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A Venus Cloud-Level Aerostat Colony as a Superior Offworld Settlement Strategy to a Mars Surface Colony: A Monte Carlo and Neural Network Analysis

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Abstract

This study tests the proposition that a crewed aerostat colony floating within the Venus cloud deck at 54 to 60 km altitude represents a superior offworld settlement strategy to a crewed surface colony on Mars. The author constructed first-principles physical and economic models of both colonies and propagated the uncertainty in 367 input parameters through Monte Carlo simulation of 20,000 draws per test. An H2O deep learning surrogate was refitted on bootstrap resamples of each response to produce per-prediction perturbation sensitivities, while a paired permuted-refit null arm supplied per-variable p-values alongside permutational multivariate analysis of variance. Five research questions were evaluated as ten one-sided tests against an alpha test statistic of 0.05. The null hypotheses were rejected for radiation ($p = 0.00015$; median Venus advantage 143.8 mSv per year) as well as for colony net present value in both habitat configurations ($p = 0.024$ and 0.022; median Venus advantage approximately USD 228 million per colonist). The null hypotheses for water and oxygen cost, for four export lines and for a gravity health benefit were not rejected. These findings suggest a possible systemic Venus advantage arising from several moderate benefits acting together rather than any single commodity.

1. Introduction

Mars has dominated planning for permanent human settlement beyond Earth since at least the publication of Zubrin and Wagner's *The Case for Mars* [1]. This preference has rested largely upon the planet's accessible surface, its water ice, its comparatively shallow gravity well and its day length of roughly 24.6 hours. Venus, by comparison, has generally been dismissed as a settlement candidate because its surface, at approximately 460°C and 92 bar beneath clouds of sulfuric acid, ranks among the most hostile environments in the solar system.

Landis [2] nonetheless observed that the Venus atmosphere at approximately 50 km represents the most Earth-like environment in the solar system other than Earth itself, offering near-Earth pressure, temperature and gravity as well as substantial shielding by the overlying atmosphere. He accordingly proposed aerostat habitats that would float at that level as the basis for permanent cities. The High Altitude Venus Operational Concept of the National Aeronautics and Space Administration (NASA) Langley Research Center later extended the idea to a crewed airship mission of approximately 30 days [3].

These proposals have remained qualitative, with the result that the comparison between the two destinations has been argued from favorable anecdotes on each side rather than tested. The present study addresses that gap by building comparable first-principles models of a Venus cloud-level colony and a Mars surface colony, propagating the uncertainty in every input through Monte Carlo simulation and testing each comparison against a stated null hypothesis that can fail.

The modeling is deliberately even-handed, in that both colonies receive the same technologies wherever either could utilize them (fission power, nuclear thermal shuttles, mass-driver departure, rotating-tether capture and robotic mining) as well as the same economic terms (research income, quality-of-life compensation, bulk-supply sales and a conditional public cost share). Thus, a difference in outcome reflects a difference between the planets rather than a difference in assumed engineering.

The statistical approach follows the author's simulation-based framework, in which a deep learning network is fitted inside the simulation as a differentiable surrogate and refitted on bootstrap resamples to yield per-prediction perturbation sensitivities. A paired permuted-refit null arm provides each input with its own p-value, with permutational multivariate analysis of variance (PERMANOVA) reported alongside on the local sensitivity matrix. This research thereby contributes both a falsifiable comparison of the two settlement strategies and a ranked account of which uncertain parameters govern each result, which in turn identifies the measurements that would most reduce the remaining uncertainty.

The study is organized around five research questions (RQ):

- • RQ1: Does a Venus aerostat habitat at cloud level receive a lower annual radiation dose equivalent than a Mars surface habitat?

- • RQ2: Is delivered water and oxygen cheaper per kilogram when extracted from Venus cloud aerosol than when mined from Mars ice and purified?
- • RQ3: Can a Venus colony export products at a profit, whether high-value botanical pharmaceuticals and cannabis products delivered to Earth, microbial protein delivered to off-Earth markets, or helium-3 and heavy water recovered as co-products of acid mining?
- • RQ4: Is the net present value of a Venus colony economy greater than that of a comparable Mars colony economy?
- • RQ5: Does the near-Earth gravity of Venus confer a health-adjusted productivity advantage over Mars that exceeds a 5% materiality margin?

2. Hypotheses

Each research question was cast as a one-sided test in which the alternative hypothesis states the Venus advantage. Each test was evaluated separately against an alpha test statistic of 0.05 without correction across research questions, since each question addresses a distinct decision that a settlement planner would weigh on its own terms. Two research questions were evaluated under more than one configuration, with RQ2 and RQ4 each tested with the acid collector carried by the whole city as well as with a detachable uncrewed collector section, while RQ3 was tested under four export scenarios, giving ten tests in all.

- • H1-0: The modeled annual dose equivalent for a Venus aerostat habitat is not lower than that for a Mars surface habitat.
- • H1-A: The modeled annual dose equivalent for a Venus aerostat habitat is lower than that for a Mars surface habitat.
- • H2-0: The delivered cost per kilogram of water and oxygen extracted from Venus cloud aerosol is not lower than that of water and oxygen mined from Mars ice and purified.
- • H2-A: The delivered cost per kilogram of water and oxygen extracted from Venus cloud aerosol is lower than that of water and oxygen mined from Mars ice and purified.
- • H3-0 (rocket and full launch scenarios): The landed value of Venus-produced high-value botanical pharmaceutical and cannabis products does not exceed their full delivered cost per kilogram to Earth.
- • H3-A (rocket and full launch scenarios): The landed value of Venus-produced high-value botanical pharmaceutical and cannabis products exceeds their full delivered cost per kilogram to Earth.
- • H3-0 (protein scenario): The delivered cost of Venus microbial protein to off-Earth markets is not lower than that of supply from Earth.
- • H3-A (protein scenario): The delivered cost of Venus microbial protein to off-Earth markets is lower than that of supply from Earth.
- • H3-0 (isotope scenario): The net margin from helium-3 and heavy-water co-products of sulfuric acid mining does not exceed zero.
- • H3-A (isotope scenario): The net margin from helium-3 and heavy-water co-products of sulfuric acid mining exceeds zero.
- • H4-0: The net present value of a Venus colony economy is not greater than that of a comparable Mars colony economy.
- • H4-A: The net present value of a Venus colony economy is greater than that of a comparable Mars colony economy.
- • H5-0: The Venus advantage in health-adjusted productive hours per colonist-year does not exceed 5% of scheduled working hours.
- • H5-A: The Venus advantage in health-adjusted productive hours per colonist-year exceeds 5% of scheduled working hours.

The materiality margin in H5 was adopted because the modeled health response to gravity is monotone, in that a colony at 0.889 g can never fare worse than one at 0.379 g, which would render a test against a zero difference uninformative.

All results are generated by simulation from the supplied parameter table and script with a fixed random seed (20261013), so the study uses no proprietary data and can be reproduced in full from the archived release, which regenerates the raw Monte Carlo draws and local sensitivity matrices omitted from the archive for size.

NPV, net present value; M, million.

3 Background

The two settlement environments differ along nearly every axis that matters to a colony. Table 1 summarizes the contrasts that enter the models, with the Venus column describing the 54 to 60 km habitat band adopted in this study and the Mars column describing a surface site, drawing upon the Venus International Reference Atmosphere (VIRA) [4] and the surface radiation measured by the Curiosity rover [5].

Table 1
Environmental contrasts entering the models.

Factor	Venus aerostat, 54 to 60 km	Mars surface
Gravity	About 0.889 g	About 0.379 g
Ambient pressure	About 0.6 to 0.2 atm, so the habitat needs only a small overpressure	About 0.006 atm, so every structure is a pressure vessel
Ambient temperature	About 40°C to − 10°C across the band [4]	About − 60°C mean
Sunlight	About 1.9 times Earth's, steady above the main cloud deck	About 0.43 times Earth's, cut by global dust storms
Radiation shielding	Hundreds of g/cm^2 of overlying atmosphere	About 16 g/cm^2 of thin CO_2 atmosphere; unshielded surface dose about 0.64 mSv/day [5]
Water source	Sulfuric acid cloud aerosol, also yielding O_2, SO_2 and sulfur	Subsurface and scarp ice, or 1.5 to 3 wt% soil water
Nitrogen	About 3.5% of an atmosphere 93 times Earth's mass	Scarce in a 6 mbar atmosphere
Weather hazard	Convective layer to about 55.5 to 59 km, planetary-scale cloud disruptions, stationary mountain waves	Regional and global dust storms
Ascent to orbit	About 8 to 10 km/s	About 4 km/s

The gravity contrast is the least understood of these, because no human data exist between microgravity and 1 g. Mice housed at 1/6 g aboard the International Space Station on the Multiple Artificial-gravity Research System of the Japan Aerospace Exploration Agency (JAXA) kept their soleus muscle mass but still underwent the slow-to-fast fiber shift seen in microgravity [6]. Simulated Mars gravity of 0.38 g likewise produced only mild changes in plant root meristem cells relative to 1 g [7]. The threshold below which partial gravity harms human health therefore remains unknown, which led the author to treat it as an uncertain parameter spanning 0.10 to 0.60 g.

Weather at cloud level also required explicit treatment, because a drifting aerostat moves with the superrotating winds and therefore experiences shear across its height and gusts rather than the mean wind. Venus Express measured low-latitude zonal winds of approximately 60 to 70 m/s near the cloud base at about 47 km, rising to approximately 105 m/s at the cloud tops near 66 km [8], with the strongest vertical shear concentrated in the upper cloud.

The principal hazard at lower levels is convection, as demonstrated by the VEGA balloons, which floated at 53.6 km in 1985 and recorded downdrafts of up to approximately 3 m/s [9]. Peralta et al. [10] likewise described a planetary-scale disruption

front in the lower cloud. In addition, Akatsuki imaged a stationary gravity wave approximately 10,000 km long above Aphrodite Terra [11], which is regional and anchored to fixed terrain and can therefore be avoided by drift routing.

4 Methods

4.1 Overview

Each research question was answered by a first-principles model that maps a vector of uncertain inputs to a response D, defined such that D > 0 favors Venus in every test. Inputs were drawn independently from the ranges in the parameter table archived with the analysis software [12], in which each parameter carries a basis tag marking it as sourced from the literature [S], derived from physics within the model [D] or assumed by the author [A], with items still awaiting a primary source marked [VERIFY]. The same draws served both the Monte Carlo test of each hypothesis and the training of a surrogate network utilized to attribute the result to its inputs.

4.2 Radiation model (RQ1)

Annual dose equivalent was computed for each habitat from galactic cosmic ray and solar particle event components. Solar particle events were simulated as discrete events with a sampled annual count, event dose and scatter. Both colonies were given a water-wall storm shelter, although the Mars facility is water-walled throughout against cosmic rays as well, whereas the Venus colony walls only its crew quarters because the overlying atmosphere provides the bulk shielding. The Venus dose depends on habitat altitude within the 54 to 60 km band.

4.3 Water and oxygen model (RQ2)

Venus water is extracted from sulfuric acid aerosol by fluoropolymer mesh-pad collectors whose mass follows from cloud loading, droplet size, face velocity and pad pressure drop, with acid processing yielding oxygen, sulfur dioxide and sulfur as co-products. Because aerosol loading is highest in the lower cloud at 47.5 to 50.5 km, acid is drawn by periodic descent under two configurations, with either the whole city descending for 5 to 30% of the time or a detachable uncrewed collector section with its own buoyant hull descending for 50 to 90% of the time.

Mars water, by contrast, is mined robotically from ice whose mass fraction depends on latitude, ranging from scarp ice [13] to the 1.5 to 3 wt% soil water measured by Curiosity, with oven mass derived from thermal duty, excavator throughput and abrasion spares. Both planets share condensers and CO_2 electrolysis, while the Venus plant additionally carries acid-corrosion spares.

4.4 Export model (RQ3)

Four export scenarios were tested, the first two of which, the rocket and full scenarios, have the colony export high-value botanicals to Earth, namely paclitaxel from plant cell culture, vinca alkaloids, premium cannabis flower, tetrahydrocannabinol (THC) distillate and isolates of cannabigerol (CBG) and tetrahydrocannabivarin (THCV), with product identity entered as a factor. The rocket scenario utilizes a single-stage nuclear thermal rocket on hydrogen from acid-derived water as well as a mass-driver departure, whereas the full scenario utilizes balloon launch, a winged nuclear ramjet on atmospheric CO_2 and a rotating-tether catch. In both scenarios, cargo aerocaptures into Earth orbit in elongated containers and descends as consolidated downmass at USD 50 to 10,000 per kg.

The protein scenario sells gas-fermentation microbial protein to buyers in low Earth orbit, cislunar space or Mars orbit against Earth launch at USD 100 to 7,000 per kg. The isotope scenario values helium-3 recovered from the air already drawn through the acid collectors, as well as heavy water enriched from acid-derived water whose D/H ratio of 0.0156 to 0.025 is 100 to 150 times that of Vienna Standard Mean Ocean Water. Because the Venus $^{3}He/^{4}He$ ratio has never been measured, it was drawn from the terrestrial value of 1.4×10^{-6} to the Pioneer Venus upper limit of 3×10^{-4} [14].

4.5 Colony economy model (RQ4)

Net present value per colonist was computed for each planet over a horizon of 20 to 40 years at a real discount rate of 3 to 10%, with the response defined as the Venus value minus the Mars value. Capital includes habitat structure derived from pressure physics, greenhouses, hydroponic lighting derived from the daily light integral, power with night storage, the acid or ice plant and shuttles, as well as cloud-level weather surcharges on Venus and solar capacity sized to ride out global dust storms on Mars.

Annual flows include import savings, exports, co-product revenue limited by helium-3 market depth, bulk-supply sales to cislunar buyers (Venus nitrogen, Mars water), research-contract income on the Antarctic-station model, a quality-of-life hardship premium on colonist compensation, protein production and the gravity-linked labor, attrition and crop-yield terms of the gravity model. A public cost share of 0 to 30% of startup capital is paid under the same rule on both planets, although only to a colony that supplies helium-3 or heavy water at a profit.

4.6 Gravity model (RQ5)

Health-adjusted productive hours per colonist-year were computed from a logistic dose-response in gravity whose threshold was drawn from 0.10 to 0.60 g, with countermeasure exercise of up to 2.5 hours per day, attrition with replacement and a crop-yield effect, at 0.889 g for Venus and 0.379 g for Mars, the response being defined as the Venus advantage less 5% of scheduled working hours.

4.7 Shared technology and terms

Both colonies were given access to the same technologies wherever either could use them, including Kilopower-class fission at 40 kWe per unit, reusable nuclear thermal shuttles with locally built carbon-composite airframes, mass-driver departure with sabot recovery, rotating-tether capture and robotic surface mining. Transport costs scale with throughput through a cost-capacity exponent of 0.6 to 0.9 applied to tether and mass-driver capital, with traffic set by colony size (100 to 10,000 colonists) and per-colonist two-way traffic of 500 to 5,000 kg per year. The Venus colony drifts with the superrotation, since station-keeping would require about 1.7 MW of propulsion per colonist.

4.8 Monte Carlo test

Each test drew n = 20,000 independent input vectors, with the hypothesis evaluated by the Monte Carlo p-value

$$p_{MC} = (1 + \#\{D_i \le 0\}) / (n + 1) \quad (1)$$

for which the smallest attainable value is approximately 5×10^{-5}, with the null hypothesis rejected whenever p_{MC} fell below the alpha test statistic of 0.05. The median of D, its 2.5th to 97.5th percentile interval, its 5th percentile and the share of draws with D > 0 were reported alongside each decision.

4.9 Surrogate network and attribution

The first 12,000 draws trained a deep learning regression network in the H2O machine learning platform, with two hidden layers of 64 and 32 rectified linear units, hidden dropout of 0.05 per layer, L2 regularization of 1×10^{-5} and 40 epochs, while the next 1,000 draws served as a holdout set and a further 300 as the evaluation set for local sensitivities. Categorical inputs entered through one-hot encoding with all factor levels retained, whereas heavy-tailed responses were transformed by asinh(D/s), with s the median absolute value of D.

The network was then refitted on B = 100 nonparametric bootstrap resamples of the training rows. For each refit, every continuous input of every evaluation row was perturbed by plus and minus 0.10 standard deviations to produce a central-difference sensitivity. Every factor was likewise swapped through its other levels to produce a counterfactual sensitivity, which yields a distribution of local sensitivities for each input and each prediction.

Input significance was assessed by a paired null arm in which, on each of the first B_{null} = 40 bootstrap samples, the network was refitted once for each input with that input randomly permuted. The variable p-value is the share of those 40 refits whose

holdout error did not exceed that of the intact refit, computed as $(1 + \text{count})/(B_{null} + 1)$, which places the smallest attainable variable p-value at 0.024. PERMANOVA (adonis2, 999 permutations) was then applied to the matrix of local sensitivities, grouped by the sign of D, to test whether favorable and unfavorable draws are driven by different input profiles.

4.10 Software and computation

The analysis was written in R 4.6.1 with the h2o (3.44.0.3) and vegan (2.7-6) packages and executed as a single script (version 26, archived as [12]) on a Windows 11 laptop with a 16 GB H2O heap and all but two processor cores, with the ten tests running sequentially over approximately 126 hours. Each H2O operation was retried in place after transient client connection drops, of which 245 occurred and were absorbed without restarting any test, while completed tests were checkpointed to allow a rerun to skip them.

5 Results

Three of the ten null hypotheses were rejected at an alpha of 0.05, namely those for radiation and for colony net present value in both habitat configurations, while the remaining seven were not rejected. Table 2 reports each test, in every row of which D > 0 favors Venus.

Table 2

Monte Carlo test results, n = 20,000 draws per test. In every row D > 0 favors Venus; network R^2 is the surrogate holdout R^2.

Test	Response D (units)	Median D	95% interval	P(D > 0)	p_{MC}	Decision	Network R^2	Significant inputs	adonis2 F, R^2, p
RQ1	Mars minus Venus dose equivalent (mSv/yr)	143.8	65.6 to 1,019	0.9999	0.00015	Reject H1-0	0.959	7	69.3, 0.189, 0.001
RQ2 city	Mars minus Venus delivered cost (USD/kg)	−32.1	−3,163 to 972	0.361	0.639	Fail to reject	0.939	21	68.2, 0.186, 0.001
RQ2 section	Mars minus Venus delivered cost (USD/kg)	19.6	−860 to 1,413	0.647	0.353	Fail to reject	0.923	20	74.0, 0.199, 0.001
RQ3 rocket	Profit per kg exported (USD/kg)	−3,524	−10.77M to 15,881	0.228	0.772	Fail to reject	0.982	6	25.1, 0.078, 0.001
RQ3 full	Profit per kg exported (USD/kg)	−4,364	−10.77M to 15,450	0.209	0.791	Fail to reject	0.983	5	17.8, 0.056, 0.001
RQ3 protein	Earth-supplied minus Venus-delivered cost (USD/kg)	−1,103	−16,551 to 5,120	0.301	0.699	Fail to reject	0.983	15	55.6, 0.157, 0.001
RQ3 isotope	Net He-3 and D_2O margin (USD/t acid-derived water)	−271,144	−32.3M to 2.59M	0.285	0.715	Fail to reject	0.987	15	121.7, 0.290, 0.001
RQ4 city	Venus minus Mars NPV (USD/colonist)	227.1M	2.57M to 1,279M	0.977	0.024	Reject H4-0	0.904	15	3.98, 0.013, 0.013
RQ4 section	Venus minus Mars NPV (USD/colonist)	229.4M	3.22M to 1,292M	0.978	0.022	Reject H4-0	0.913	16	10.7, 0.035, 0.001
RQ5	Venus minus Mars productive hours net of 5% margin (h/colonist-yr)	259.2	−128.3 to 882.4	0.696	0.304	Fail to reject	0.998	4	97.9, 0.247, 0.001

NPV, net present value; M, million.

Table 3
Parameters by research question of first definition.

Group	Parameters
RQ1, radiation	16
RQ2, water and oxygen	71
RQ3, exports	107
RQ4, colony economy	166
RQ5, gravity	7
Total	367

5.1 Radiation (RQ1)

The Venus habitat received a lower dose equivalent in all but about 1 in 10,000 draws, with a median advantage of 143.8 mSv per year and a 2.5th percentile of 65.6 mSv per year, so H1-0 was rejected (p = 0.00015). The significant inputs were dominated by the Mars solar particle event terms, chiefly event dose, event scatter and event count, followed by the transmission of the Mars habitat shielding. The Venus dose itself rises with altitude across the habitat band, from a median of about 6 mSv per year at 54 to 56 km to about 30 mSv per year at 58 to 60 km, which remains far below the Mars median of about 160 mSv per year.

5.2 Water and oxygen (RQ2)

Neither collector configuration rejected H2-0, the two having instead come close to an even split, with Venus cheaper in 36% of draws when the whole city descends and in 65% when a detachable section performs the collecting. The base cost of transport, the spread of cloud aerosol loading, the collection duty cycle and Mars excavator throughput carried the largest sensitivities. This indicates that the comparison turns upon how much aerosol the collector can reach and how quickly Mars ice can be excavated, rather than upon any intrinsic cost advantage of either source.

5.3 Exports (RQ3)

None of the four export scenarios rejected H3-0, with the botanical export scenarios profitable in only 21 to 23% of draws and exhibiting extreme left tails, their 2.5th percentile lying near minus USD 10.8 million per kg. The product factor dominated both botanical scenarios, which suggests that the export case depends chiefly upon which product is shipped rather than upon the launch architecture.

Microbial protein undercut Earth supply in 30% of draws, with the base cost of transport and the Earth launch price as the leading inputs. The isotope co-product margin was positive in 29% of draws, its leading inputs being the energy needed to separate helium from collector air and the unmeasured Venus $^{3}He/^{4}He$ ratio.

5.4 Colony economy (RQ4)

H4-0 was rejected in both configurations, with Venus ahead in about 98% of draws, a median advantage of USD 227 to 229 million per colonist and a 2.5th percentile that remained positive at USD 2.6 to 3.2 million per colonist. The two configurations agreed within about 1% at the median and shared the same four leading inputs in the same order, namely the base cost of transport, the cost of Mars water, the loss of Mars solar output in dust storms and the gravity health threshold carried over from RQ5. The surrogate networks for RQ4 had the lowest holdout R^2 of the study (0.904 and 0.913), consistent with their much larger input sets.

5.5 Gravity (RQ5)

H5-0 was not rejected (p = 0.304), although the median Venus advantage was 259 productive hours per colonist-year beyond the 5% margin and about 70% of draws were positive. The result was governed almost entirely by the gravity health threshold, whose sensitivity of about 242 hours per standard deviation exceeded that of every other input by roughly an order of magnitude, followed distantly by the width of the threshold transition, maximum attrition and maximum countermeasure hours.

5.6 PERMANOVA

The local sensitivity profiles of favorable and unfavorable draws differed in every test, with adonis2 p = 0.001 in nine tests and p = 0.013 in RQ4 city. The weaker result in RQ4 city has a plain explanation, in that only about 2.4% of RQ4 draws fall in the unfavorable group, so the test compares a small minority against the bulk of the distribution, an effect that did not recur in RQ4 section.

6 Discussion

6.1 A systemic advantage

The central finding of this research is that Venus prevails at the level of the whole colony economy even though it fails to win any single cost or export line on its own. A possible explanation is that the Venus advantage is systemic, arising from several moderate benefits that accumulate within the net present value.

These benefits include lower radiation exposure, the gravity-linked gains in labor and crop yield, lighter habitat structure under near-ambient pressure, stronger and steadier sunlight, abundant nitrogen, a lower hardship premium and co-product revenue that is realized only when profitable. No one of these is decisive, yet together they place Venus ahead in approximately 98% of the simulated futures. This pattern carries a practical consequence for how the case for Venus should be made, in that a single prospective commodity, whether helium-3 or a pharmaceutical crop, cannot carry the argument, whereas the aggregate economics potentially can.

6.2 What Mars does better

Mars holds one structural advantage that the models do not erase, which is its shallow gravity well, since ascent to orbit costs about 4 km/s from Mars against about 8 to 10 km/s from Venus cloud level. Mars therefore ships bulk goods more cheaply per kilogram, which obliges Venus to win on what it ships rather than on what shipping costs. The RQ2 and RQ3 results bear this out, because the comparisons that depend most on moving mass off the planet are the ones in which neither world holds a clear edge.

6.3 Transport cost as the common driver

The base cost of transport from Earth ranked first or second among significant inputs in six of the ten tests, so the relative merit of the two destinations depends on how cheaply mass can be moved from Earth. In RQ4 a higher transport cost favored Venus, which is consistent with the Mars colony importing more mass per colonist for its heavier pressure structures, its shielding and its storm-sized solar capacity. Reductions in launch cost would narrow the Venus advantage, so the result is conditional on the transport regime and should be revisited as launch prices evolve.

6.4 Gravity as an open physiological question

The failure to reject H5-0 should not be read as evidence against a gravity benefit, because the modeled outcome depends almost entirely upon where the human partial-gravity threshold lies. Venus clears the 5% margin in nearly every draw if the threshold lies above approximately 0.3 g and in almost none if it lies below approximately 0.2 g, yet no human data exist with which to locate it. The defensible conclusion is therefore that near-Earth gravity removes a long-term health risk that a Mars colony cannot yet quantify, which makes the gravity contrast a question of risk rather than of expected value until partial-gravity physiology is measured.

6.5 Implications for policy and settlement

The isotope results identify a specific and inexpensive measurement with high decision value, since the Venus $^{3}He/^{4}He$ ratio, which spans more than two orders of magnitude in the absence of data, ranked among the leading inputs to the isotope margin, yet a single mass spectrometer aboard a descent probe could fix it. Should the ratio prove high, the startup phase could potentially draw upon a public cost share or an anchor-customer role justified by diversifying helium-3 supply, which the United States obtains today mainly from tritium decay.

The dependable base of the economy would nonetheless remain the supply of nitrogen, carbon, protein and water to other settlements, which parallels the history of Oregon, a territory that grew more as supplier to the California gold rush than from gold of its own. Even so, the capital cost per colonist on either world remains far above the level at which settlers could repay their own passage. Neither colony would therefore attract migration on economic grounds alone without large further cost reductions, although Venus begins closer to that threshold.

7 Limitations and Future Work

The conclusions of this research are bounded by the ranges assigned to the inputs, many of which are engineering assumptions for systems that have not yet been built, while some remain tagged as awaiting a primary source. The inputs were likewise drawn independently, which means that correlations that might exist in practice, for example between launch cost and technology maturity, were not represented. Several specific gaps warrant attention:

- • The Venus $^{3}He/^{4}He$ ratio is unmeasured, and its range spans more than two orders of magnitude.
- • No human partial-gravity dose-response data exist, so the RQ5 threshold range rests on rodent and plant studies.
- • The cloud-level weather treatment uses capital surcharges and disruption losses rather than a coupled flight-dynamics model of the aerostat, with mountain-wave turbulence represented only through the gust surcharge.
- • Night energy storage through the roughly 50-hour Venus dark period is the largest weakness of the Venus economy in the models, an estimate that regenerative fuel cell data would sharpen the most.
- • The Mars solar particle event tail is heavy, with a 99th percentile near 1,500 mSv in a bad year before shelter, so the RQ1 result depends partly on the shelter assumptions.
- • The H2O R package used (3.44.0.3) ran on Java 18, which H2O does not formally certify, although all ten networks converged with holdout R^{2} of 0.90 or greater.

Following the full run, the author checked the ten flagged inputs that proved significant in at least one test against primary sources. Four fell within their assigned ranges, namely the delivered transport cost [15], the drift latitude [8], the Mars excavator throughput [16] and the Venus $^{3}He/^{4}He$ ratio [14]. For the remaining six, the correction would in every case either favor Venus or bear upon a test that had already failed to reject its null hypothesis.

Specifically, a Carrington-class solar particle event would exceed the 300 mGy upper bound at the Mars surface [17]. In addition, dry regolith at 40 to 100 g/cm^{2} transmits nearly all of the free-surface dose equivalent rather than the 30 to 80% assumed here, because the production of secondary neutrons peaks within the first meter of shielding [18]. The 15% upper bound on Venus acid-plant spares likewise exceeds the 2 to 10% of fixed capital typical of chemical plants [19], whereas the helium separation energy and the cost of returning cargo to Earth bear only upon export lines that were unprofitable regardless. The reported results for radiation and colony net present value are therefore conservative toward the hypothesis. A corrected rerun would accordingly be expected to widen rather than narrow the Venus advantage.

Future work should prioritize the measurements with the highest decision value identified by the sensitivity analysis, specifically an in situ $^{3}He/^{4}He$ determination, partial-gravity physiology at intermediate levels and the lower-cloud aerosol loading available to a descending collector, while the comparison itself should be repeated as Earth launch costs fall.

8 Conclusions

Under even-handed models of both colonies and a wide propagation of uncertainty, a Venus cloud-level aerostat colony offers a markedly lower radiation dose and a higher colony net present value than a Mars surface colony, with both results significant against an alpha test statistic of 0.05 and robust across habitat configurations. Venus holds no clear advantage in the cost of water and oxygen, while none of the four export lines is reliably profitable on either measure tested. The gravity benefit, although large in most draws, likewise cannot be confirmed until the human partial-gravity threshold is known.

The evidence therefore supports the hypothesis that Venus represents the superior settlement strategy at the level of the whole colony, provided that the case is argued from its aggregate economics and its radiation environment rather than from any single resource. The author believes that a single atmospheric measurement of the Venus $^{3}He/^{4}He$ ratio, together with a program of partial-gravity physiology, would accomplish more toward settling the remaining questions than any further refinement of the models.

Declarations

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The research questions, hypotheses, study design, physical and economic models and statistical framework are the work of the author, building upon methodologies and research software developed in the author's previous studies. Claude (Anthropic), a large language model, was used as an assistant under the author's direction to implement the author's specifications in R code adapted from that software, to draft and edit portions of the manuscript text and to locate and check references. The author reviewed and revised all output and takes full responsibility for the content of this paper.

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Appendix A: Parameters and Data Availability

The version 26 parameter table defines 367 uncertain inputs, each with its distribution, bounds, units and basis tag. Table 3 groups the parameters by the research question in which they are first defined, although later questions reuse earlier ones, so that the RQ4 economy draws on inputs from all five groups.

By basis, 109 parameters are sourced from the literature [S], 43 are derived from physics within the model [D] and 209 are assumptions [A], with 6 untagged. In addition, 41 parameters carry a [VERIFY] flag marking ranges that rest on engineering judgment pending a primary source, of which the ten that proved significant in at least one test were checked against primary sources after the run. The full table, the R script (venus_mars_mc_ann_v26.R) and the summary outputs of every test (hypothesis results, variable tests, adonis2 tables and figures) are archived on Zenodo [12] and maintained in a public GitHub repository under the MIT License.

All results are generated by simulation from the supplied parameter table and script with a fixed random seed (20261013), so the study uses no proprietary data and can be reproduced in full from the archived release, which regenerates the raw Monte Carlo draws and local sensitivity matrices omitted from the archive for size.