Performance Analysis of Solar Fixed-wing Drones on Venus. B. K. Herkenhoff[1], J. M. Fisher[1], and M. Hassanalian[2], [1]Undergraduate student, Department of Mechanical Engineering, New Mexico Tech, Socorro, NM 87801, USA, [2]Assistant Professor, Department of Mechanical Engineering, New Mexico Tech, Socorro, NM 87801, USA.

Introduction: Unmanned Aerial Vehicles (UAVs) have been developed and implemented for a range of potential applications due to their ease of use, low cost, and form factor. Unfortunately, as it stands, traditional drone technology is extremely limited by flight endurance. Drones typically rely on battery power as it is an inexpensive, highly efficient alternative to systems, such as a combustion engine, although this comes at the cost of a lower energy density. For this reason, the implementation of passive and active energy harvesting systems becomes an important element in modern drone design with the aim of greatly increasing potential mission duration.

With this in mind, the application of a fixed-wing drone design becomes necessary as it has greatly improved flight efficiency over what may be considered a more traditional drone style, such as a multirotor drone. In addition to this, methods intended to recharge the power supply of a drone are crucial in the application of extended flight duration. Solar energy harvesting is one such method and is very commonly applied in a variety of applications.

The concept of solar-powered flight is not new to the world of aviation, but one that has not been extensively explored or commonly implemented. In the early 1970s, the first fully solar-powered flight was achieved with a flight time near 20 minutes. Since then, substantial advancements in solar harvesting technologies have been made, providing a platform for extreme endurance drones given the correct environment [1]. This concept could be applied in a multitude of applications, including the exploration of Venus (see Fig. 1). Venus' atmosphere contains a section approximately 5 km in height that contains an operable temperature range [2-4]. This range also conveniently has a similar density and irradiance to that of Earth's atmosphere providing a convenient zone of operation for a continuously flying fixed-wing drone platform. The deployment of such a system would provide means for long term data collection and monitoring of Venus' atmospheric conditions through a suite of onboard sensors.

Fig.1. Views of fixed-wing concept for Venus exploration.

Operational Altitude: Venus' atmosphere is home to some of the harshest operational conditions within our solar system. The surface temperatures are swelteringly high, in the range of 700 K, and the winds can blow up to 150 m/s [3, 5]. On top of this, there are layers of sulfuric acid over a substantial range of the planet's atmosphere. All of this amounts to an extremely hazardous operational environment and provides multiple challenges in designing platforms for extended operation on or above the planet.

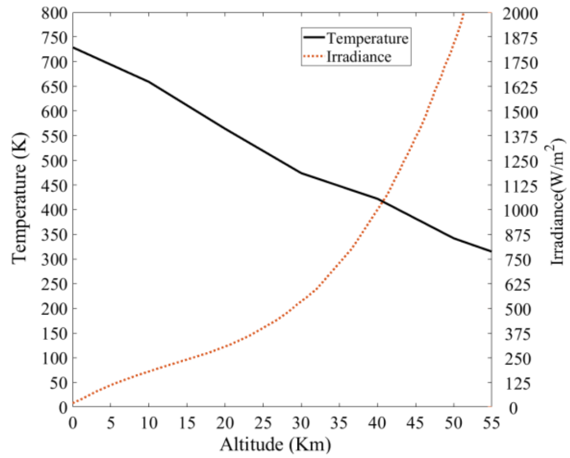

Fig.2. Views of average temperature and irradiance changes versus altitude on Venus.

Within this harsh environment, there is a layer with Earth-like elements. Looking at the region between 50 and 60 km above the planet's surface there is a temperate zone in which standard electronics could operate. This is significantly important in regards to battery operated electronics as most rechargeable battery systems have an operation range of 278 K to 328 K [2-6]. The operation of a drone within this altitude range would allow for the implementation of relatively standard electronic components, including any necessary sensors and the batteries required to power the drone.

Although this altitude range provides ideal temperatures for electronics operation, it has several other harsh environmental factors to take into consideration. The winds in this range have the potential to reach upwards of 125 m/s, which could prove to be a significant hurdle for autonomous drone flight, especially in a lightweight platform [5]. This does, however, provide for an interesting opportunity to harvest a substantial amount of energy in the form of increased lift. It should also be noted that special care will need to be taken in the selection of the drone materials as this region of the atmosphere also houses clouds of sulfuric acid [7].

Solar-Powered Drones: There are several important factors that must be considered when designing a solar-powered drone, especially the maximum potential efficiency of the panels, as this determines the maximum power produced. Following this, the maximum voltage is another factor that must be considered, and this is directly related to the efficiency and maximum current. Finally, the efficiency degradation of the panels must be considered as this characteristic is determined by the operational temperature of the solar cells.

Even while operating at peak efficiency, there are a multitude of external elements that have a significant impact on the potential power absorption and, thus, output, the most crucial of which is known as solar irradiance. The energy from the sun can be referred to as radiant energy and can be measured and referred to as solar irradiance. Irradiance is the power measured per unit area (W/m^2) and varies with respect to a combination of the altitude, latitude, and longitude.

The weight and structure of the solar panels are also important criteria to consider in the application of a solar-powered drone. Traditional solar panels are typically a rigid construction, and thus can be rather costly from an aerodynamic perspective. With this in mind, the implementation of a flexible solar panel becomes a point of interest as it would improve aerodynamic efficiency. Thin-Film Solar Cells (TFSC) can meet these criteria and easily be implemented on the top surfaces of fixed-wing drone designs without greatly reducing the aerodynamic efficiency. There is an increasing selection of solar companies that produce thin, flexible, lightweight, and efficient solar modules that can be applied to different types of drones. Currently, there are two types of TFSCs, mono-crystalline, and multi-crystalline, and in recent years the efficiency of both cell types has become very similar, meaning the choice of TFSC comes down to the color of the panels as this has a significant impact of the panels emissivity coefficient.

To assess the performance of a solar panel, the above factors must be calculated. The current, voltage, and efficiency of a solar panel can be expressed as seen below [1, 4]:

$$I_{pv} = I_{ph} - \frac{V_{pv}+I_{pv}R_S}{R_{sh}} - I_o[exp(\frac{q(V_{pv}+I_{pv}R_S)}{mkT_p}) - 1] \quad (1)$$

$$V_{oc} = V_{oc,STC} + \frac{mkT_P}{q} ln(G_s) + \mu_{Voc}(T_P - T_R) \quad (2)$$

$$\eta = \eta_{TR}[1 - \beta_R(T_P - T_R) + \gamma log_{10}(G_s) \quad (3)$$

where I_{pv}, I_{ph}, I_o, R_s, R_{sh}, V_{pv}, m, k, q, T_P, T_R, $V_{oc,STC}$, μ_{Voc}, G_s, η_{TR}, β_R, and γ are the photovoltaics current (A), light generated current (A), reverse saturation current (A), module series resistance (Ω), module parallel resistance (shunt resistance) (Ω), module output voltage (V), the ideality factor (diode factor), Boltzmann's constant (J/K), the charge of an electron (coulomb), and module temperature (K), reference temperature of cells (K), open-circuit voltage at standard test conditions (V), thermal coefficient of the open-circuit voltage (V/^{o}C), solar irradiance (W/m^2), photovoltaic module's electrical efficiency in the reference temperature and standard test condition solar radiation, temperature coefficient, and solar radiation coefficient, respectively.

Solar Performance: Several important metrics for how the solar panels are anticipated to perform on Venus are depicted within the ideal operating range. The target elevation at which the drone should be flying will be from 50 km to 60 km above the surface of the planet. This is where the batteries are limited to functioning given the harsher and much more drastic atmospheric conditions of Venus discussed previously. The current, power, voltage, and irradiance of the solar panels provide valuable insight into how effective such methods would be. A Flisom eFlex Wp 30 was used for the following analysis.

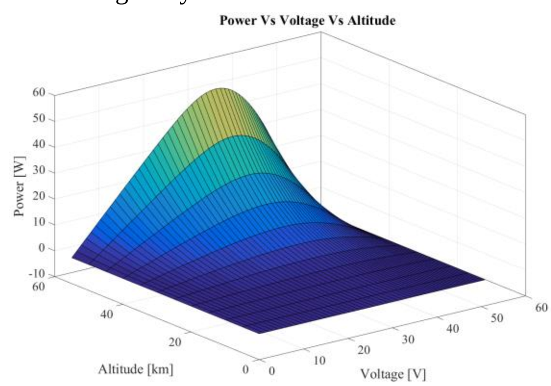

Fig. 3. Power vs. voltage vs. altitude for PV on Venus.

Table 1. Efficiency and generated power by solar panels on Venus from 0 to 60 km.

Altitude (km)	Temp. (K)	Irrad. (W/m^2)	Effeciency (%)	Power (W/m^2)
0	729	20	0	12.2
5	694	107	0	14.4
10	659	178	0.22	17.0
15	612	233	0.80	21.4
20	564	240	1.47	27.0
25	519	363	2.63	33.4
30	474	480	3.76	41.1
35	448	604	4.47	46.2
40	422	800	5.16	51.8
45	382	1110	6.09	61.1
50	342	1440	6.91	71.6
55	315	1875	7.20	79.3
60	288	2640	7.10	87.4

References:

[1] Shahmoradi, J.et al. (2020) *AIAA SciTech 2020.* [2] Jenkins J. M. 1995 *Stanford.* [3] Pätzold M. et al. 2007 *Nature* Vol 405. [4] Aguirre A. A. G. (2020) *AIAA.* [5] Lang K. R. (2010) *Tufts Univ.* [6] Taylor F. W. (2014) *Cambridge Press.* [7] Lebonnois S. et al. (2017) *Nature geoscience.*