansive sheets of insulation and massive cooling systems. Obviously, this likewise falls under the category of mega-engineering. While a long-term problem, the situation would not be permanent; plant sequestration of carbon and the oxidation of rocks would require steady influxes of carbon dioxide on a more or less permanent basis, as Venera data indicates FeO quantities of 7.7 to 9.3 percent in the rocks sampled.

An additional proposal from Birch involves pulverizing the surface of Venus to a depth of 1km or more to expose sufficient surface rock to the atmosphere to form carbonates. This however appears likely to require first cooling the planet and the creation of water in order to mediate carbonate formation and allow them to exist in a stable form - thus requiring in part the situation it is designed to accomplish.

As mentioned in the previous chapter, a proposal from Landis is the concept that simply "moving the surface" is in effect terraforming.[682] That is to say, the more colonies one

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[678] Pollack, J. B., Sagan, C. (1994). *Planetary Engineering*. Resources of Near-Earth Space. Tucson: The University of Arizona Press.
[679] Gillet, S. L. (1996). *Inward Ho*. Islands in the sky bold new ideas for colonizing space (Zubrin, R. M., & Schmidt). John Wiley & Sons.
[680] Birch, P. (1991). Terraforming Venus Quickly. *Journal of the British Interplanetary Society*, Vol. 44, pp. 157-167.
[681] Elkins-Tanton, L. T., Smrekar, S. E., Hess, P. C., & Parmentier, E. M. (2007). Volcanism and volatile recycling on a one-plate planet: Applications to Venus. *Journal of Geophysical Research, 112*(E4). doi:10.1029/2006je002793
[682] Landis, G. (2011). Terraforming Venus: A Challenging Project for Future Colonization. *AIAA SPACE 2011 Conference & Exposition*. doi:10.2514/6.2011-7215

builds in the habitable zone, the more increasingly massive and increasingly interconnected the lofted structures are, the more it becomes as if the surface of the planet actually is at cloud height. As these habitats increasingly shade the atmosphere below, it slowly cools and shrinks. This, like all other proposals, can easily be classified under "mega-engineering". However, unlike previous proposals, this could be seen as a natural progression from simple straightforward floating colonies as populations grow and human civilization expands.

A final proposal is, straightforwardly, the outright ejection of Venus's atmosphere to spin up the planet. Concepts range across the board from mass drivers to space fountains and beyond. As Landis points out, the amount of energy required - 2.5e28 joules - is equal to a terawatt of power applied continuously for 850 million years.

Other proposals to accelerate the planet's rotation have ranged from impactors (facing the same size / availability / damage-from-impact problems as for impact-based atmosphere removal) to a stream of pellets moving between the sun and Venus at 1/10th the speed of light and magnetically deflected by a belt girdling Venus's equator.[683]

Discussion

Let us back up for a moment and make a few general observations.

- Terraforming is not a near-term activity by any stretch. The terraforming of Venus most certainly not.

- The “new surface” proposal raises the prospect of simultaneous freezing out of the lower atmosphere. However, this will not occur passively. At Venus’s ~9 MPa surface pressure, CO_2 freezes at 230°K, significantly below comfortable habitat temperatures; hence the crust would be undergoing convective and radiative exchange with an insufficiently cold layer of habitat undersides. However, active cooling of the underside of the habitats could render this a possibility.

- Ignoring all issues of practicality, mass ejection technically could spin up the planet at the same time as depleting the atmosphere. With earth-rate rotation requiring imparting 2.5e28J and the atmosphere massing 4.8e20kg, each kilogram ejected must impart a minimum of 52MJ to Venus, corresponding to a velocity of 10.2km/s. This is roughly the same as Venus's escape velocity of 10.36 km/s. Mass with sufficient escape velocity could be ejected on an intercept with other outer solar system bodies, potentially helping provide them with a warming atmosphere.

- Arriving hydrogen for water generation could impart angular momentum to Venus as well.

- All of the masses involved mass ejection or hydrogen import are vastly beyond anything we have ever done in the history of our species.

[683] Birch, P. (1993) How to spin a planet. *British Interplanetary Society*, Journal (ISSN 0007-094X), vol. 46, no. 8, p. 311-313.

- Using atmospheric ejection to eliminate the atmosphere and spin up the planet would expose a new problem: as soon as you succeeded and then tried to create an oxygen-rich atmosphere, surface rocks would oxidize and deplete it. By contrast, the proposals which sequester Venus's carbon locally (analogous to coal and shale deposits on Earth), would not suffer from this problem, as the oxygen freed in CO_2 decomposition would have oxidized the iron.

- Concerning rotation, 1 petawatt at 100% efficiency, would require 792k years to accelerate Venus's angular momentum to match that of Earth. With a radius of 6050 km and a solar constant of 2586 W/m², all of the light falling on Venus combined is 297.4 PW - which if entirely harnessed at 100% efficiency would still take 2664 years to fully change Venus's day length. The light currently arriving from the sun cannot on its own impart the sort of energy necessary to do the task quickly. Additional energy sources would be needed. Such levels of energy production would almost certainly render the planet uninhabitable while in use; utilizing 100 times as much power as the sun currently provides, at 99% efficiency, would still double the net heating on the planet.

- These together suggest that the most common alternative approach to Venus's rotation problem may be more realistic. Birch proposed a solar-sail like "soletta", large enough to entire blot out the sun from Venus, orbiting on a 24-hour polar orbit. As it passes on Venus's day side, it creates an artificial night; as it passes on the night side, it creates an artificial day. He suggests a solar sail material weighing an extremely light 30 micrograms per square meter, with a net system mass of 4GT.

  Such a system falls into a potentially practical mass range for launch from a future industrialized society, although in no uncertain terms presents a huge technological challenge on numerous fronts that we are ill equipped to tackle today. By the time there would be an interest / need for it, however, it could be a potentially viable solution. It also meets the standard of incremental benefit: a partially completed sunshade is better than no sunshade at all. Each incremental piece launched makes the planet a little more Earthlike, thus helping justify the continuation of the development programme over long periods of time.

The atmosphere's bulk mass, however, still remains a problem - barring extreme solutions such as freezing it out and storing it.

It has been estimated that, had Sagan's initial microbial plan been "successful", it still would have taken between eleven thousand and 1.1 million years to complete, depending on how optimistic the assumptions are about photosynthesis.[684] But there's the rub: there would never have been some sudden, instantaneous flux of graphite and oxygen, some great fire hazard waiting to go off. Rather, it would have meant low levels of oxygen in the atmosphere, as well as low levels of a carbonaceous precipitate. Iron(II) oxide is quite reactive with oxygen at 400-500°C; surface rocks would thus would consume it as fast as it was being created, until the FeO resource (and other reducing species) were exhausted or

[684] Fogg, M. J. (1995) *Terraforming: Engineering Planetary Environments*, SAE Press, ISBN 1-56091-609-5

completely buried. So long as the transport of weathered rock continues to expose fresh, unweathered rock, the entire planet will continue rusting. Venus would be laying down its own dry-deposited banded iron formations.

In short, what we would be looking at would be a Venusian equivalent of Earth's Great Oxygenation Event, when cyanobacteria began to photosynthesize and release oxygen, first oxidizing all of *Earth's* ferric iron, then subsequently transforming Earth's atmosphere to one full of oxygen.[685] On Earth, it heralded the death of most life. On Venus, it would be life's birth.

The dynamics are not simple and, without further study, are only speculation. However, if one has patience - and can produce Sagan's hypothetical microbe - or artificially achieve the same effect - then perhaps it was not so absurd of an idea after all.

No planet in our solar system will likely ever be another Earth. Mars will always be small and low gravity. Radiation shielding requires mega-engineering. The planet may simply have to suffice with having low levels of nitrogen - whatever ended up sequestered in regolith rather than stripped - and plant life hindered as a consequence. But it could still become a home. Sufficient oxygen pressures could be established for breathing without excess fire hazard (0.3-0.4 atm). Heavy amounts of greenhouse gases could raise the temperature, and allow seas - however sparsely inhabited - to form.

Venus, too, might never become another Earth. Accelerating its rotation speed might never be achieved - a soletta may need to suffice. Its radiation shielding may be nothing more than its overinflated, 2.5 bar nitrogen atmosphere. Large amounts of water might never be delivered, and plant life hindered as a consequence. It would be a world whose residents live as if always having a mild alcoholic buzz due to the lower ends of nitrogen narcosis,[686] until life managed to sequester a large portion of the nitrogen in the lithosphere (as is the case on Earth).[687] Perhaps the extra hydrogen, and thus water, will never come. But even in such a scenario, it could still become a home - Earth's desert twin.

This is, perhaps, too pessimistic. The first mammals evolved 225 million years ago. Homo sapiens evolved 200 thousand years ago. 6800 years ago the first known permanent structures were built. One hundred years ago horse-drawn buggies outnumbered cars in industrialized nations. The rate of our technological advancement, while highly uneven between technological fields and timeperiods, has been astounding. Perhaps in the future our species will be controlling such energies and moving such tremendous masses as to be able to convert our wayward sibling planets into new Earths - a paradigm to be repeated as our species reaches out into the stars.

If we do not destroy ourselves first, who knows what the future might hold.

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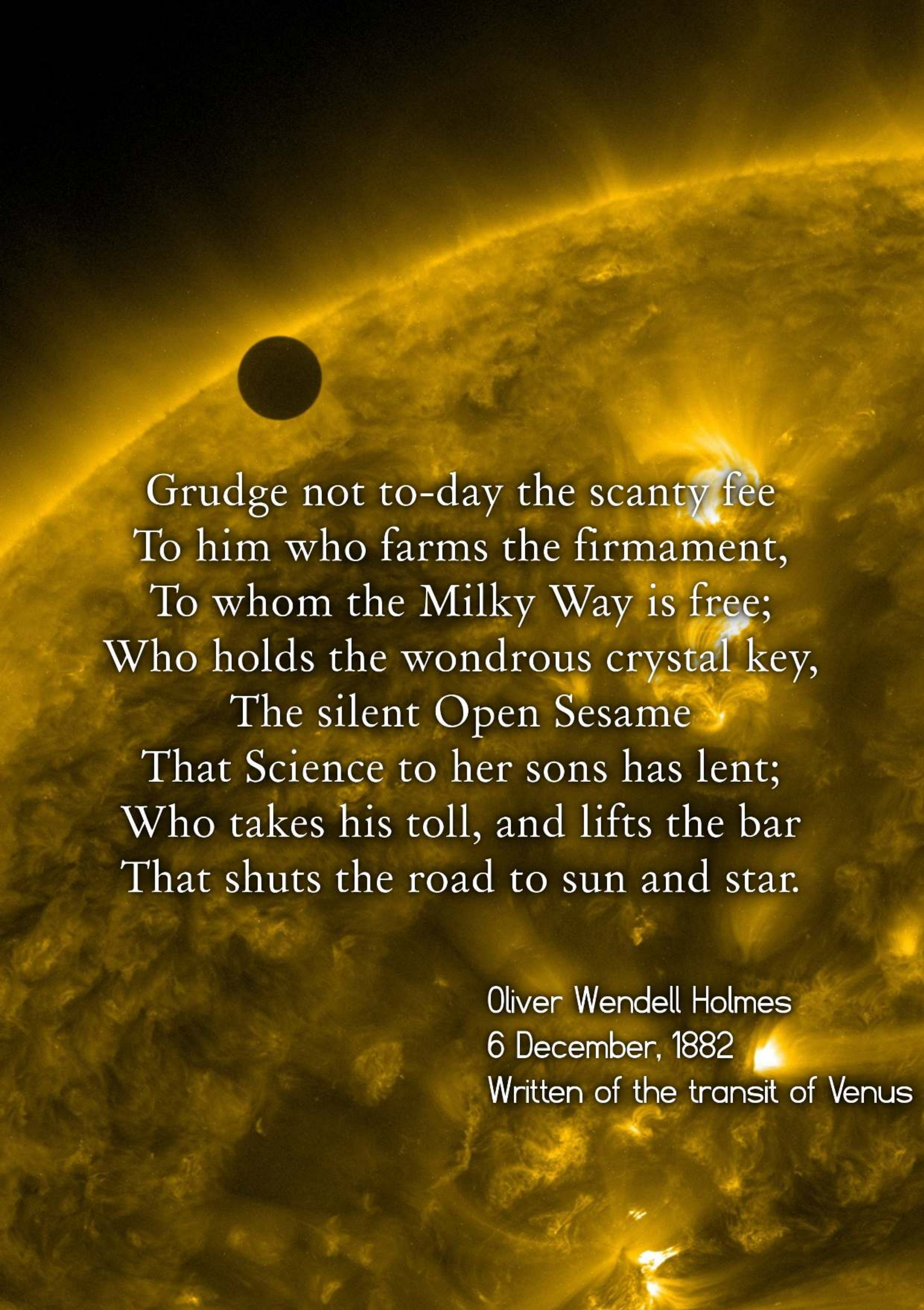
[685] Pinti, D. (2011). Great Oxygenation Event. *Encyclopedia of Astrobiology,* 693-693. doi:10.1007/978-3-642-11274-4_1752
[686] *Diving Physics and You*. Maritine and Coastguard Agency.
[687] Jacob, D. J. (2011). *Introduction to Atmospheric Chemistry*. Princeton University Press.


Grudge not to-day the scanty fee
To him who farms the firmament,
To whom the Milky Way is free;
Who holds the wondrous crystal key,
The silent Open Sesame
That Science to her sons has lent;
Who takes his toll, and lifts the bar
That shuts the road to sun and star.
Oliver Wendell Holmes
6 December, 1882
Written of the transit of Venus

Glossary

Aerial vehicle terminology

Airworm	A series of roughly spherical envelopes linked with an outer, low overpressure skin. Provides a way to minimize loadings on a non-rigid envelope of a large airship while still maintaining an aerodynamic shape.
ALICE	A series of Earth-based experiments which demonstrated the viability and behavioral properties of phase-change balloons.
Ballonet	An inner envelope of variable size containing external gas. The inflation and deflation of the ballonets allows an airship to maintain its shape and pressure as the volume of its internal gas changes.
Ballute	A self-filling balloon that functions as a parachute; air inlets allow air in while a toroidal "burble fence" allows it to maintain stability. Used as a drag device at high velocities that are problematic for parachutes, and is being researched for use as an inflatable reentry system.
Bellows balloon	An accordion-like balloon, generally built out of metal, which can be winched down or expanded out and thus experience varying levels of lift. In research as a means for moving around Venus's surface.
Blimp	Non-rigid airship; has no internal rigid framework or keel.
Catenary curtain	A curtain of fabric, shaped like an inverted catenary curve, running across the top of a non-rigid envelope. Transfers loads from internal cables to the envelope fabric, which is in turn supported by the overpressure.
Differential load	The property that, due to buoyancy, there tends to be a difference in the load at the top of the envelope and the bottom, with the top load being greater.
Empennage	The tail/rudder assembly of an aerial vehicle, which allows for stability in wind and maneuverability.
Envelope	The skin of an airship.
Landis habitat	A type of aerial habitat lofted by breathable air, which humans can live inside.
Lifting body	An aircraft, lacking wings, whose shape yields a meaningful L/D ratio.
Munk load	Stress on the envelope caused by the difference between forces encouraging an airship to twist and the empennage resisting rotation.
Nacelle	A housing for an engine; provides an additional margin of safety, better control of airflow, and options for vectored thrust.
Phase-change balloon	A balloon incorporating a material which boils/condenses or is released/absorbed as the external temperature and pressure change. This yields a passive means of regulating lift without requiring a high overpressure. Phase-change balloons tend to create an oscillating effect, based on the rate of heat transfer.
Rigid airship	Airship whose form (and structural strength) are provided for by a rigid lattice

	framework. The extra mass cost of the reinforcement reduces the stress on (and thus mass of) the envelope.
Semi-rigid airship	Airship whose form is maintained by pressure, like a blimp, but utilizes a rigid keel.
Static load	Stress on an airship caused by differences in lift between different parts of the body, particularly between the empennage and the remainder of the envelope.
Superpressure balloon	A balloon designed to handle significant amounts of overpressure. Superpressure balloons tend to hold to within a particular altitude range for a given load without the need for ballonets, phase change envelopes, etc, and have reduced load distribution needs. This comes at the cost of a much heavier envelope.
Vectored thrust	The use of vanes or steerable ducts to change the direction in which air leaves an engine.

Rocketry terminology

Ablative	Ablative materials are by their nature designed to erode in a controlled manner under extreme temperature conditions, such as during atmospheric entry, and by doing so carry away heat that would have otherwise transferred to the spacecraft.
Acetylene	C_2H_2, the simplest alkyne and a good-performing low-hydrogen fuel.
Aerobraking	The reduction of a spacecraft’s velocity by passing through the outer layers of a planet’s atmosphere.
Aerocapture	Entering a planet’s orbit or entry trajectory based on a single aerobraking pass.
Aeroshell	A rigid structural element which protects a primary payload during entry before falling away.
Biprop / bipropellant	A commonly used rocket design where two substances, typically a fuel and an oxidizer, are burned together for thrust.
Carbon monoxide	A fuel option for propellant combinations that do not require hydrogen. Cryogenic, toxic, moderate density, and poor specific impulse.
Cyanogen	A fuel option for propellant combinations that do not require hydrogen. Non-cryogenic, toxic, good density, and good specific impulse, but very high chamber temperatures (particularly with LOX) unless diluted with hydrogen-bearing propellants.
CyHy	A fuel combination involving cyanogen and hydrogen, improving combustion properties versus pure cyanogen.
CyMet	A fuel combination involving cyanogen and methane, improving combustion properties versus pure cyanogen.
Cycler	A spacecraft that travels on a periodic cycle between two or more celestial bodies which requires little delta-V to maintain the trajectory. While a cycler does not “stop” at its destinations (requiring a separate local ascent/descent stage), it allows a large amount of mass (shielding, etc) to accompany passengers en route.
Delta-V	Change in velocity (and thus orbital energy states). Often used as a measurement of how much capacity a rocket has for orbital maneuvers and how much of that capacity would be consumed by a given maneuver.

DSN	Deep Space Network, an global series of communications complexes run by NASA to allow for communications with distant spacecraft.
ETO	Earth Transfer Orbit
HEO	High Earth Orbit or Highly Elliptical Orbit
Hold-down	A common practice where rockets are physically held down after ignition until it can be confirmed that all systems are operating nominally.
HVO	High Venus Orbit
Hypergolic	Having the property of spontaneous ignition. Hypergolic fuels are favored in rocketry wherever simplicity and reliability are important.
Interstage	A structure that connects two separate rocket stages and is designed to allow for their separation.
I_{SP}	Specific impulse. Generally reported in “seconds”, representing the velocity of the exhaust divided by 9.81. I_{SP} represents a measure of how much delta-V can be achieved with a given mass of propellant in otherwise equivalent stages.
LEO	Low Earth Orbit
LH / LH2	Liquid hydrogen. When burned with LOX (*Hydrolox*), it represents the highest I_{SP} (but lowest density) propellant combination in wide usage. Deeply cryogenic.
LOX	Liquid oxygen. A powerful and very widely used oxidizer in rocketry. Cryogenic.
LVO	Low Venus Orbit.
Mass ratio	The ratio between the dry mass of a stage and its mass when fully loaded with propellant. Low mass ratio rockets can achieve more delta-V than high mass ratio rockets, all other factors being equal.
MON	Mixed Oxides of Nitrogen. Primarily nitrogen tetraoxide (N2O4), but containing small amounts of nitric oxide to reduce corrosion and otherwise improve handling properties.
Nitric oxide	NO - a minor additive to MON and chemical precusor to other oxides of nitrogen.
Nitrogen tetroxide	N_2O_4 - a toxic, storable oxidizer; the primary component of MON.
Nitrous oxide	N_2O (“laughing gas”), a self-pressurizing oxidizer with lower toxicity, density and impulse versus MON.
Nytrox	A mixture of nitrous oxide and oxygen, boosting the performance and stability versus pure nitrous oxide.
Terraforming	The process of converting a body in space (typically a planet) to one resembling Earth.
TRL	Technology Readiness Level, a measure of how mature a technology is. TRL ranges from 1 (“Basic principles observed and reported”) to 9 (“Actual system 'flight proven' through successful mission operations”).
Triprop / tripropellant	A relatively uncommon rocket design involving the simultaneous combustion of three chemicals, often involving one reaction that yields a high heat of combustion and another that yields a low molecular weight exhaust.
VTO	Venus Transfer Orbit.

Spacecraft / probes

Akatsuki	“Dawn” - a Venus orbiter launched by JAXA in May 2010, arrived December 2010 but failed to enter orbit due to engine failure, and successfully entered orbit December 2015 via a burn from its attitude control thrusters. The mission seeks to explain Venus’s superrotation, gather details about its weather, lightning, and detect any ongoing volcanism.
AREE	Automaton Rover for Extreme Environments, a NIAC concept for an electronics-free wind-powered walking rover for long-term operations on Venus’s surface.
DAVINCI	Deep Atmospheric Venus Investigation of Noble gases, Chemistry and Imaging, a proposed atmospheric probe to better study trace gases in Venus’s atmosphere. It was not chosen in in the 2017 Discovery selection process.
EVE	European Venus Orbiter - ESA proposal for a superpressure balloon to float at 55km (middle cloud layer) and investigate Venus’s atmosphere and weather.
HAVOC	High Altitude Venus Operational Concept, a multiphase proposal for human settlement on Venus, beginning with a manned orbital mission and preceded by small manned missions with a small crew arriving with a pre-fuelled ascent vehicle, living inside a small insulated gondola.
Kosmos-27	See *Zond 3MV-1 No.3*.
Kosmos-96	See *Venera 3MV-4 No.6*.
Kosmos-167	See *Venera 4V-1 No.311*
Kosmos-482	See Venera 4V-1 No.671
Mariner 1	US flyby mission to Venus launched in July 1962. Failed without returning data.
Mariner 2	US flyby mission to Venus launched in August 1962, with a Venus flyby in December 1962. Discovered that Venus’s nightside is nearly as hot as it’s dayside and lacks an intrinsic magnetic field.
Mariner 5	US flyby mission to Venus launched in June 1967, with a successful flyby in October 1967. Radio occultation data helped provide context to the atmospheric entry data from Venera 4.
Mariner 10	US mission to Mercury with a Venus flyby, launched in November 1973. The flyby in February 1974 revealed the first closeup images of Venus from space, including the varying appearance of the clouds in UV.
Magellan	US orbiter mission to Venus, launched May 1989 and arrived in October 1990. Assembled the most detailed radar maps of Venus to date, and was the last mission to Venus (excluding flybys en route to other destinations) until the arrival of Venus Express in 2006.
Pioneer Venus Orbiter	US orbiter to Venus, launched in May 1978 and arrived in December 1978. Conducted direct and radar observations of the planet, and in 1991 was reactivated to assist the Magellan spacecraft’s mapping of the surface.
Pioneer Venus Multiprobe	US atmospheric mission to Venus launched in August 1978, arrived in December 1978. Three small and one large descent probes created profiles of different parts of Venus’s atmosphere.

Planet-C	See *Akatsuki*.
SAGE	Proposed US lander mission to Venus. Intended to use a Raman-LIBS instrument, similar to ChemCam on the Curiosity rover.
Shin'en	Japanese student mission to Venus, launched May 2010 and intended as the first student-built mission to leave Earth orbit. Contact was lost shortly after launch.
VALOR	Venus Aerostatic Lift Observatories for in-situ Research, a proposed NASA long-duration balloon mission.
VAMP	Venus Atmospheric Maneuverable Platform, a proposed lighter-than-air flying wing probe for Venus, utilizing an inflatable lifting body entry system. Designed by Northrop-Grumman.
VCM	Venus Climate Mission, a proposed NASA balloon / dropsonde mission.
Vega 1	Soviet flyby / balloon / lander mission to Venus, launched December 1984, arrived in June 1985. Vega 1 and 2 remain the only balloon missions to Venus to date, operating for approximately 2 days each in the middle cloud layer before crossing out of transmission range and, ultimately, battery failure.
Vega 2	Soviet flyby / balloon / lander mission to Venus, launched December 1984, arrived in June 1985. A sister mission to Vega 1, it contained the same design and instrumentation.
VEGAS	Venus Geoscience Aerobot, a phase-change balloon mission design study at NASA / JPL.
Venera 1VA No.1	Soviet impactor mission to Venus, launched in February 1961. Failed to enter VTO.
Venera 1	Soviet impactor Mission to Venus, launched February 1961. Flew within 100,000 kilometers of Venus but lost communications, with no data returned.
Venera 2MV-1 No.1	Soviet lander mission to Venus, launched in August 1962. Failed to leave LEO.
Venera 2MV-1 No.2	Soviet lander mission to Venus, launched in September 1962. Failed to leave LEO.
Venera 2MV-2 No.1	Soviet flyby mission to Venus, launched in September 1962. Failed to leave LEO.
Venera 2	Soviet flyby mission to Venus, launched in November 1965. Successfully flew by Venus in February 1966 but the spacecraft failed before data could be returned.
Venera 3	Soviet lander mission to Venus, launched in November 1965. Entered Venus's atmosphere in March 1966, but no data was returned.
Venera 3MV-4 No.6	Soviet flyby mission to Venus, launched in November 1965. Failed to leave LEO.
Venera 4	Soviet lander mission to Venus, launched in June 1967. Successfully entered Venus's atmosphere in October 1967 and returned data, but failed to reach the surface intact. The returned data included the lack of water, basic atmospheric constituents, and chemical / temperature profiles.
Venera 4V-1 No.311	Soviet flyby mission to Venus, launched in November 1965. Failed to leave LEO.

Venera 5	Soviet atmospheric probe to Venus, launched in January 1965, with entry in May 1969. Returned more elaborate atmospheric composition data, and by using a smaller parachute, penetrated deeper into the atmosphere than Venera 4 before its battery ran out.
Venera 6	Soviet atmospheric probe to Venus, launched in January 1965, with entry in May 1969. A sister probe to Venera 5, it carried the same design and instrumentation.
Venera 7	Soviet lander to Venus, launched in August 1970 and touched down in December 1970. Initially thought lost at impact, a later review of the data recovered the signal and retrieved basic data about the surface conditions.
Venera 8	Soviet lander to Venus, launched in March 1972 and landed in July 1972. The first fully successful lander, it survived for 50 minutes on the surface and completed the first analysis of Venus's surface.
Venera 4V-1 no.671	Soviet lander to Venus, launched in March 1972. Failed to leave LEO.
Venera 9	Soviet orbiter / lander to Venus, launched in June 1975, arrived in October 1975. The lander survived for 53 minutes and returned the first images from the surface of another planet. Both lander and orbiter significantly expanded our knowledge of Venus's atmosphere and clouds.
Venera 10	Soviet orbiter / lander to Venus, launched in June 1975, arrived in October 1975. A sister probe to Venera 9, it carried the same design and instrumentation.
Venera 11	Soviet flyby / lander to Venus, launched in September 1978, arrived in December 1979. The lander suffered multiple instrument failures but returned the first evidence of thunder and lightning on Venus.
Venera 12	A sister probe to Venera 11, it carried the same design and instrumentation, and returned similar results.
Venera 13	Soviet flyby / lander to Venus, launched in October 1981, arrived in March 1982. The lander survived for 127 minutes and conducted the first XRF analysis of Venus surface minerals.
Venera 14	Soviet flyby / lander to Venus, launched in November 1981, arrived in March 1982. A sister probe to Venera 13, it carried the same design and instrumentation, and returned similar results.
Venera 15	Soviet orbiter to Venus, launched in June 1983, arrived in October 1983. Conducted radar mapping of the surface.
Venera 16	Soviet orbiter to Venus, launched in June 1983, arrived in October 1983. A sister probe to Venera 15, it carried the same design and instrumentation, and returned similar results.
Venera-D	A proposed Russian probe to Venus involving a radar-mapping orbiter and a lander designed for long-duration surface operations.
Venus Climate Orbiter	See *Akatsuki*.
Venus Express	ESA orbiter mission to Venus, launched in November 2005 and arrived in April 2006. It creates thermal maps, confirms the presence of lightning, finds evidence of past oceans, and analyzes the upper atmosphere.
VEP	Venus Entry Probe, an ESA reference study for balloon / dropsonde missions to

Venus.

VERITAS Venus Emissivity, Radio Science, InSAR, and Spectroscopy, a proposed radar mapping mission to Venus designed to significantly increase our resolution of Venus's surface and detect tectonic / volcanic surface changes. It was not selected in the 2017 discovery mission selection.

VESSR Venus Surface Sample Return, a proposed mission in the NSF Decadal Survey for a lander to collect a surface sample in a canister; a balloon to carry it to higher altitude; a rocket to take it to orbit; and a return stage to take it back to Earth.

VEVA Venus Exploration of Volcanoes and Atmospheres, a proposed NASA Discovery mission involving a balloon with four dropsondes designed to capture aerial imagery of their descent.

VISE Venus In-Situ Explorer, a proposed precursor to VESSR which would bring a sample to high altitudes but not return it, in order to allow for sample analyses which can take significant lengths of time to conduct.

VITaL Venus Intrepid Tessera Lander, a NSF Decadal Survey concept for a lander capable of landing on very rough surfaces, in order to do direct surface studies of a tessera.

VIP-INSPR Venus Interior Probe Using In-situ Power and Propulsion, a NIAC Phase II study for a balloon probe which scrubs sulfuric acid from the atmosphere and uses it to generate hydrogen and oxygen for lift.

VME Venus Mobile Explorer, a NSF Decadal Survey concept designed to explore the surface with a single-use bellows balloon, to help advance the technology for more elaborate missions in the future.

Zephyr A proposed NASA Discovery-class mission involving a wind-propelled surface rover.

Zond 1 Soviet flyby / lander mission to Venus, launched in April 1964. Failed en route to Venus.

Zond 3MV-1 No.2 Soviet flyby mission to Venus, launched in February 1964. Failed to reach orbit.

Zond 3MV-1 No.3 Soviet flyby / lander mission to Venus, launched in March 1964. Failed to leave LEO.

Materials

Aclon A brand name for PCTFE

Acrylic glass A common name for PMMA sheeting.

ATO Antimony Tin Oxide, , a transparent conductor and additive for low-emissivity / infrared rejection properties, similar to ITO.

Barex A PAN/PMMA copolymer, utilized as a barrier film.

BoPET Biaxially-oriented polyethylene terephthalate (PET)

CF Carbon fibre, polymer fibres (most commonly PAN) pyrolyzed under extreme heat, yielding a mostly pure carbon backbone. Boasts extreme heat tolerance, low creep, high strength, and - unusually for a polymer - a moderate degree of electrical conductivity.

COC Cyclic-olefin copolymer, a highly transparent, heat resistant, moisture-insensitive polymer.

Dacron A brand name for PET fibre

Dyneema A brand name for UHMWPE fibre

ECTFE Ethylene chlorotrifluoroethylene, a copolymer of PCTFE and ethylene. While generally similar to PCTFE, it boasts greater workability but lesser (although still excellent) barrier properties.

ETFE Poly(ethene-co-tetrafluoroethene) a half-fluorinated fluoropolymer, sometimes used for transparent inflatable polymer cushion roofs.

EVA Ethylene vinyl acetate, a copolymer of ethylene and vinyl acetate, used as a hot melt adhesive, tackifier, elastomer ("foam rubber"), and as a precursor to EVOH.

EVAL A brand name for EVOH.

EVOH Ethylene vinyl alcohol (occasionally referred to by the misleading acronym EVA), a highly permeation-resistant, water-sensitive polymer most commonly used as a barrier film.

FEP Fluorinated ethylene propylene, a copolymer of HFP and TFE. Similar in most regards to PTFE (and likewise fully fluorinated), it boasts better workability, lower permeability, and higher strength.

Halar A brand name for ECTFE.

HDPE High density polyethylene (PE).

ITO Indium tin oxide, a transparent conductor and additive for low-emissivity / infrared rejection properties, similar to ATO.

Kel-F Former brand name for PCTFE.

Kynar Brand name for PVDF

LDPE Low density polyethylene (PE).

Mylar Brand name for biaxially oriented polyethylene terephthalate (PET). Mylar balloons are, however, no longer made from Mylar / PET.

Neoflon Brand name for PCTFE.

PAN Polyacrylonitrile, a moderately high temperature/strength polymer used in textiles and filters. In the context of a Venus habitat, it's most notable as the precursor to high quality carbon fibre.

PBO Polybenzoxaxole, a very strong, extremely heat tolerant liquid crystal polymer. More favored than PIBO for use in fibres.

PC Polycarbonate, a hard transparent polymer often used in rigid greenhouse glazing.

PCTFE Polychlorotrifluoroethylene, a fully halogenated (but not fully fluorinated) fluoropolymer. Boasts good mechanical properties and among the highest barrier to water permeation of any known plastic, but has relatively poor workability.

PE Polyethylene, the world's most commonly used plastic. Boasts a simple path to production, excellent workability, good abrasion and chemical resistance, and in long chains offers high strength; however it suffers from a low melt temperature, high creep, and UV sensitivity.

PET	Polyethylene terephthalate, a common polyester with moderate to good permeation resistance, high stability and good workability.
PEX	Cross-linked UHMWPE, commonly used in plumbing
PFA	Perfluoroalkanes, a family of fully fluorinated copolymers between TFE and perfluoroethers. Properties are in general similar to TFE, but with better workability, permeation and creep resistance, similar to FEP.
PIBO	Polyimidobenzoxazole, a extremely heat-tolerant polymer with properties broadly similar to PBO, but with little to no crystallinity. Solvent castable; more favored than PBO for use in films.
Plexiglass	A brand name for PMMA.
PMMA	Poly(methyl methacrylate), a highly transparent polymer used in transparent sheeting and fibre optics.
PP	Polypropylene, the world's second most commonly consumed polymer. Properties are broadly similar to those of polyethylene (PE), but with somewhat superior thermal properties and somewhat inferior chemical resistance properties.
PU	Polyurethane, a polymer comprised of a di- or polyisocyanate groups linked with a polyol. Commonly used in foams, elastomers, adhesives and sealants.
PTFE	Polytetrafluoroethylene, the simplest of the fluoropolymers and a fully fluorinated equivalent to polyethylene. Very heat tolerant and extremely chemical and UV resistant, but with high permeability, high creep, limited strength and poor workability.
PVA	Polyvinyl acetate, a water soluble polymer (sold dissolved as Elmer's glue, and the basis for many other adhesives). Precursor to PVOH.
PVC	The most commonly sold halogenated polymer, used in applications that can take advantage of its high workability, rigidity (or, with plasticizers, flexibility), and high level of chemical resistance.
PVDC	A polymer similar to PVC commonly used as a barrier film. Has poorer workability in comparison to PVC but excellent permeation resistance.
PVDF	A half-fluorinated fluoropolymer. Combustion of Kynar insulation on the Pioneer multiprobes is the leading theory as to their electrical anomaly during descent.
PVF	The fluorinated equivalent of PVC; mixes the properties of fluoropolymers (high chemical / weathering resistance, heat tolerance) with, to a lesser degree, those of their non-fluorinated equivalents (high tensile strength, low density).
PVOH	Polyvinyl alcohol (occasionally referred to by the misleading acronym PVA), an extremely permeation-resistant, water-soluble polymer used in lubricants, adhesives, dissolvable packaging/substrates, and barrier films where moisture is not present.
Saran	A brand name for PVDC. "Saran Wrap" is, however, no longer made from Saran / PVDC.
Spectra	A brand name for UHMWPE fibre
Tedlar	A brand name for PVF
Teflon	A common brand name for PTFE, and occasionally FEP.

UHMWPE	Ultra-high molecular weight polyethylene (PE). Has properties broadly similar to other forms of polyethylene, but yields fibres with a superb strength to weight ratio and high abrasion resistance.
Water gel	A general name for water-soluble polymers (such as PVA and PVOH) in their dissolved state.
Vectran	A liquid crystal copolymer of 4-hydroxybenzoic acid and 6-hydroxynaphthalene-2-carboxylic acid popular for use in aerospace
Zylon	A brand name for PBO

Chemistry / physics

Biaxial orientation	Biaxially-oriented polymers are stretched linearly and laterally as they are extruded, causing the polymer molecules to be stretched out rather than coiled up. While unoriented polymers often have tensile strengths in the dozens of megapascals, biaxially oriented polymers often range into the hundreds of megapascals.
Cascade	In isotopic enrichment, a series of individual enrichment stages connected to each other such that the output from one stage feeds in as the input to the next, with each successive stage at a higher enrichment level compared to the previous one.
Creep	The process by which a material, subjected to continuous stress over long periods of time, elongates. This has the generally undesirable property of transferring loads borne by the element into other connected elements.
Cross-linking	The interconnection of individual polymer chains, generally by means of chemical treatment or exposure to ionizing radiation. Done in controlled conditions, it can yield improvements in creep and abrasion resistance without sacrificing tensile strength; however, random scission and crosslinking by long-term UV exposure is associated with brittle failure modes of polymers.
Cryogen	A chemical stored at low temperatures. Use of cryogens is common in the rocket industry due to the much higher density of liquids over gases, and the fact that many high performing fuels are only liquids at low temperatures; however, dealing with cryogens presents significant mass, energy and materials challenges.
Cryopumping	A process in which a gas, contacting a surface at below its boiling point, condenses onto the surface, leaving a partial vacuum in its place that draws in more gas. In the case of gases that condense to liquids, when the droplet reaches a large enough size, it tends to run off, allowing the cycle - which draws off significant amounts of heat - to continue indefinitely.
Crystallinity	In polymers, the percentage of the bulk which is comprised of crystals (lamellae / spherulites) rather than amorphous structure. Highly crystalline polymers tend to be strong, rigid, low permeability, and opaque, while amorphous polymers tend to be weaker, flexible, high permeability and transparent.
ESP / Electrostatic precipitator	Device which uses a high charge gradient and coronal discharge to draw particles out of a gas stream. Related to EHD thrust devices.
Eutectic	A mixture between two substances which allows for a favorable lattice structure. Eutectics allow for thorough dissolution and mixing of the two substances. As the

mixing ratio approaches the eutectic point, the density tends to increase while the boiling / melting point tends to drop.

Fluidized bed A hollow channel filled with a loose packing material, designed such that the fluid passing through lofts and churns it. The high surface area is utilized for industrial applications such as catalysts and scrubbing.

Ionic liquid A chemical which is a liquid at approximately room temperature which has no meaningful vapour pressure.

ISRU In Situ Resource Utilization - the process of using locally-available resources to meet the needs of a mission.

LCP Liquid crystal polymer - a high crystallinity polymer, generally characterized by high tensile strength, low creep, low permeability and low transparency.

Mist collector A device which, using vanes, fabrics, or other means, captures particles out of a gas stream into a fluid stream.

Packed bed A hollow channel filled with a static porous packing material. The high surface area is utilized for industrial applications such as catalysts and scrubbing.

Supercritical A substance where, above its critical point, it tends to adopt properties similar to both a liquid (such as solvent properties) and a gas (such as effusion through fine pores in solids).

Tensile strength The ability of a material to withstand tensile (stretching) loads. Ultimate tensile strength represents the stress at which the material breaks, while yield strength represents the stress at which the material will permanently deform.

Uniaxial orientation Similar to biaxial orientation, except that the polymer is stretched only on one axis, causing all molecules to adopt the same orientation. This is commonly used for fibre production, allowing for tensile strengths of several gigapascals or more.

Geology

Anorthosite An intrusive igneous rock composed overwhelmingly of plagioclase feldspar.

Arachnoid A category of large weblike volcanic structures only found on Venus. Similar to a small corona, with a series of compressive ring shapes, they are set apart by a dense network of steep rifts radiating away from their centres.

Basalt A broad category of low-silica extrusive igneous rocks.

Carbonatite A highly fluid, very low temperature lava. Found in only one active volcano on Earth (Ol Doinyo Lengai), it appears like flowing oil during the day, with a maroon radiative glow at night, and oxidizes to bright white. Often associated with valuable mineral deposits.

Corona Very large (up to 2100km diameter) circular formations with a flat centre and surrounded by rings of dense rifts. Believed to represent the collapse of an area uplifted by a mantle plume, but the exact details are still uncertain.

Differentiation The process in which magmas undergo chemical changes (depleting or enriching various fractions) via cooling, reheating, settling, and other processes.

Dike Igneous intrusion through rock, which cools to form a wall-like structure in the ground which can later be exposed via erosion.

Eolian	Related to the wind. Eolian processes move particulates around, forming sedimentary features (such as dunes) and erosive features (such as yardangs).
Incompatible element	Elements which tend to be concentrated into the melt phase of magma during differentiation.
Gabbro	A dark, large-crystalled intrusive igneous rock formed from slow-cooled basaltic magma. Forming a major component of Earth's oceanic crust, it is mined as a decorative stone under the misnomer "black granite".
Labradorite	A feldspar mineral commonly found in anorthosite which displays a striking bluish iridescence known as labradorescence.
Lithosphere	The outermost layers of a planet, which tend to deform elastically and through brittle failure rather than through viscous flow.
Mass wasting	The movement of material, rapidly or slowly, from high altitudes to low under the force of gravity.
MORB	Mid-Ocean Ridge Basalt
Natrocarbonatite	See carbonatite.
Pancake dome	Large, steep-sided volcanic edifices, considered likely to be related to rhyolite domes on Earth, and potentially comprised of the silica-rich fraction of differentiated basaltic lavas.
Phased-array radar	A radar system comprised of multiple independent antennas working together to create the effect of a single radar with a far larger aperture.
Radar-reflective terrain	One or more types of terrain found in at high altitudes on Venus which resemble snows or frosts on Earth, comprised of one or more unknown conductive or semiconductive materials.
Regolith	Loose broken rock, sand, dust and debris found on the surface of bodies in space.
Resurfacing	The eradication of all surface features, typically involving large expanses of molten rock. Venus appears to have undergone a global or near-global resurfacing event approximately 500 million years ago.
Scalloped margin domes	Large bowl-shaped depressions representing the remnants of volcanic cones that have undergone a series of mass wasting events.
Synthetic Aperture Radar / SAR	A type of radar used for surface mapping, utilizing the motion of the antenna over the surface between the emission and echo return of radio waves to create the effect of a larger aperture.
Terra, terrae	Continent-sized, tesserae-rich masses of land. Venus has three: Lada, Aphrodite, and Ishtar.
Tessera, tesserae	Large, chaotic, highly deformed areas, possibly representing areas of old crust which survived the last global resurfacing event.
Tholeiitic basalt	Subalkaline, non-oxidized basalt. MORBs are a type of tholeiitic basalt.
Tick	See scalloped margin domes.
Troctolite	An olivine-rich relative of anorthosite.
Yardang	A wind-carved rock structure forming a natural aerodynamic shape, with a blunt face on the upwind side and a tapered face on the downwind side.

Atmosphere and illumination

Albedo	The reflection coefficient of a surface. In astronomy, the albedo plays a strong role in determining a planet's temperature.
Atmospheric convection	Convective regions of an atmosphere, such as Earth's troposphere, involve heat transfer via the motion of fluids. The corresponding dynamic instability creates turbulence and regional variations weather conditions. Venus contains multiple convective layers, including the middle cloud layer.
Dynamic stability	Dynamically stable regions of an atmosphere, such as Earth's stratosphere, are thermally stratified and no work can be done by the motion of gas from one layer to the next. The result is a general lack of turbulence and uniformity in weather properties.
Insolation	The amount of sunlight received by a perpendicular flat surface per unit area.
Lower cloud layer	A dense but variable thickness cloud layer at above earth temperatures and pressures. Generally extends from around 48 km to 51 km.
Lower haze	A sparse mist or virga extending from around 32 km to the lower cloud layer at around 48 km.
Meridional wind	Relatively weak north-south or south-north winds, driven largely by the Hadley cell in the lower latitudes.
Middle cloud layer	A moderate density cloud layer extending from 51 to around 57 km. Portions of this layer fall into the potential habitable zone for humans without the need for additional control of temperature or pressure.
Nephelometer	A device for measuring haze density.
Solar constant	The insolation received by a sun-facing square meter surface at a given distance from the sun.
Superrotation	The rotation of a planet's atmosphere at a rate significantly faster than its surface rotation.
Upper cloud layer	A low density cloud layer extending from 57 km to ~72 km in the low latitudes and to ~64 km in the polar region, where it forms an irregular polar depression. Pressures in the upper cloud layer are too low for human life.
Upper haze	A tenuous haze layer extending from the upper cloud layer for several dozen kilometers.
VeRa	The Venus Radio Science experiment onboard Venus Express, used to assemble temperature and wind profiles of the planet.
VIRTIS	The Visible and Infrared Thermal Imaging Spectrometer, an instrument used for cloud-tracking methods to assemble atmospheric profiles of Venus.
Zonal wind	Powerful winds that circle Venus east to west, generally over the course of several Earth days.

Venus locations

Aphrodite Terra	A highly buckled equatorial terra around the size of Africa, centered around 10°S

	100°E. While much more rugged than Ishtar terra, its mountains only reach up to around half as high.
Baltis Vallis	The longest river channel in the solar system - at least 7000 kilomters long, 1-3 kilometers wide and 20-100 meters deep. The fluid which carved it is unknown, although low-temperature, low viscosity lavas such as carbonatites and kimberlites are likely contenders.
Dali and Diana Chasmas	Deep troughs bordering Aphrodite Terra, extending for 7,400 km and with cliffs up to 7 km tall at its edges, bearing a form of radar-reflective material at the top.
Ishtar Terra	A terra centered around 70°N 28°E. Noteworthy features include Maxwell Montes, the highest mountain on the planet, and Cleopatra, a much debated 105km-wide double ring crater whose lava pool spilled out into the surrounding plains.
Lada Terra	A terra centered around 60°S 20°E. It is interpreted as a recently active volcanic hotspot rise. It is dominated by a large (~800km diameter) corona, shows evidence of surface dikes, and is surrounded by massive rift belts.
Maat Mons	0.5°N 194.6°E. The second highest mountain (and highest volcano) on Venus, at approximately 8km over the planetary mean. Recent volcanic activity is suspected but not confirmed.
Maxwell Montes	65.2°N 3.3°E. The tallest mountain on Venus, located on the edge of Ishtar Terra. It rises 6,4km over the surrounding plains, 10.7km over the planetary mean, and approximately 13km over the lowest altitudes. Its summit displays a type of radar-reflective terrain with a distinct, snowline-style cutoff. The mountain appears to have formed from compressive faulting.
Ovda Regio	Comprising the western portion of Aphrodite Terra from 10°N-15°S and 50-110E, dominated by ribbon canyons 1-3km wide and 500m deep. High areas in Ovda regio become increasingly radar reflective, without a distinct "snowline".
Polar vortices	Irregular and changeable bowl-shaped depressions in Venus’s atmosphere at the poles, superficially resembling hurricanes on Earth.
Skadi Mons	The tallest peak on Maxwell Montes.