PAL: The Photovoltaic Array Lander

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In response to the 2018 NASA Breakthrough, Innovative, and Game-changing (BIG) Idea challenge, this paper describes one possible Martian solar array able to deploy 1000 $m^2$ of effective solar area from a 10 $m^3$ launch volume and to maintain itself by actively mitigating dust. The design we describe here consists of a trigonometric ‘flower’ able to slide its petals over each other and mitigate dust through electrostatic shielding. We undertake a systems analysis of the design and find it to be an effective solution for Martian solar power.

I. Introduction

The Red Planet has captured mankind's imagination since even before the advent of science fiction. More hospitable than the closer Venus, Mars is the second stepping-stone out of Earth's gravity well into the rest of the solar system. Mankind has vicariously explored Mars through robotic systems, but that hardly satiates the longing to walk upon the Martian soil. Yet manned visitation to Mars is demanding and will require many considerations, especially energy considerations. Photovoltaics are naturally part of the roll-out of any major Martian power system, but they are challenged by efficiency. Any Martian photovoltaic system will require a large effective surface area, but because the system cannot be fabricated on Mars from native materials, it will have to be packaged for launch from Earth. As such, the system must be able to compress itself into a small volume for the journey to Mars.

Any solution to this problem must also have the following characteristics: it must be able to withstand the launch environment; it must be able to endure the Martian weather; and it must be able to actively mitigate dust buildup.

PAL is one possible solution to this multi-part problem. It addresses the many facets of the problem through its geometry, and it promises to be an effective and flexible solution.

II. Definition of Terms

Bloom The solar array’s deployed configuration, in which the petals lay flat and overlap the least

Bud The solar array’s undeployed configuration, in which the petals overlap the most

Petal An individual photovoltaic wing of the solar array; has its shape defined by one lobe of the PV area defining polar curve

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III. Requirements and Design Focus

The requirements of the 2018 Breakthrough, Innovative, and Game-changing Idea Challenge are as follows:

1. The array must have at least 1000\(m^2\) of total PV cell area per lander
2. The array must have less than 1500\(kg\) of total mass including all mechanical and electrical components
3. The array must have less than 10\(m^3\) total launch volume
4. The array must have a height greater than 0.5\(m\) to avoid wind-blown sand collection
5. The array must have a lifetime of 10\(yr\)
6. The array must be able to endure launch Loads of 5\(g\) axial acceleration, 2\(g\) lateral acceleration, and 145\(dB\) Overall Sound Pressure Level (OASPL)
7. The array must be able to endure up to 50\(\frac{m}{s}\) Martian surface winds
8. The array must be able to endure daily thermal cycling from \(-100\degree C\) to \(25\degree C\)
9. The array must be able to deploy/undeploy at \(-50\degree C\) on terrain with up to 0.5\(m\) surface obstacles and 15\(\degree\) slopes
10. The array must produce positive power output within 1 Martian Sol of landing
11. The array must have integrated dust mitigation and abatement methods

These eleven requirements can be organized into three types: requirements for power production (requirements 1, 5, and 10); requirements for launch (requirements 2, 3, and 6); and requirements for Martian survival (requirements 4, 7, 8, 9, and 11).

There are also several key design factors that must be taken into consideration. These are: Innovation in design; Creativity in operational approach; Technology readiness level; Efficiency in launch packaging; Viability in lander-based deployment; and Reliability in long-term power generation

IV. Concept Overview

PAL is meant to address the Martian photovoltaic solar problem through its unique geometry. Inspired by Mother Natures millennia of experience, PAL has the shape of a polar trigonometric flower, and its petals are able to slide over each other as the system opens from its bud shape to flatten out. This complex 3D motion allows for active dust mitigation, using an electric traveling wave to ward off the electrically charged dust and sand. The petals are solar fabric held taught by a loop of spring wire that can fold to provide an additional degree of compression for the systems launch configuration.

V. Subsystem Overview

A. Structures

In determining the optimal structural configuration, the geometry of flowers offers a unique way to maximize deployment surface area from as small of a volume as possible. This is due to the efficient packaging advantages of a lightweight, high surface area structure. Qualifying the feasibility of an organically-shaped solar array structure is naturally primarily focused on applied theory. This being said the major technologies being applied are as follows:

- Highly flexible, lightweight and efficient PV material
- Spatially optimized geometry of panels that achieve the desired compression factor to meet the packaging requirements.
- Shape-memory material to assist with deployment
1. Geometry

Photovoltaic Geometry

The shape of the photovoltaics is defined by two overlapping polar trigonometric curves, which will be called $r_1$ and $r_2$ for simplicity. Assuming an eight-petaled array, $r_1$ and $r_2$ take the following form:

$$r_1 = B\cos(2\theta) + B\sin(2\theta) \tag{1}$$

$$r_2 = B\cos(2\theta) - B\sin(2\theta) \tag{2}$$

where $B$ is the Cartesian axes intercept. A superposition of sine and cosine has been chosen so the curves together maximize the effective deployed solar surface area of the “flower” for a given number of petals.

The total area enclosed by $r_1$ and $r_2$ can be found straightforwardly through direct polar integration of the two curves from $\theta = 0$ to $\theta = 2\pi$; so:

$$A_T = 2\pi B^2 \tag{3}$$

The area of the overlap of the curves is more tricky, but with the right integration limits and multiplicative factor, it can be found. These limits are $\theta_{\min} = \frac{3\pi}{8}$ and $\theta_{\max} = \frac{\pi}{2}$ and this multiplicative factor is 16. This provides an overlap area of:

$$A_{\text{overlap}} = B^2(\pi - 2) \tag{4}$$

Altogether, this provides an effective deployed solar area of:

$$A_{PV} = A_T - A_{\text{overlap}} = B^2(\pi + 2) \tag{5}$$

One may also ask what the length and width of one of the petals is as a function of $B$. Clearly, $l = r_{\text{max}}$, and one can find $r_{\text{max}} = r_1(\theta = \frac{\pi}{8})$, so:

$$l = B\sqrt{2} \tag{6}$$

The width of the petal requires shifting the curve by a factor of $\frac{\pi}{4}$ such that $r_{\text{shift}} = B\cos(2\theta - \frac{\pi}{4}) + B\sin(2\theta - \frac{\pi}{4})$ and putting some of the curve into Cartesian coordinates. The result of this derivation is as follows:

$$w = 2B \left[ 1 + \frac{2 + \sqrt{2}}{2 - \sqrt{2}} \right]^{-\frac{1}{2}} \approx B(0.766) \tag{7}$$

where $w$ is the width of one petal of the eight-petaled flower.

The curves have a single control parameter—$B$—and naturally the value of $B$ for the required 1000$m^2$ must be known. Clearly, $B_{1000m^2} = \sqrt{\frac{1000}{\pi + 2}} \approx 194.5m$. This leads to a petal length of $l_{1000m^2} = B_{1000m^2}\sqrt{2} \approx 338.4m$. 

![Figure 2. Polar Plot of $r_1$ and $r_2$ for $B = 1$](image)

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and a petal width of $w_{1000m^2} = 2B_{1000m^2} \left[ 1 + \frac{2+\sqrt{2}}{2-\sqrt{2}} \right]^{-\frac{1}{2}} \approx 149.0m$. These dimensions are quite large, and given the array’s ‘resting’ bud-shaped geometry, an additional compression factor is required. This additional factor is discussed below in Section D.

**Array Geometry**

The array’s shape and motion are very close to those of a metal folding vegetable steamer like that seen in Figure 3. However, the array’s petals are more flexible than the steamer’s fins to allow for an additional factor of system size compression.

The steamer-like geometry allows the array’s petals to slide over each other as the array transitions between its “budding” and “bloomed” configurations. This in turn allows for active dust mitigation with the attachment of a static wiper on the overlapping edges. The array’s geometry also provides a protective shape when in its budding configuration, and through partial deployment, the array will be able to produce power and maintain its integrity during weeks-long Martian storms.

**B. Solar**

The BIG Idea Challenge tasks teams with implementing an electronic power system which can withstand the drastic climate on the Martian Surface. On Mars, the daily temperature cycle ranges from $-100^\circ C$ to $25^\circ C$ with winds up to $50\frac{m}{s}$. The goal for the electrical power system is to efficiently capture solar energy and convert that energy to stored chemical energy in the form of a battery.

Currently, most basic photovoltaics consist of a single p-n junction of silicon and dopant to create the “p” and “n” layers of the cell. Silicon, when doped with an atom from Group V, will create the n-type layer; when doped with an atom from Group III, silicon will create the p-type layer. Fusing together both layers results in a large difference in charge. When given enough energy, electrons will move from the valence band to the conduction band; from there, the electrons are free to flow to more positively charged areas known as holes. These free electrons can move from the valence band to the conduction band if they are given enough energy from an outside energy source such as solar photons. If a photon with more energy than the bandgap energy (bandgap energy is the energy required to move an electron from the valence band to the conduction band) of the material strikes the cell, then that electron will be free to flow to a hole in the p-layer, through an electrical connection on both the “p” and “n” layer, overcoming the depletion region between both layers through which electrons cannot cross. If a photon with a less energy than the bandgap energy of the material strikes the cell, then the photon will not be absorbed by the cell.

Therefore it seems logical to seek a material with the lowest bandgap energy to allow for absorption of photons of short and long wavelengths. However, if when striking a material, the bandgap energy is far lower than that of the incident photon, some of the photons energy is lost to a loss mechanism known as electron relaxation (Figure 6). For this reason, most photovoltaics use a semiconductor with a bandgap energy of around $E_g = 1.4eV$. 

![Figure 3. Steel Vegetable Steamer](image-url)
With an efficiency maxing out at approximately 20 percent for flat plate collectors, these photovoltaics are fairly inefficient. This has proven to be the best compromise for absorbing a broad spectrum of wavelengths while maintaining some efficiency. However, at the lower technology readiness level (TRL) required by this competition, more experimental methods of building photovoltaics are viable. One method is to use multiple layers of p-i-n junctions which allows for the usage of multiple materials across one array. The difference between typical p-n junction cells and p-i-n junction cells, is that in the latter three layers are used; as before the positively and negatively doped layers remain, however a third layer is added between the two original layers. The third layer is an intrinsic layer which remains undoped.

By layering three different materials one over another we are able to utilize the benefits of both high and low bandgap energy. The top layer of the cells features the material with the highest bandgap energy, the lower layer have progressively lower bandgap energies. The top layer of the cell will feature gallium arsenide (GaAs), the second layer will be made of germanium (Ge), and the lowest layer will be comprised of gallium antimonide (GaSb). Efficiency from a multiple junction cell similar to this one have reached lab efficiencies of over 30 percent.\textsuperscript{15}

1. \textit{Multiple Exciton Generation}

Research in the area of multi-junction quantum dot solar cells has proven promising in minimizing energy loss. Quantum dots are extremely small semiconductors made to be smaller than the exciton Bohr radius of the atom. By simply changing the quantum dots’ size one can tune the bandgap energy of the dot to a desired bandgap and therefore choose which light is absorbed. These quantum dots can be embedded in a layer of the multi-junction solar cell.

Quantum dot solar cells are interesting due to their intrinsic ability to have their bandgap energies finely tuned. This ability to tune the bandgap energy of an QDSC (quantum dot solar cell) allows for a phenomenon known as MEG(multiple exciton generation). Multiple exciton generation allows for one photon to excite multiple electron-hole pairs as seen in Figure 5.

Typically, when a photon of far higher energy than the bandgap strikes a cell the photon’s extra kinetic energy is lost and converted to heat through phonon emission (Figure 6). However, if the incident photon’s energy is multiple times greater than the bandgap energy of the semiconductor, then it is possible that the photon yields multiple electron-hole pairs.

It is difficult for MEG to occur in bulk collectors due to the fact that the required energy of the incident photon must be many times greater than the band gap energy of the material. Therefore MEG is not a feasible method of increasing efficiency of bulk collectors. However, with the inclusion of quantum dots embedded in the collector, the increase in efficiency MEG brings can be utilized. This is because quantum dots require a much lower incident photon energy for MEG to occur, and thus more light is usable. By embedding Indium Arsenide (InAs) quantum dots into a layer, the cell efficiency can be brought upwards of 40 percent under one sun concentration.\textsuperscript{24} Embedding quantum dots in our solar array would allow us to tune its bandgap energy to allow MEG, thus vastly increasing our efficiency.

2. \textit{Heat Management}

The above stated high efficiency can be quickly lost however, if the cells are not properly cooled. As the cells become warmer, they lose much of their efficiency no matter the type of cell. This is because as
the cell gets warmer, phonons move more frequently throughout the material which impedes the uniform flow of electrons throughout the material. With each one Kelvin increase in temperature, the cell loses an estimated one percent efficiency. To properly cool the cells the array must be outfitted with some passive cooling mechanisms; an interesting technology being developed currently is an integrated system of cones and pyramids on the cell surface. These small cones and pyramids are only microns thick in each dimension and can effectively dissipate heat from the arrays surface\textsuperscript{20} (Figure 7).

![Multiple Exciton Generation Diagram](image)

Figure 6. Multiple Exciton Generation Diagram\textsuperscript{24}

C. Non-Solar EPS

1. Battery

Another crucial part of the EPS that affects efficiency is the type of battery chosen. Different batteries will all feature different efficiencies, emitting a different charge output than the charge inputted. This ratio is known as Faraday efficiency. As well as being efficient, the ideal battery would also have a long cycle life, able to be charged drained and recharged over and over again. The battery that best fits these requirements was found to be an aluminum graphite-urea battery. This battery also has a very high energy density of around 150 Wh/kg and a power density of 1200 W/kg.\textsuperscript{26} Both of these figures are considerably higher than most traditional batteries.\textsuperscript{22}

![Passive Heat Sink Design](image)

Figure 7. Passive Heat Sink Design\textsuperscript{20}

D. Packaging

Due to the large size of the array, a launch compression factor beyond the array’s bud configuration is required. To minimize the mechanical complexity of this additional degree of complexity, we elected to fold the petals. To achieve this, the petals have their individual shape defined by a loop of spring wire. The wire can be deformed by twisting so the petals occupy a smaller volume, and when provided a touch of force, the wire springs back into its undeformed shape, thus unfurling the petals.

E. Deployment

The process of deployment is analogous to the blooming process of a lotus. Each ‘petal’ section is attached to a retractable and collapsible spring wire made of a non-magnetic non-corrosive alloy. Upon deployment, the petals deploy laterally and slide across each other in a rotational motion on its vertical axis.
The deployment of the array is a little tricky due to the need to properly constrain the complex motion of the petals as the array transitions from its launch configuration into its ‘budding’ configuration and as the array moves between its ‘budding’ and ‘bloomed’ configurations. The later motion is far easier to constrain than the former motion; when the petals are moving such that their angle to the vertical is changing, the overlapping between the petals produces a force on each one such that they slide over each other and fan out. This means the blooming and closing of the array can be controlled by a single motor with the proper gear reduction. The motion of the transition from launch configuration to budding configuration involves the unfurling of the spring wire on the edges of the petals. Through a series of latches and actuators on the base of the array, we can keep the petals folded and ensure they can unfurl individually.

F. Dust Mitigation

The Martian topsoil is a loose, fine layer of rock and soil. Martian dust is around 30 micrometers, with storms consisting of even finer particles. It represents a challenge for manned and unmanned missions, having effects including obscuring the solar panel and producing static discharge on the array. The buildup of charge within Martian dust storms can be attributed to the friction between the ultrafine particles of the system, as well as the photoelectric effect. PAL utilizes this phenomenon in its active dust mitigation system. An array of metallic CNT (Carbon-nanotubes) electrodes underneath the panel generates an electrodynamic shield (EDS). Such an array requires an single phase AC source to generate a traveling electromagnetic wave, which repels charged and uncharged particles. Uncharged particles are highly polarizable, possessing an extrinsic dipole moment due to the presence of equal positive and negative particles on their surface. These particles would experience a repulsive dielectrophoretic force caused by the change with the traveling wave. Figure F represents an example of the electrode geometry that would be used in such a case. The force generated can be represented by the force of an electric dipole within an electric field.

\[
\vec{F} = \pi \varepsilon_m r^3 \left[ \text{Re}(f_{CM}) \nabla \cdot \vec{E}^2 + 2 \text{Im}(f_{CM}) \nabla \times (\vec{E} \times \vec{E}_R) \right]
\]

where the particles are spherical dipoles with a permittivity of the medium \( \varepsilon_m \) and \( E_1, E_R \) representing the negative gradients of their respective potentials. The majority of particles have a differing permittivity to their surrounding medium and acts as a component of the force equation for both polarized and non-polarized particles.

The use of metallic Carbon nanotubes as the building material for the electrodes was decided based on its favorable electric and thermal conductivity properties and its rigidity, with a view of building thin films of parallel electrodes adhered to the solar panel. The amplitude of voltage for such a system should be sufficient in the frequency range of 10-50 kHz, which for particles within the range of 10-15 \( \mu \text{m} \) generates a sufficient levitation force to move the particles off the panel.

G. CDH

Computational abilities are required for the deployment of PAL, as well as keeping track of its sensors. Among PAL’s sensors would be a tension sensor to gauge the stress or imperfections on the surface of the flexible PV array, an anemometer and a pressure gauge for environmental measurements and a temperature sensor.
Robust feedback algorithms will control the blooming process such that errors in petal overlay and stress on the PV array may be autonomously fixed. The flight computer must be able to maintain periodic status on the array to regulate power, optimize solar exposure, and initiate blooming. A basic communications system can be embedded to access the deep space network for uplink of commands and downlink of telemetry. Although these tasks may be performed autonomously in the event of a loss of signal.

VI. CONOPS

The undeployed array platform was designed keeping entry descent and landing (EDL) in mind, ensuring that the integration of an EDL system would be straightforward in later design iterations. For the scope of this proposal, the concept of operations begins when PAL is safely on the Martian surface in its launch state. The primary operation consists of the deployment process, with a tentative retraction stage possible in further design iterations. The deployment, or blooming process, starts by releasing the petals from their launch state one by one in order to overlay them correctly. A good way to envision this process is to imagine taking a folded up circular sun shade for the windshield of a car and letting it spring open in sequence with other sun shades adjacent to it. Once every petal is unfolded, actuators can easily adjust the collective angle of the bloomed array and act as a means to resolve any errors during the blooming process. Once bloomed, the petals will be as close to horizontal as possible and power collection will begin.

VII. Array Characterization

Naturally, the array’s power output must be characterized as a function of time of year and latitude to determine its performance. To this end, the challenge provided data on the Martian surface solar power flux in the form of the graph provided in Figure 10a.

![Graph of Martian surface solar flux](image)

(a) Provided Solar Flux Plot  
(b) Array power output as a function of time of year and latitude

Figure 9.

From the graph the data in Table 1 was obtained.

<table>
<thead>
<tr>
<th>Elapsed Sols</th>
<th>50°N Solar Flux (W/m²)</th>
<th>Equator Solar Flux (W/m²)</th>
<th>30°S Solar Flux (W/m²)</th>
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<td>480</td>
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<td>600</td>
<td>100</td>
<td>550</td>
<td>620</td>
</tr>
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</table>
The power output of a PV cell can be described in the following way:\[ P_{\text{out}} = \Phi_{\text{in}} \cdot \eta_T \cdot \cos(\theta) \cdot A \] (9)

where \( \Phi_{\text{in}} \) is the incoming solar power flux, \( \eta_T \) is the product of the cell efficiency with otherwise unaccounted for inefficiencies, \( \theta \) is the angle of incidence between the cell and the incoming power flux, and \( A \) is the area of the PV area. The following simplifying assumptions were made: the PV area is flat and normal to the incoming power flux, and the PV cells do not degrade over the course of time. While not necessarily true, these assumptions allow for an order of magnitude characterization. The following values were naturally chosen for the efficiencies \( \eta_{\text{cell}} = 0.40 \) and \( \eta_{\text{other}} = 0.95 \).

This leads to the characterization documented in Table 2 and Figure 10b.

<table>
<thead>
<tr>
<th>Elapsed Sol</th>
<th>50°N Solar Flux (W/m²)</th>
<th>Equator Solar Flux (W/m²)</th>
<th>30°S Solar Flux (W/m²)</th>
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<tr>
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<td>209.0</td>
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</table>

VIII. Technology Readiness Level & Feasibility

The technologies being used by PAL include the array’s steamer-like motion, the additional spring wire compression factor, an Al-graphite battery and the photovoltaic cells, which may be either GaAs-Ge-GaSb triple layer cell or quantum dot cells.

The steamer-like motion and the spring wire compression as PAL uses them have a TRL of 3; they both have effective proofs-of-concept but nothing more.

The triple-layer and quantum dot PV cells both have a TRL of 4; they have both been tested in laboratory environments.

The Al-graphite battery has a TRL of 6; Angell et. al. built and tested a prototype on the ground in 2016.\[1\]

IX. Reliability & Lifetime

The degree of reliability associated with the system is constrained by the deployment process. If a petal is released and deploys in a non-recoverable way, that compromises the entire systems performance. The long term reliability of the system is robust in that its main constraint is the deterioration of the solar panel performance over time. As previously mentioned, the dust mitigation techniques will alleviate most of the implications of dust collection. The flexibility of the array surface and degree of nominal deflection in the spring wire structure will act as a dampener for any larger debris that could potentially cause a destructive impact had the structure been more rigid. All together, PAL is equipped to last until its solar panels or battery deteriorate.

X. Requirement Satisfaction

1. The array must have at least 1000m² of total PV cell area per lander
   - The array is able to meet this requirement through its high degree of PV area compression.
2. The array must have less than 1500kg of total mass including all mechanical and electrical components
   - Mass budget of the array depends entirely on material choice. Mass estimation of the battery, with a peak power storage of 235.6 kW and a rate of 1200 Watts/kg, lie around 196.3 kg or 13 percent of the total mass.
3. The array must have less than $10m^3$ total launch volume
   • The array is by design able to compress its large PV area into this small launch volume

4. The array must have a height greater than $0.5m$ to avoid wind-blown sand collection
   • Support legs protruding from the base of the array will provide the required height to meet this requirement.

5. The array must have a lifetime of 10yr
   • The lifetime of the array is limited by the solar array degradation and battery degradation rates, which are difficult to quantify due to experimental nature of the cell technology being implemented.

6. The array must be able to endure launch Loads of $5g$ axial acceleration, $2g$ lateral acceleration, and $145dB$ Overall Sound Pressure Level (OASPL)
   • The load tolerances of the system remain undetermined, although there are no remarkably protruding or delicate features in the budding state, which suggests susceptible vibration modes and loading will likely satisfy this requirement.

7. The array must be able to endure up to $50\frac{\sqrt{3}}{str}$ Martian surface winds
   • In its budding state, the drag profile is greatly reduced and the center of gravity lowered, which will be enough to reduce the wind loads such that the system remains anchored.

8. The array must be able to endure daily thermal cycling from $-100^\circ C$ to $25^\circ C$
   • The most sensitive temperature dependency resides within the efficiency of the photovoltaic petals, which can endure the expected temperature ranges. There is concern about proper actuator function at low temperatures, but should be fine given proper use of lubricant. The material selection must also be done carefully, as thermal expansion may compromise system performance or functionality greatly.

9. The array must be able to deploy/undeploy at $-50^\circ C$ on terrain with up to $0.5m$ surface obstacles and $15^\circ$ slopes
   • The only concern with regard to temperature during deployment was that the flexible solar array fabric of the petals would become brittle and compromise the blooming process. Since there are no readily apparent ways in which temperature would reduce the degree of flexibility in the petals, it is of no concern. The geometry of the bloomed petals brings them above the $0.5m$ threshold. The slope of the terrain will result in a potential increase of wind loading, but is predicted to remain statically stable.

10. The array must produce positive power output within 1 Martian Sol of landing
    • The deployment from launch configuration is not a many-step process, so the array would certainly be able to fully deploy within 1 Martian Sol of landing to produce power.

11. The array must have integrated dust mitigation and abatement methods
    • The array certainly meets this requirements through its electric shielding and dynamic cleaning. The point of concern lies in the power consumption of such a system. The voltage drop required depends on the dimensions of the shield layer and the solar fabric itself.

**XI. Conclusion**

With the first human steps on Mars approaching quickly, a preliminary colonial energy grid infrastructure must be established to attain any degree of sustainable presence. While a significant presence requires a much more powerful source of energy, the solar power system we’ve proposed is qualified to provide that critical function. By combining innovative and creative thinking, using technologies that will be ready by the 2030’s, and focusing heavily on packaging through modular design, PAL is capable of providing reliable, long-term power generation in the Martian environment.
References


