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# Photovoltaic Balloon for Autonomous Energy Generation on Mars (MEGA-PB)

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#### 1. Abstract

We propose two Martian atmosphere CO<sub>2</sub>-filled, solar-power-generating balloons with 1000 m<sup>2</sup> total PV cell area divided between them. Several balloon concepts were considered and the optimum design is two grounded and anchored balloons on the Martian surface to minimize dust accumulation. The balloon material consists of a lightweight, low-emissivity-coated polyimide LaRC-CP1 Kapton-Kevlar film to withstand the Martian environment. The upper area of the balloon consists of an array of high-efficiency, high-stability, and flexible InGaP/GaAs photovoltaic cells for reliable energy production with the capability to produce roughly triple the 40 kW estimated human power consumption for Mars. The system mass weighs less than 1500 kg in total and fits within the allotted 10 m<sup>3</sup> designated by NASA. Providing us with advantages, such as the elimination of dust accumulation, increased solar intensity, in situ resource utilization, and transportation mobility when compared to traditional, ground-based approaches.

#### 2. Introduction

The objective of our proposal is to provide future Mars exploration, scientific, and habitation missions with a reliable, sustainable, and autonomous source of electricity. The sun provides Mars with an abundant source of energy -- the only problem is developing a system that can harness the energy without human support while overcoming the various challenges put forth by the Martian environment. Seasonal variations and fine, powdery dust impede the effectiveness of fixed and grounded solar panels. While specialized mechanical deployment and retraction methods offer varying forms of dust abatement, they contain moving parts which will eventually be rendered ineffective by the dust.

The design we propose consist of a spherical balloon filled with Martian atmosphere, which is primarily  $CO_2$ , and can be heated to generate partial buoyancy if needed. The flexible solar panels will sit on top of the balloon, so they will easily evade dust while receiving increased solar flux due to their height and the lower dust concentrations at increased altitudes. Additionally, since the balloon can be made partially buoyant via solar power heating within the Martian atmosphere, it is easy to transport and rotate especially when compared to terrestrial PV systems. This additionally will reduce the number of moving parts for the PV deployment system which would be prone to failure with Martian dust buildup or other mechanical issues and will also reduce the overall system weight.

A lightweight, attached and filtered  $CO_2$  pump will provide each balloon with  $CO_2$  to inflate. Lightweight sensors will control the pressure and monitor temperature of the gas inside of the balloon. The pump will be wired to the flexible solar panels on the top of each balloon and both the pump and panels will be connected to two 0.7-cm-diameter, wound, alloyed aluminum cables for power transmission and stability. These cables will be connected to the Mars cargo lander to power the pump and store power once the balloon begins producing positive power output.

While wind storms are rare, they can provide high wind speeds which may not sound ideal for a balloon. Fortunately, due to the low atmospheric density of Mars, Martian winds equate to winds 1/10 the strength on Earth, meaning our system will likely remain unaffected by Martian wind and the cables will not experience catastrophic strain [1, 2]. Additionally, an aluminized Ni-P microlattice with aluminized Kapton covering will be used to contain and store Martian sand to anchor our balloon to the Martian ground, ensuring it doesn't move from its grounded location during global dust storms.

#### 3. Design Concept and Analysis

### 3.1 Design Concept, Balloon Material and Structure

The shape of the balloons will be that of a sphere with a 25 m radius. Several possible materials for the balloon fabric were considered including polyethylene naphthalate (PEN), nylon, and urethane-based fabrics. The requirements for the fabrics were similar to the solar cell requirements because it needed to be lightweight and very durable. Additionally, the fabric had to be able to handle extreme temperatures and could not wear out quickly. A low permeability was also required in order to limit how quickly the gas will escape from the balloon. For the balloon material, a LaRC-CP1 and aluminized Kapton<sup>®</sup>-Kevlar<sup>®</sup> based composite structure is considered. LaRC-CP1 is a polyimide material resistant to UV-light and harsh space environments. Kapton<sup>®</sup> is a light material which will endure temperature in a range from -269 °C to 400 °C, has a very low outgas rate, is thermally insulating, and is widely used for space applications [3]. The aluminized material will provide a low emissivity surface that contributes to the thermal exchange of the balloon and the Mars atmosphere. With a density of 1420 kg/m<sup>3</sup> and a thickness of 10 microns for solar panels and 50 microns for Kevlar structural support mesh, the total mass required for the fabric is 529 kg per balloon. The layer of Kevlar-29, in a mesh of 55 denier, will provide extra strength and support to the balloon and will contribute to support the solar cells. The whole material will be encapsulated with a 25-micron optically transparent polyimide film (LaRC-CP1 NeXolve), which has been previously used on space applications, sunshields and membrane optics [4,5], resulting in a balloon film of less than 100 µm thick in total including space grade silicon adhesive layers for holding the films. As the adhesive contributes to the total weight of the balloon by 28 kilograms, we have considered a second option for the layer adhesion based on thermally bonding the layers for holding them together and encapsulation of the solar cells.

A diagram of the balloon structure is shown in Fig. 1. In order to reduce the energy lost through radiation, a thin aluminum coating will be applied to the surface of the balloon which should lower the emissivity to 0.02 [6].



Fig. 1: Mars PV balloon material structure.

Fig. 2: Design concept.

#### 3.2 Balloon Design and Advantages

An illustration of the proposed design is shown in Fig. 2. The balloons were chosen to be shaped like a sphere in order to reduce aerodynamic drag, increase the amount of sunlight on the photovoltaic array, maximize the volume, and reduce the presence of dust. The array will be placed on the upper half of the balloon in order to maximize the array's exposure to sunlight since this is the area receiving the most direct sunlight. When considering possible shapes, a teardrop shape was also discussed, but the increased structural stability of the sphere outweighed the benefits of the teardrop, namely the smaller required surface area. Originally, a general ellipsoid was looked at and Fig. 3 was created comparing the volume vs surface area of ellipsoids with different axes. The sphere was eventually chosen because it provides the maximum volume for any given surface area. This is illustrated in Fig. 3 as all of the points on the left edge are spheres. The logic behind this decision is that balloons with larger volumes have more buoyancy because they displace more  $CO_2$ . With a larger volume, more  $CO_2$  will be needed to inflate the balloon. However, the low density of the gas and larger balloon volume would lead to a decrease in the balloon's density and would generate more buoyancy than a balloon of a smaller size. As such, balloons with larger volumes require less heating in order to achieve buoyancy. Furthermore, the surface on which the array would be situated would be more curved for a sphere than on a general ellipsoid which should help with dust prevention.



6 5.75 5.5 5.5 5.25 4.75 0 500 1000 1500 2000 2500 Height (m)

**Fig. 3:** Plot of balloon surface area vs. volume. Chosen dimensions are indicated by the red box.

**Fig. 4:** Dust concentration vs. height in Martian atmosphere.

Dust is one of the largest obstacles for achieving solar power on Mars because it scatters and reflects the sunlight reaching the Martian surface and dust buildup on flexible cells reduces their capability of generating power. Dust accumulation on the Sojourner rover resulted in a 0.2-0.3% power loss per Martian sol which can eventually result in a significant reduction of power [8]. This challenge was kept in mind with the design of our balloon. First, the curvature of the balloon, along with the higher wind speeds at higher altitudes, should help clear the dust from the panels. This is evidenced by the prior cleaning events on Mars that all involved high angles of attack and large wind speeds. Additionally, the balloon should experience some pendulum-like oscillations as a result of wind hitting it, and the vibrations may help to clear the dust.

The selected radius for the spheres is 25 meters, giving it a surface area of  $7854 \text{ m}^2$  and a volume of  $65,450 \text{ m}^3$ , roughly the size of Epcot's Spaceship Earth. The radius was chosen with care to create a more ideal ratio between the balloon's surface area and volume. Determining an ideal volume was difficult because there were advantages and disadvantages for both extremes. Increasing the radius would increase the volume at a greater rate than the increase in surface area which makes it easier to achieve buoyancy. However, the problem with increasing the volume is that it increases the load stress on the balloon and makes transportation to Mars more difficult. A higher load stress is a risk to the balloon if it is left unsupported, but more support means more weight and greater difficulty storing the balloon during launch. Additionally, the larger surface area would require more space for transportation. Smaller volumes would help with the load stress, but, as the balloon volume gets too low, the temperature required for buoyancy becomes more extreme and unfeasible. As a result, the balloon's radius had to be selected so that the disadvantages in both directions were balanced. The volume and surface area of the chosen design is marked by the red box in Fig. 3.

An alternative design that was considered was using one large balloon that would float to increase the solar flux and decrease the dust. However, the low density of the Martian atmosphere meant that a huge volume would be required to achieve sufficient lift. Additionally, the gas inside the balloon would need to be heated to large temperatures that make this design complicated. However, an analysis of this design, described in section 3.8 below, shows that it is potentially viable and further investigation could be conducted. The design with two balloons was selected for the proposal because its redundancy would be advantageous as there would still be an operable balloon if something happened to one of them. If there is only one balloons, there would be no replacement or backup if it became inoperable. Furthermore, multiple balloons mean power could easily be generated in different places on Mars as it would not be difficult to relocate one or more of them. In other words, all of the power generated would not need to occur in one location.

The arrays will be situated at high altitudes where, as displayed in Fig. 4, there is less dust thereby increasing the amount of sunlight reaching the panels. The dust concentration decreases as the altitude increases exponentially. Also, along the same line, the high altitudes of the balloon will reduce the amount of light that is blocked by the atmosphere further increasing the amount of sunlight that reaches the solar array. We have considered how the sloped surface of the sphere effects the uniformity of light on the panels and have concluded that that 1000 m<sup>2</sup> of panels on a spherical cap will receive 94% of the flux of a planar panel arrangement. This is true regardless of the number of balloons since the panel area per balloon will scale with the number of balloons. However, this curvature has an added benefit in that panels at various angles will receive incident flux at varying times in the day, unlike planar arrangements which will only receive incident flux at one point in the day. The balloon offers several advantages over a solar array on the surface of Mars. First, the arrays on the balloon would be 50 meters in the CO<sub>2</sub>, so there would be less blockage from dust and less sunlight reflected and absorbed before it reached the array. Second, no extraordinarily complex mechanism for deployment would be needed. As described later in the report, the system can be packaged in a way to make for an easy deployment. Third, the balloons would be able to be transported to a different location more easily than a traditional array. Fourth, all of the potential issues such as spacing between balloons and stability during wind can be reasonably reduced or solved.

#### **3.3 Solar Panels**

The efficiency of the panels is an important factor because it is directly linked to how much electricity the panels would be able to generate meaning higher-efficiency panels are preferable. Furthermore, the panels have to be operable on Mars and resistant to the harsh Martian conditions. Other important factors included rigidness and low density. From preliminary calculations, it was determined that conventional panels were too rigid in order to be able to store enough panels to achieve a 1000 m<sup>2</sup> area in a 10 m<sup>3</sup> space. Additionally, a lower density means a lower mass which means easier storage and less stress on the balloon.

Due to these factors, Gallium Arsenide (GaAs) materials system was selected for the solar cells. GaAs panels are very durable and naturally resistant to damage from radiation and ultraviolet light, which is necessary for being able to operate on Mars. Furthermore, GaAs cells have high efficiencies, even for thin, 2µm layers, which enables them to be flexible and lightweight [9]. These properties aid in storage and in maintaining a reasonable total design weight. The design incorporates light and flexible double-junction InGaP/GaAs that can bend up to a 5 cm radius of curvature [10]. These flexible GaAs solar cells are now commercially available from Alta Devices on light polymeric substrates with an efficiency of 29% (AM1.5) and promise an increase in efficiency in the next years. The schematic cross-section of the solar cells is shown in Fig. 5.



**Fig. 5:** InGaP/GaAs double-junction flexible solar cell device. By utilizing two photovoltaic materials of different energy band gap, it captures a wider range of the solar spectrum more efficiency (indicated by the multicolored arrows) [14, 15].

**Fig. 6:** Estimated daily power output of the PV system from mission start date 1/15/2035 to 12/13/2036 for a total of 680 sols at varying Martian latitudes [16].

The lift off process developed for GaAs thin film cells fabrication on flexible substrates is a new technology that enables the fabrication of flexible and reduced-weight solar cell arrays, which is already in use for high altitude long endurance aircraft, unmanned aerial vehicles, and satellites [11,12]. With a single solar cell weighing only 0.112 g, the total mass of the array for 1000 m<sup>2</sup> will be around 130 kg [13]. By 2030, flexible multijunction GaAs panels will most likely have higher efficiencies and lower weight. The solar cells will be integrated to the two balloons, covering 500 m<sup>2</sup> of the top half of each. Placed on the balloon top surface, the solar array will be exposed during daytime to the solar irradiance being able to generate a total of 63 kW in the optimum conditions with 500 W/m<sup>2</sup> irradiance. This will give us a short-circuit current density of 8.24 mA/cm<sup>2</sup> and an open-circuit voltage of 2.4 V. Assuming the cells are wired for 1000 V and transmitted through two cables with a resistance of 36.65 mΩ, our current through each wire is 32.5 A, giving us a negligible power loss of 38 W from the 63 kW produced. This provides the ground with 126 kW of power total. The solar cells are expected to have a lifetime of 10 years and can withstand thermal cycling between -80 °C to 80 °C. The height of the balloon will contribute to reduction of dust accumulation on the cell. A summary of balloon power generation at various latitudes is shown in Fig. 6. The calculated total weight of the solar array (without the balloon material) is 130 kg. The details of the solar cells proposed for Martian irradiance (500 W/m<sup>2</sup>) and at Air Mass Zero, AM0 (space sunlight at Earth orbit) are listed in table 1.

Alta Double Junction	MARS 500 W/m <sup>2</sup>	AM0 1366 W/m <sup>2</sup>
Material	InGaP/GaAs	InGaP/GaAs
Efficiency [%]	-	25
Short Circuit Current Density [mA/cm <sup>2</sup> ]	8.24	16.71
Open Circuit Voltage [V]	2.5	2.59
Power per cell [W]	0.11	0.30
Power density [W/m <sup>2</sup> ]	126	345
Power by 1000 m <sup>2</sup> [kW]	126	345
Single cell size [mm]	50 x 17.1	50 x 17.1
Single cell weight [g]	0.112	0.112

**Table 1.** Solar cells parameters calculated for a Mars solar irradiance of 500  $W/m^2$  and AM0 irradiance in space at Earth orbit, based on Alta Device's specifications [15].

#### **3.4 Electric Power Transfer**

In order to transfer the power, two wound aluminum alloy cables containing trace amounts of iron and rhenium will be connected from the panels on top of the balloon to the pump and the lander-based battery system on the ground [17]. Assuming a maximum panel height (*l*) of 50 meters and a wound wire diameter (*d*) of 0.7 centimeter, the total weight of each wire would be near 5.22 kg with an ultimate yield strength ( $s_{min}$ ) of roughly 3.96 kN and resistance loss of about 36.65 m $\Omega$  [18]. This is determined by the following equations:

$$m = \rho_m l\pi \left(\frac{d}{2}\right)^2 = \left(2700 \frac{kg}{m^3}\right) (50 \ m)\pi \left(\frac{0.7 \ cm}{2}\right)^2 = 5.22 \ kg \tag{1}$$

$$R = \frac{\rho_r l}{\pi (d/2)^2} = \frac{(2.7 \times 10^{-8} \ \Omega m)(50 \ m)}{\pi (0.35 \ cm)^2} = 36.65 \ m\Omega \tag{2}$$

$$s_{min} = y_{min} A = (103 MPa) \left( \pi \left( \frac{1 cm}{2} \right)^2 \right) = 3.96 kN$$
 (3)

Where  $\rho_m$  is the density,  $\rho_r$  is the resitivity, and  $y_{min}$  is the yield strength.

The panels can be wired in series for high-voltage-low-power-loss (1000 V) setup with one wire connected to the sunrise and sunset sides of the balloon to limit current loss. The wires will be insulated with 10  $\mu$ m of LaRC CP1 polyimide, which has a high dielectric strength of 196.6 V/ $\mu$ m and is space resilient [4]. The wires will be situated on a reel that unrolls automatically as the balloon floats up. The wires will serve as an absolute limit in height to the balloon while securing it to the base. Since the atmospheric density of Mars is 0.016 kg/m<sup>3</sup>, roughly 1% of Earth, high speed (97 km/h) winds will generate as much force as 9.6 km/h Earth winds, which can be deduced from the dynamic pressure equation:

$$q = \frac{\rho v^2}{2} \tag{4}$$

Where q is the atmospheric pressure,  $\rho$  is the atmospheric density, and v is the wind velocity. Given a balloon cross sectional area of 1963 m<sup>2</sup> and a drag coefficient of 0.47 for a sphere, our balloon would experience a drag force (via the drag equation for a sphere) of 5.36 kN in the strongest recorded Martian storm (96 km/h), which would be safe for our electrical cables.

#### **3.5 Laboratory Testing of Balloon Structure**

In order to test the proposed concept on Earth, an environment can be configured to simulate the temperature, pressure, dust composition, and solar flux of Mars. A small laboratory-scaled model of the balloon can be made and inserted in the controlled environment. However, the thickness of the plastic cannot be scaled down, but the area of the panels and size of the balloon can be. The model can be used to test the packaging, deployment, overall structure and operation. The model can also simulate and test the amount of energy generated and how well the design clears the dust from the panels.

To determine the uniformity of illumination on a spherical surface, we measured the change in power as a function of the radial angle on a sphere and fitted with a cosine curve.

#### **3.6 Flight Analysis for Alternative Design**

This section analyzes a different possible design than the one proposed above: a single floating balloon. The mass  $m_b$  that can be lifted by the balloon with volume  $V_b$  is given by Equation 5 below where  $\rho_a$  is the density of the Martian atmosphere and  $\rho_b$  is the density of the gas inside the balloon. The radius used for the alternative design was 37 meters.

$$m_b = V_b(\rho_a - \rho_b) \tag{5}$$

In order to find the density of the Martian atmosphere, the ideal gas law can be modified to the form shown in Equation 6 where  $R = 8.314 \text{ (m}^3\text{*Pa)/(K*mol)}$ . The pressure in kilopascals and ambient temperature in degrees Celsius can be found using the equations from [19] that describe the typical conditions on Mars at an altitude h.

$$\rho_m = \frac{PMW}{RT} \tag{6}$$

$$P = 0.699 \times exp(-0.00009 * h) \tag{7}$$

$$T = -31 - (0.000998 \times h) \tag{8}$$

Assuming an altitude of 0 m, the pressure is 699 Pa and the temperature (T) is 242 K. The mean molecular weight (MW) of the Martian atmosphere is 43.34 g/mol [20]. Under these conditions, the density of the Martian atmosphere at an elevation of zero can then be calculated to

be 0.015 kg/m<sup>3</sup>. In order to calculate the density of the  $CO_2$  inside the balloon, Equation 9 can be used where the temperature is in Kelvin and T is the exterior temperature and T<sub>b</sub> is the temperature of the gas inside the balloon.

$$\rho_b = \rho_a \left(\frac{T}{T_b}\right) \tag{9}$$

The pressure at the inside of the balloon can be approximated with an analysis from the forces acting on the balloon material in the Mars environment. The internal pressure  $P_{in}$  will be equivalent to the Mars atmospheric pressure plus the balloon weight force  $W_b$  over the surface area A=7854 m<sup>2</sup> of the balloon:

$$W_b = m_f * g_M = 1967.88 \,\mathrm{N} \tag{10}$$

$$P_{in} = P_{atm} + \frac{W_b}{A} = 699 Pa + 0.25 Pa = 699.25 Pa$$
(11)

As the Mars gravity  $g_M = 3.72 \text{ m/s}^2$  acting on the mass of the balloon fabric,  $m_f = 529 \text{ kg}$ , is relatively small, the internal pressure of the martian-CO<sub>2</sub>-inflated balloon is almost equal to the atmospheric pressure. The outer balloon material LaRC-CP1 is rated to withstand forces of tensile strength up to 87 MPa, Kapton of 231 MPa, and Kevlar of 3,600 MPa, which compared to the pressure exerted from the gas inside the balloon suggest the materials will withstand easily the deployment forces. The total weight of both balloon including the solar panels, balloon material, and an estimate of up to 50 kg for equipment is 1320 kg. Given this mass and the balloon volume of 212175 m<sup>3</sup>, Equations 4 and 9 can be rearranged to solve for the required balloon temperature to lift the balloon under standard conditions. This calculation shows that the required temperature is 424 K or 151°C. Fig. 8 below shows the required temperature in °C as a function of height in meters. Thus, the temperature required increases as the balloon goes up higher in the atmosphere. As such, the maximum height should be 100 meters because anything beyond that would increase the risk to the solar array from heat-related damage while increasing the time required to heat the balloon. This height would require a temperature of about 154 °C. To determine if solar energy would be enough to heat up the balloon, the amount of solar energy coming in, or Pin, was compared to the amount of energy Pout being lost from radiation and convection. Fig. 7 below shows the density and density scale height of the Mars atmosphere, which allows us to extrapolate the solar irradiance at various heights above the surface. Assuming that the solar flux F is the only source of energy and that the flux is equal to  $500 \text{ W/m}^2$ , a typical value near the equator, the rate of energy coming in is given by the flux multiplied by the cross-sectional area which is shown in Equation 12. The power lost is given by the Equation 13 which incorporates the Stefan-Boltzmann Law and energy lost to convection. The emissivity is given by  $\varepsilon$ , the Stefan-Boltzman constant is  $\sigma$ , the surface area is SA, and h is the convective heat transfer coefficient.

$$P_{in} = F \times A \tag{12}$$

$$P_{out} = \varepsilon \, \sigma \, SA \, (T - T_0)^4 + h \, S \, A \, (T - T_0)^4 \tag{13}$$

Since the balloon consists of two distinct sections with different emissivities, the radiation was found for each section. The emissivities used were 0.11 for the upper half and 0.02 for the lower half. For the heat transfer coefficient h, the value for LaRC-CP1 and aluminized Kapton® was not known so was approximated as 0.02 using the coefficients of similar insulators such as Polyurethane. Setting the two equations equal will yield what that temperature will be when the balloon is in thermal equilibrium. This calculation shows that the equilibrium temperature under standard conditions is 437 K which is slightly higher than the required temperature. From this



analysis, it is clear that this design would be a difficult choice as an alternative to the proposed design.

**Fig. 7**: Density of the Martian atmosphere vs altitude (left axis, black) and atmospheric density scale height with varying altitudes (right axis, red). The density scale height is the height at which the atmospheric density changes by a factor of *e*. [21].



**Fig. 8:** Plot of the balloon height vs. temperature required to provide sufficient lift. The temperature required quickly becomes untenable for flexible polymers and solar cells.

#### 4. Longevity Analysis

In order to guarantee that the balloon design is feasible for a long-term Martian mission, longevity analysis of the balloon was carried out. Specific analysis was performed to ensure that materials are stable in the Martian environment, that the balloon will stay inflated, and that the balloon is capable of withstanding the wind storms that occur on Mars. Based on our analysis, the balloons should last for the required ten years.

A primary issue in designing a solar array for use on the Martian surface is ensuring that the materials are suitable for space missions. Material properties such as low outgassing, good thermal stability, and non-reactivity with the surrounding atmosphere are required. The materials used in our design are LaRC-CP1, aluminized Kapton, Kevlar, and GaAs solar cells which are all space qualified.

#### 4.1 Solar Cell Reliability in Martian Environment

In our design, the solar cells are not directly exposed to the Martian atmosphere, as they are encapsulated by a Kapton layer. As such, material degradation due directly to the atmosphere is not expected to be an issue. Additionally, thermal cycling tests performed by Alta Devices on their cells showed excellent thermal stability over 200 cycles between -80 °C to 85 °C. Furthermore, GaAs is naturally resistant to UV light, making it suitable for AM0 illumination conditions. Lastly, the solar cells are projected to last 10 years or longer by Alta Devices.

#### 4.2 LaRC-CP1 and Kapton Reliability in Martian Environment

LaRC-CP1 and aluminized Kapton/Kevlar material were carefully chosen due to their extensive use in space missions, including Mars-based missions. LaRC-CP1 has been rated for a space (GEO) lifetime of 10 years [4,22]. Kapton is extremely resistant to temperature changes, being manufacturer tested between -269 °C and 400 °C and is expected to last for 10-20 years by Dupont. It also possesses a very low outgassing rate similar to stainless steel, making it a suitable candidate for space imaging and electronics systems similar to solar cells [23]. Kapton is vulnerable to UV radiation, as are most polymers. However, despite the slight increase in UV radiation in the AM0 spectrum compared to AM1.5, the amount of UV radiation is not significant enough to warrant a large concern. Additionally, the presence of atomic oxygen (AO) on the Martian surface is extremely low, with AO levels peaking at ~90 km altitude, and reducing to near zero below 40 km [24]. Therefore, the high amount of AO degradation seen in Kapton films is not as issue, as the balloon will be located on the Martian surface. The Kapton/Kevlar weave is also commonly used in space missions and should not present any additional issues to the balloon system.

#### 4.3 Balloon Outgassing and Permeability by the Martian Atmosphere

Because the proposed design is a non-pressurized, inflated balloon filled with Martian atmosphere (primarily  $CO_2$ ), calculations and analysis must be performed to ensure that the balloon stays inflated throughout the ten year duration of the proposed mission. In order to calculate the amount of  $CO_2$  escaping from the balloon, we have made two assumptions:

- A) the balloon consists only of one material layer, Kapton, with a thickness of 25 microns. This is done due to the lack of availability of CO<sub>2</sub> permeability through all other balloon materials. However, this assumption will actually result in a higher outgassing rate than the balloon will actually experience.
- B) the Martian atmosphere filling the balloon is 100% CO<sub>2</sub>. This is done due to simplicity and data availability.

First, data was obtained from the literature regarding Kapton permeability. A publication from Koros et. al. measured the CO<sub>2</sub> permeability through a Kapton film to be 0.22 Barrers [25]. One Barrer is defined by the SI units 1 Barrer =  $1 (\text{cm}^3 \text{ cm})/(\text{cm}^2 \text{ s cmHg})$ . This, converted into a more useful unit for our purposes, is:

$$1\frac{cm^3 cm}{cm^2 s \ cmHg} = 3.04 \times (10^{-14}) \ \frac{cc \ 20 \ \mu m}{m^2 \ day \ atm}$$
(14)

Note that in Barrers (and its converted units), "cc" is defined as the amount of gas present in 1 cc (cubic centimeter) at STP. Therefore, cc is not a volume, but a mol quantity. In the case of an unpressurized container (balloon) at the same temperature as the surrounding atmosphere, this equates to ~125 cc of gas. This was calculated using the conversion between standard volume and actual volume, given as:

$$V_s = V_a \times \left(\frac{P_{line}}{P_{std}}\right) \times \left(\frac{T_{std}}{T_{line}}\right)$$
(15)

where  $V_s$  and  $V_a$  are the standard and actual volumes, respectively, and the subscript "std" denoted the SI unit standard value for each quantity. For pressure and temperature, these are 1 atm and 288 K, respectively. The line pressure in our balloon is Martian atmospheric pressure, 0.006 atm, and the temperature was taken to be the average Martian temperature of 218 K. Therefore, to get our permeability value in volume, we need only multiply the result by 125. To calculate the total amount of gas lost per day through  $CO_2$  permeability, we need only to insert the values for our system into the conversion given above.

total gas loss = 
$$\frac{125}{3.04 \times 10^{14}} \times \frac{\frac{25}{20} \mu m}{day \times 0.006 \ atm} \times (7853.98m^2) = 1.36 \times 10^{-6} \frac{cc \ CO_2}{day}$$
 (16)

Based on this number, the balloon should be expected to easily stay inflated over the course of the 10-year mission. When all the layers are taken into account, such as the LaRC-CP1, aluminized Kapton and solar cells, the value should drop to nearly 0, as CO<sub>2</sub> will not permeate through the metal films. Therefore, balloon inflation will not be an issue. If inflation were to become as issue through damage to the system, the pump could be run to keep the balloon inflated until the necessary repair is made.

#### 4.4 Wind Mitigation

It is important to consider the effects of wind on the balloon system. Storms on the Martian surface pose a challenge, as the winds could potentially move the system in an unwanted manner. In order to avoid this, we propose an anchoring system making use of the Martian soil, as will be explained in Section 5. In order to calculate how much additional anchoring weight is required to keep the balloon from being pushed along the ground, a basic analysis was performed using the drag equation. The results of these calculations are shown in Fig. 9.





In order to calculate the required additional mass, we need to subtract the normal force of the balloon (its weight) from the wind force pressing on the balloon. We have chosen to neglect the rolling of the balloon both for simplicity and because the balloon is anchored at the bottom and is therefore bottom-heavy. The rolling of the balloon on a horizontal plane is an extremely complex calculation which would either require numerical simulation or a direct measurement. Therefore, the drag equation was used. The equation used to generate the wind force on the sphere is:

$$F_{wind} = \frac{1}{2} c_d \rho v^2 A \tag{17}$$

where  $c_d$  is the drag coefficient of a sphere (0.47),  $\rho$  is the Mars atmosphere density, v is the wind velocity, and A is the cross-sectional area of the balloon. In order to generate the curve for additional required mass, the friction force of the sphere was subtracted from the force of the wind. At values below 55 km/h, no additional force is needed. Approximately once every three years, extremely large storms will occur on Mars and wind speeds can reach as high as 96 km/h. These speeds would require an additional mass of just under 1400 kg based on our calculations. As a result, our anchoring system is designed to hold more than 1400 kg of additional sand mass. Based on the results presented in this section (4), we conclude that our balloon has been designed to sustain the Martian environment without issue over the course of the ten year mission time.

#### 5. Packaging, Storage and Deployment

#### 5.1 Storage and Packaging

The balloon will be packaged by rolling it into a spiral structure via a two-step process with the flexible solar panels integrated in the material. The solar cells are highly flexible and can withstand up to a 5 cm radius of curvature, allowing the two balloons to have a package size of less than 10 m<sup>3</sup>. First, the balloon is rolled laterally from both sides, forming two conjoined cylindrical structures. The second rolling is done on itself downwards along the horizontal axes, forming a compact spiral with a diameter of 4.6 m. The pump, connected to the balloon, has a height of 0.8 m, making the total height of the package 5.4 m. Thus, the volume of 1 rolled balloon takes about 3.32 m<sup>3</sup>, weighing 605 kg. Care will be taken to ensure that no folding damage occurs for the cells at any bends. There are two internal electrical cables running inside the balloon that are 50 m long each, connecting the PV cells to the power outlet. There will be two such balloon packages packed independently in their respective outer package in the storage capsule.



**Fig. 10:** Rolling and packaging of the balloon in the storage capsule. (1) The balloon rolls inwards, (2) the balloon rolls downwards, (3) one of the balloons stored in its package.



**Fig. 11:** Detail of the balloon material unfolding for deployment. The pump directs pressurized  $CO_2$  flow to the balloon, causing the primary roll to unfold, followed by the lateral rolls unfold and full balloon inflation.



**Fig. 12:** Schematic diagram of the pump and sand tube ring.

**Fig. 13:** Cross-section of the pump and sand tube ring.

The machinery attached to the balloon consists of a two-way pump and a sand-storage tube ring along with separate  $CO_2$  and sand inlets. The dimensions of the pump are 4.5 m x 0.8 m x 0.2 m, taking a volume of  $0.72 \text{ m}^3$  with a weight of approximately 44 kg per pump, for a total of 88 kg and volume of 1.44 m<sup>3</sup>. Each pump has a maximum power rating of 3.1 kW and each pump motor has 4.21 HP rating. The flow rate of each pump is constant at 46 m<sup>3</sup>/min. Each sand tube ring is a hollow rectangular structure, running along the perimeter of the pump, with a height of 0.73 m and width of 0.164 m. They consists of 2 cm thick multilayers of a Ni-P microlattice (0.204 kg: 0.2266 m<sup>3</sup>), covered with 0.1 cm Al coating (16.03 kg; 0.005 m<sup>3</sup>). The upper portion of the ring is made of 50 µm aluminized Kapton. The sand tube ring would be capable of storing a 0.92 m<sup>3</sup> volume of Martian sand, weighing 1400 kg based on the average Martian sand density of 1.5 g/cm<sup>3</sup>. The sand will be used to anchor and ground the balloon to the Martian surface so that it remains fixed in its position. The Al covering will grant additional mechanical support to the structure. The pump will be a two-way system, which is able to pump in and out CO<sub>2</sub> and sand, if required. There will be a sensor operated valve, which would enable the pump to take in CO<sub>2</sub> through CO<sub>2</sub> inlet and sand through sand inlet independently. A particle-filter will be used at the CO<sub>2</sub> inlet to prevent the entry of sand particles into the balloon. Since, the Ni-P Micro-lattice (93%-7% by wt.) has a density of only 0.9 mg/cc, hardness of 6 GPa, modulus of 210 GPa, grain size of 7 nm, and a recovery from  $\geq$  50% compressional strain, it is a favorable ultra-light material which will be used to contain 1400 kg of Martian sand [26]. The balloon will be attached to the pump, using a durable and long lasting hermetic seals to hold the balloon in place and ensure it will not fatigue with time. The total weight of a single balloon package is 665 kg which occupies 4.27 m<sup>3</sup> volume, fitting well within the NASA specifications.

#### **5.2 Deployment Strategy**

There are two main reasons for which a definite strategy has to be adopted in the deployment process on the Martian surface. The first reason is that there is a huge probability of

collisions and inter-disposition of two fully inflated balloons. The second reason is that there will be times when one of the balloons will cast shadows on the second one, thereby decreasing the PV modules efficiency. So, in order to avoid these setbacks, there should be distances of at least 100 m between the centers of the two 50 m diameter balloons.

#### **5.3 Deployment**

The deployment process begins with the first stage where each individual balloon package opens after the piezo-electric sensors, which are attached to the package, detect that the package is stationary. This initializes the pump, which will utilize solar power. The pump initially connected to the sand tube ring and begins taking in Martian sand. The pump takes less than 30 seconds to fill up the sand tube ring, depending on the local sand density. The energy required to do so will be 1.03 Wh. After the tube ring is filled, the inner main valve will be actuated and changed with the help of a sensor. The pump then connects to the rolled balloon and starts taking in CO<sub>2</sub>. In order to inflate the 65,450 m<sup>3</sup> volume of a single balloon, it will take less than one day for complete inflation. The energy required for this purpose is approximately 74.4 kWh. Within an hour of initial inflation, the PV modules will be exposed to the sun and can begin generating power, even though it will not have its full dust abatement capability. If relocation is required, the pump can suction out the sand or CO<sub>2</sub> from the system, making it easier for relocation.



Fig. 14: Schematic diagram of the different stages of deployment. (1) The balloon package after landing, (2) the package opens, (3) the pump begins, (4) balloon unfolds.

#### 6. Conclusion

In this proposal, we put forth the concept of a lightweight, spherical, Martian atmosphere (CO<sub>2</sub>)-filled solar balloon for reliable long-term (more than 10 years) power generation to support missions on Mars. The balloon concept will mitigate typical issues faced in the Martian environment, such as dust which damages moving parts and reduces the amount of solar flux available to the photovoltaics. In addition to increased solar flux, the use of high-efficiency, lightweight, and flexible InGaP/GaAs photovoltaic cells mounted on plastic substrates will further increase the energy output capabilities and allow for the generation of approximately 125 kW of energy. This number can potentially be further increased through optimization of the balloon geometry and panel position in relation to latitude in order to maximize the incident sunlight on the cells. With preliminary human Mars surface energy requirements projected to be 40 kW, this is less than a third of the projected power output of the proposed balloon solar array, leaving significant room to accommodate system losses from transmission, conversion, and dust. A photovoltaic system of this nature should be more than sufficient to power human endeavors on Mars, with little risk of system damage or failure due to the nearly dust-free location of the solar panels. Our design is practicable, utilizes ultra-lightweight materials and flexible solar cells, has a simple design with few moving parts, is resilient to the Martian environment, with lab scale models that could be tested on Earth. Additionally, it is entirely autonomously deployed, long lasting, and dependable. It utilizes technology that is commercially available and space tested, is effectively packaged so as to maximize the available space, and is capable of providing reliable and long term power.

The UVa team has provided adequate and rigorous analysis to confirm the structural integrity and power output predictions for our design and that NASA and the Game Changing Development Program considers our BIG Idea attractive for future missions.

## **References**

- [1] K. Mersmann, "The fact and fiction of martian dust storms", NASA Goddard Space Flight Center, (2017). <u>https://www.nasa.gov/feature/goddard/the-fact-and-fiction-of-martian-dust-storms</u>
- [2] M. L. Ruppenthal, "Balloon safety tips", U. S. Department of Transportation Federal Aviation Administration (White Paper).
- [3] J. Bartl and M. Baranek, "Emissivity of aluminium and its importance for radiometric measurement," Measurements of Physical Quantities, Vol. 4. pp. 31-36, (2004).
- [4] NeXolve Corporation, CP1 Technical Data Sheet (2018). http://www.nexolvematerials.com/low-cure-polyimides/cp1-polyimide
- [5] ASA Spinoff "Thin films protect electronics from heat and radiation" (2012). https://spinoff.nasa.gov/Spinoff2012/ip\_6.html
- [6] Product data sheet Kapton® HN general-purpose polyimide film. DuPont USA, Wilmington, DE. (2016). <u>http://www.dupont.com/content/dam/dupont/products-and-</u> <u>services/membranes-and-films/polyimde-films/documents/DEC-Kapton-HN-</u> <u>datasheet.pdf</u>
- [7] H. Askari, H. Fallah, M. Askari, M. Mohmmadieyh, "Electrical and optical properties of ITO thin films prepared by DC magnetron sputtering for low-emitting coatings" arXiv Condensed Matter: Materials Science. arXiv:1409.5293 (2014).
- [8] R. Lorenz and D. Reiss, "Solar panel clearing events, dust devil tracks, and in-situ vortex detections on Mars," Icarus Vol. 248, 162-164 (2015).
- [9] "Why use gallium arsenide solar cells?" Alta Devices, 1 Nov. 2017, www.altadevices.com/use-gallium-arsenide-solar-cells/.
- [10] Alta Devices: The world's most efficient solar (Brochure). Alta Devices, Sunnyvale, CA. (2017) <u>https://www.altadevices.com/wp-content/uploads/2017/06/alta-brochure-0617.pdf</u>
- [11] Selecting solar for UAVs (White paper). Alta Devices, Sunnyvale, CA. (2017) https://www.altadevices.com/wp-content/uploads/2016/11/uav-app-brief.pdf
- [12] Selecting solar for high atitude long endurance aircraft (White Paper). Alta Devices, Sunnyvale, CA. (2017) <u>https://www.altadevices.com/wp-</u> content/uploads/2016/11/selecting-solar-for-hale-whitepaper.pdf
- [13] "Wafer calculator." Wafer Calculator, PV Lighthouse Pty. Ltd., www2.pvlighthouse.com.au/calculators/Wafer%20calculator/Wafer%20calculator.aspx.
- [14] B. M. Kayes, L. Zhang, R. Twist, I.-K. Ding, and G. S. Higashi, "Flexible thin-film tandem solar cells with >30% efficiency", IEEE Journal of Photovoltaics, Vol. 4 (2), pp. 729-733, (2014).
- [15] Technology brief Dual junction (White Paper). Alta Devices, Sunnyvale, CA. (2017). https://www.altadevices.com/wp-content/uploads/2017/11/dual-junction-product.pdf
- [16] Competition basics Resources "Max horizontal surface solar fluxes", Big Idea Challenge, National Institute of Aerospace (2017). <u>http://bigidea.nianet.org/competition-basics/</u>
- [17] H. Zhang, D. Jin, and X. J. Zhao, "Low resistivity aluminum alloy of high tensile strength and elongation", Advanced Materials Research, Vol. 676, pp. 3-7, (2013).
- [18] I. J. Polmear "Light alloys: metallurgy of the light metals (3rd ed.)", Wiley, (1995).

- [19] "Mars atmosphere model." NASA, NASA, 5 May 2015, <u>www.grc.nasa.gov/www/k-12/airplane/atmosmrm.html</u>.
- [20] E. Grayzeck, "Mars fact sheet", NASA, 23 December 2016. https://nssdc.gsfc.nasa.gov/planetary/factsheet/marsfact.html
- [21] C. G. Justus and R. D. Braun, "Atmospheric environments for entry, descent and landing (EDL)", Fifth Interplanetary Probe Workshop, Bordeaux, France. pp. 37. (2007).
- [22] D. Edwards, D. Willowby, W. Hubbs, M. Piszczor and M. Bowden "Space environmental effects on the optical properties of selected transparent polymers" (1997). <u>https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19970026598.pdf</u>
- [23] E. A. Moshey, "A compilation of outgassing data on vacuum materials," Princeton Plasma Physics Laboratory Engineering Memorandum, (15 Feb 1982).
- [24] NASA Press Release, May 6 2016. <u>https://www.nasa.gov/feature/ames/sofia/flying-observatory-detects-atomic-oxygen-in-martian-atmosphere</u>
- [25] W. J. Koros, G. K. Fleming, S. M. Jordan, T. H. Kim, and H. H. Hoehn, "Polymeric membrane materials for solution-diffusion based permeation separations," Progress in Polymer Science, Vol. 13, 339-401 (1988).
- [26] T. A. Schaedler, A. J. Jacobsen, A. Torrents, A. E. Sorensen, J. Lian, J. R. Greer, L. Valdevit, and W. B. Carter. "Ultralight metallic microlattices." Science, Vol. 334 (6058), pp. 962-965 (2011).