THE LOW ALTITUDE VENUS AIRCRAFT.

L. Lemke[1], I. Kroo[2], D.W. Hall[3], E.Z. Noe Dobrea[4], and A. Brecht[5]. [1]NASA Ames Research Center - Retired; [2]Stanford University, Stanford CA; [3]DHC Engineering; [4]Planetary Science Institute.

Introduction: Exploration of Venus has long been impaired by the planet's massive CO_2 atmosphere, corrosive trace gases, and high opacity. No lander has thus far survived more than 2 hours due to the extreme temperature and pressure at the surface. Additionally, the 20 km-thick cloud deck that extends between 50 and 70 km altitude blocks the view of the surface and lower portion of the atmosphere from orbit (thus far, the surface has only been mapped via synthetic aperture radar by the Magellan mission at scales of 120 to 300 m/pixel). As a result, the surface and lower 40 km of the Venusian atmosphere are arguably the least explored regions of the inner solar system and many questions still remain regarding the nature of the surface and atmosphere. The Venus Exploration Analysis Group (VEXAG) publication "Goals, Objectives, and Investigations for Venus Exploration" provides a science traceability matrix describing the investigations necessary to address the gaps in our understanding of Venus (VEXAG, 2019). Prolonged flight beneath the cloud deck is seen as one of the more feasible methods of addressing key questions identified by VEXAG. Prolonged flight in the atmosphere of Venus would enable an investigation to obtain key measurements identified by the Venus Exploration Analysis Group (VEXAG) including: accurate isotopic measurements; characterization of the composition, abundance, variability, and distribution of key reactive phases and aerosols; vertical and latitudinal structure and dynamics of the atmosphere beneath the cloud deck; surface composition, geology, tectonics, thermophysical properties, and volcanism.

An aircraft flying cycles between the surface and the base of the cloud deck (~40 km altitude) could enable breakthrough scientific exploration of Venus via high-resolution imaging of the surface, measurement of atmospheric profiles (temperature, pressure, dynamics, and composition) for a broad range of latitudes and longitudes, and monitoring for modern volcanism and tectonics.

Problem Statement Review: A low altitude cycling aircraft may be capable of taking advantage of the strong temperature gradient of Venus' lower atmosphere to produce sufficient thermally-derived energy to maintain powered flight. *A carefully selected heat sink material can contain more energy in the form of heat when it is moved from the surface of Venus to a high-altitude location than the amount of potential energy required to lift it to that altitude.*

For example, the ΔT between the surface (735 K) and 55 km altitude (298 K) is 437 K. The heat energy stored in some low atomic weight materials moving through ΔT can be larger than potential energy moving through ΔZ. In the case of lithium metal, ΔT energy $\approx$ 3.31 x ΔZ energy. Hence, if ΔT energy can be converted to ΔZ energy via a climbing aircraft with greater than $\approx$ 33% efficiency, aircraft can cycle continuously between high and low altitude. Additional use of internal bellows to provide variable buoyancy to the aircraft could alleviate the energy requirements of the thermal-electric generation.

Aircraft Analysis and Simulation: We performed a trade study to determine sensitivity to mass, altitude gain and loss, propulsive power available, and time to climb. We considered aircraft masses between 100 kg and 400 kg, propulsive power between 5 kW and 40 kW, and altitude variations between 5 km and 40 km. The results shown in Figure 1 are typical for cases where the aircraft cycles between 5 and 40 km and is not power limited. They show that a heat-powered engine would have to provide about 20 kWh to close the cycle. Viscous propeller and electrical system losses were considered.

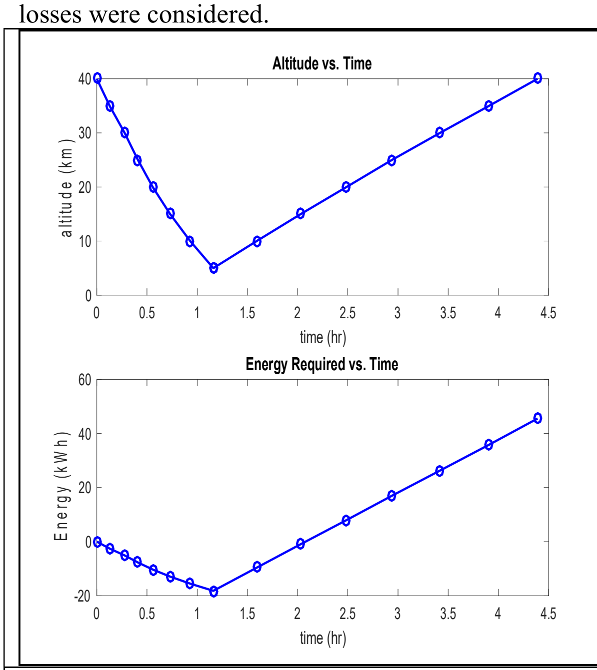

Figure 1. Typical results from modeling. Power limit = 20 kW, M = 400 kg, Net energy required = 20 kWh.

Heat Engines: We considered the use of Stirling engines for power generation. Stirling engines offer numerous advantages: 1) The working fluid is entirely enclosed, 2) they require only an external heat source to function, 3) they have a fixed hot end and a fixed cold end, leading to simple flow paths, 4) they can operate on continuously variable DT, and 5) they can be highly reliable. However, Stirling engines have a low power density and they can attain only 60% of the ideal Carnot cycle efficiency. Hence, a system using Stirling engines for power generation was found to have a mass greater than the allowed mass of the aircraft itself.

A multi-cycle Ericsson Heat Engine [1], on the other hand, uses a multi-stage compressor/expander assembly and approximates ideal isothermal heat flow. Its predicted efficiency ≈ .8 - .9 x Carnot.

Additional buoyancy: Our models indicate that an internal heat-engine alone cannot provide sufficient power to close the cycle. We therefore explored the idea of adding buoyancy, which is a form of an external heat engine in which work is done against the pressure/volume of the atmosphere. JPL developed a mission concept for Venus surface sample return using a two-stage balloon system. A subscale model was built and successfully tested at Venus-like conditions, thereby demonstrating technical feasibility. In light of this, we examined whether variable volume buoyancy cells would improve the performance and refined our performance simulation to include variable buoyancy.

In order to produce a net gain in usable energy, a buoyant cell must have a different schedule of buoyancy vs altitude on ascent, as compared to descent. In our model this can most easily be accomplished by using a Lithium metal heat sink to extract heat from the lifting gas (assumed to be Helium) during the descent. This strategy effectively makes the system heavier on the descent than on the ascent. This excess weight on descent makes the system descend faster. This excess speed powers a windmilling propeller to turn a generator and charge batteries. This stored energy can then be used to assist the ascent. Initial results show that the use of variable buoyancy control can dramatically reduce the amount of energy required from an internal heat-sink engine.

Figure 2 shows how a variably buoyant cell could be incorporated into our blended wing concept. Located at the aerodynamic center line at the aerodynamic center of lift, resulting in a more bulbous central body.

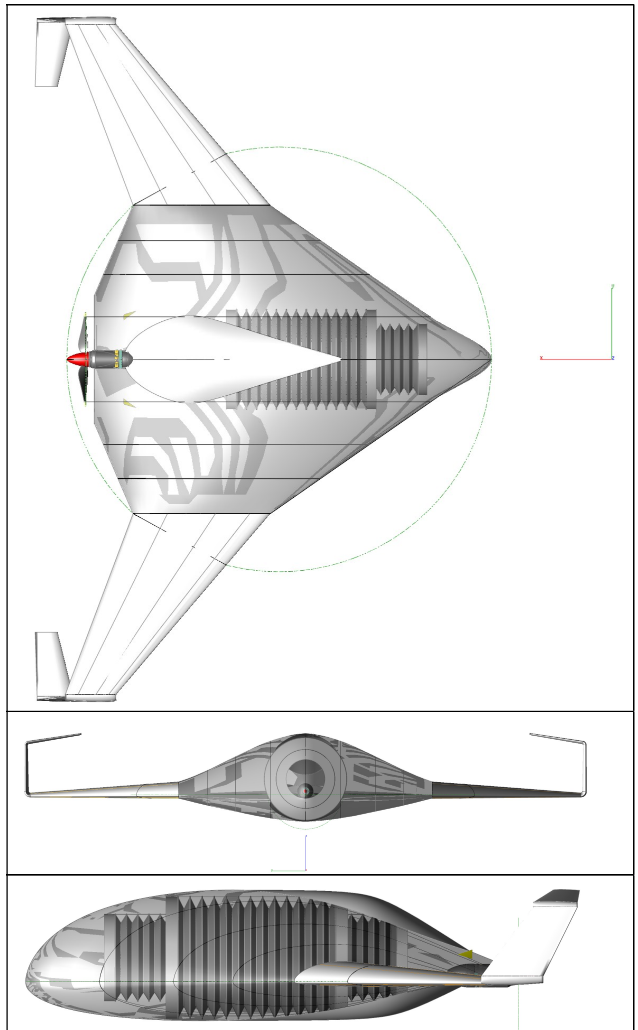

Figure 2. LAVA blended wing body aircraft with horizontal bellows.

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References: [1] Kussul, et. al. (2012) *ISRN Ren. Energ*. 2012, Article ID 613642 doi:10.5402/2012/613642. [2] *AIAA 5th ATIO and16th Lighter-Than-Air Sys Tech. and Balloon Systems Conferences doi:10.2514/6.2005-7322*