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Deployable Solar Array Structure: G1:3

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Deployable Solar Array Structure: G1:3

“Let There Be Light”

AE Senior Design - ISYE4803 Spring 2019

Advisor: Dr. Adeel Khalid

Kennesaw State University’s
Southern Polytechnic College of Engineering
and Engineering Technology

THE SOL-MATES

Daniel Bain- Project Manager, Software Lead
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Submitted: April 29th, 2019
EXECUTIVE SUMMARY

The contents of this paper serve as the report for team SOL-MATES and their deployable solar array structure, the G1:3. For this capstone project, the team is tackling the AIAA Spacecraft Structures project, which is a deployable solar array structure for a spacecraft on a mission from the Earth to Mars. The quantitative and qualitative requirements of this mission are outlined in Table 3.2-1. The reason this project is a priority for AIAA, we believe, is because the industry of solar panels and solar arrays is on the precipice of a breakthrough. This breakthrough will provide the means for mankind will step onto another planet, most likely Mars, in the next 5-10 years.

The preliminary rough calculation showed that to satisfy the stowed volume of 10cm$^3$ with maximum radius of 1.5m, the thickness of photovoltaic cells and including structures needed to be less than 3.2 $\mu$m. To understand space solar technology, the team did an extensive literature review research on NASA current and past missions, and new technology that is still being developed. This project found many dilemmas to address with the given constraints. One of many complications in the proposed project is the Technology Readiness Level (TRL) to complete this project is at TRL-1, meaning the technology is still under research and development, therefore limited data and information are proprietary use only.

The team is committed to complete the project and therefore two models will be constructed. The 2020 model will utilize the thinnest existing production photovoltaic cells and disregarding the stowed volume parameter and the 2040 models will utilize technology that are still theoretical and still being developed at MIT-Lab, but will satisfy the stowed volume constraint.

There are more challenges the team must tackle for our model to reach TRL-9, which are “flight proven worthiness”, but this report will take our project from TRL-1 to TRL-2, which application for an existing technology is formulated for space mission. In order to take this project TRL-3, resources and proprietary information will need to be disclosed for further analytic and experimental proof of concept.
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1 SYSTEM OVERVIEW

1.1 Introduction

This design project is in response to an AIAA RFP (Request-For-Proposal) to build a compact, durable, non-hinged solar array to be deployed from a spacecraft on its way from the Earth to Mars. The solar array structures are used to provide the continual supply of power to operate onboard equipment. A large array will be required but must fit within the fairing of the launch vehicle. Origami principles will be utilized to fit the given constrained stored volume of 10 cm³ while satisfying the power requirements and avoiding structural complications due to tight folds.

1.2 Overview

The system block diagram below explains the system overview for the deployable structure of the solar array. The system must be deployed autonomously without any human interaction and structurally survive the launch load parameters. The assumption for this spacecraft is an unmanned mission to mars carrying Autonomous Rover for exploration.

Figure 1: System Block Diagram
1.3 Objective

The objective of this project is to provide a continuous supply of renewable energy for the onboard equipment. The cost of launching a spacecraft is determined by the size and weight. The larger and heavier the spacecraft is, the higher the cost is of the launch operation of the spacecraft. Because of this, the given volume space for the structure of the solar array must be compact as much as possible.

The team’s objective is two-fold. They will provide and analyze one solar array structure that will satisfy the size constraints given in the RFP. They will also provide and analyze another model that will satisfy the power output, impact, heat, and vibrational constraints given in the RFP.

1.4 Justification

Two models need to be used for the following reasons. After extensive research on the literature review, the thinnest solar cell technology currently exist is 1.3 μm thickness. This is a vapor-deposited parylene substrate solar cell that is being researched at MIT. This solar cell simply doesn’t have the power output needed to satisfy the RFP, but it could satisfy the size requirements.

The second model will use the thinnest production solar cell that is currently available, which is the ELO solar cell from MicroLink. These cells are only 40 microns thick and have a significantly increased power output. However, neglecting the size of a supporting structure, the maximum thickness of our solar cell material to satisfy the minimum surface area and maximum stored volume, would be only 3.2 microns. This is the reason why two models will have to be made. There simply doesn’t currently exist a solar cell technology that will satisfy the size and power output requirements.

1.5 Project Background

1.5.1 IKAROS (Interplanetary Kite-craft Accelerated by Radiation of the Sun)

Ikaros is an experimental aircraft that was developed by Japanese Aerospace Exploration Agency (JAXA). This experimental aircraft is the first spacecraft to use solar sailing as the primary propulsion system. The solar sail is made from polyamide sheet with a thickness of 7.5 micrometer
and part of the sail is integrated with thin solar cells produced by a company Powerfilm Inc to power up onboard equipment of the satellite.

![Figure 1.5-1 IKAROS Solar Sail](image)

The thin solar cells are 25 μm thickness with amorphous silicon (A-Si) thin film. The thin solar cells are using a thin film plastic substrate that accommodate flexibility and add mechanical support to the solar cell components. The structure is thin enough that it becomes flexible rather than break during bending.

### 1.5.2 DeepSpace-1

Deep Space-1 was launched in late October of 1998, with a primary mission to flyby asteroid 9969 Braille to collect data. Its secondary mission was to further the engineering testing of new science technology. DS-1 is the first spacecraft that utilize SCARLET technology (Solar Concentrator Array using Linear Refractive Linear Element Technology). SCARLET is using an 8.5 cm wide aperture of silicone Fresnel lens to focus sunlight to the photovoltaic cells and successfully to concentrate direct sunlight with 1:8 ratio. The evolution of SCARLET technology became what is now called SLA (Stretched Lens Array), using similar guiding principles to SCARLET, but utilizing a lighter pop-up lens, which reduced the mass index tremendously for space mission application. The differentiation between SCARLET and SLA can be seen in figure 1.5-2.
1.5.3 Solar Technology on Previous Space Crafts

Solar Arrays have been the primary power source on most of the space missions to provide continuous power for the onboard equipment for both manned and unmanned spacecraft. The following table provided the information from recent past missions such as solar cell technology, array type, and power capabilities at 1 Astronomical Unit (AU). Most of the solar cells used for most of the missions are triple junction cells. The triple junction cells are using multiple p-n junctions, which were made from different semiconductor material to allow the maximum absorbance of broader range of wavelength. The ability to absorb broader range of wavelengths will translate to improving the efficiency of energy conversion from sunlight to electricity, which leads to a maximum theoretical efficiency of 86.8% at a high concentrated sunlight, comparing to the traditional single junction cells that have a maximum theoretical efficiency of 33.16%.
The limitation of current state of practice in solar array technology can be seen from general trend that is shown on Table 1.5-2. The general trends indicate that flexible fold-out arrays have significant power capabilities such as maximum power output, specific power and power density.

### Table 1 Past Mission Solar Technology

<table>
<thead>
<tr>
<th>Mission Class</th>
<th>Mission</th>
<th>Destination</th>
<th>Launch Date</th>
<th>Solar Cell Technology</th>
<th>Solar Array Technology</th>
<th>Power Capability at 1 AU (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer/planets</td>
<td>Juno</td>
<td>Jupiter</td>
<td>5-Aug-11</td>
<td>Triple junction</td>
<td>Deployable rigid</td>
<td>14000</td>
</tr>
<tr>
<td></td>
<td>Messenger</td>
<td>Mercury</td>
<td>3-Aug-04</td>
<td>Triple junction</td>
<td>Deployable rigid</td>
<td>4500</td>
</tr>
<tr>
<td></td>
<td>LRO</td>
<td>Moon</td>
<td>18-Jun-09</td>
<td>Triple junction</td>
<td>Body-mounted</td>
<td>600</td>
</tr>
<tr>
<td>Inner planetary systems</td>
<td>Lunar Reconnaissance Orbiter</td>
<td>Moon</td>
<td>18-Jun-09</td>
<td>Triple junction</td>
<td>Deployable rigid</td>
<td>1850</td>
</tr>
<tr>
<td></td>
<td>Grill</td>
<td>Moon</td>
<td>10-Sep-11</td>
<td>Triple junction</td>
<td>Deployable rigid</td>
<td>783</td>
</tr>
<tr>
<td></td>
<td>LADDEE</td>
<td>Moon</td>
<td>9-Sep-13</td>
<td>Triple junction</td>
<td>Body-mounted</td>
<td>295</td>
</tr>
<tr>
<td></td>
<td>Mars Global Surveyor</td>
<td>Mars</td>
<td>7-Nov-96</td>
<td>GaAs/Ge and Si</td>
<td>Deployable rigid</td>
<td>2100</td>
</tr>
<tr>
<td></td>
<td>Mars Odyssey</td>
<td>Mars</td>
<td>7-Apr-01</td>
<td>GaAs/Ge</td>
<td>Deployable rigid</td>
<td>2092</td>
</tr>
<tr>
<td>Mars</td>
<td>Mars Exploration Rover (2 rovers)</td>
<td>Mars surface</td>
<td>10-Jun-03</td>
<td>Triple junction</td>
<td>Deployable rigid</td>
<td>390</td>
</tr>
<tr>
<td></td>
<td>Mars Reconnaissance Orbiter Phoenix</td>
<td>Mars Surface</td>
<td>12-Aug-05</td>
<td>Triple junction</td>
<td>Deployable rigid</td>
<td>6000</td>
</tr>
<tr>
<td></td>
<td>MAVEN</td>
<td>Mars</td>
<td>18-Nov-13</td>
<td>Triple junction</td>
<td>UltraFlex</td>
<td>1255</td>
</tr>
<tr>
<td>Asteroids/comets</td>
<td>Deep Impact/EPOXI</td>
<td>Tempel-1</td>
<td>12-Jan-05</td>
<td>Triple junction</td>
<td>Body-mounted</td>
<td>620</td>
</tr>
<tr>
<td></td>
<td>Dawn (with solar electric propulsion)</td>
<td>Vesta, Ceres</td>
<td>27-Sep-07</td>
<td>Triple junction</td>
<td>Deployable rigid</td>
<td>10300</td>
</tr>
<tr>
<td></td>
<td>OSIRIS-REX</td>
<td>Bennu</td>
<td>8-Sep-16</td>
<td>Triple junction</td>
<td>Deployable rigid</td>
<td>3000</td>
</tr>
</tbody>
</table>

LCROSS—Lunar Crater Observation & Seismic Exploration; LADDEE—Lunar Atmosphere Dust & Environment Explorer; MAVEN—Mars Atmosphere & Volatile Evolution; EPOXI—Extraterrestrial Planetary Observation & Characterization Investigation (EPOXI); Deep Impact Extended Investigation (DIXI)

### Table 2 Power Output on Array Technology

<table>
<thead>
<tr>
<th>Array Technology</th>
<th>Maximum power at 1 AU (current state-of-practice), approximate*</th>
<th>Specific power at 1 AU, BOL (W/kg)**</th>
<th>Areal power density at 1 AU, BOL (W/m²)**</th>
<th>TRL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body-mounted array</td>
<td>2 kW</td>
<td>314</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>Deployable rigid array</td>
<td>25 kW</td>
<td>330</td>
<td>330</td>
<td>9</td>
</tr>
<tr>
<td>Flexible-fold-out array</td>
<td>120 kW</td>
<td>338</td>
<td>338</td>
<td>9</td>
</tr>
<tr>
<td>Flexible-roll-out array</td>
<td>25 kW</td>
<td>338</td>
<td>338</td>
<td>7</td>
</tr>
</tbody>
</table>

* Based on demonstrated capability
** Assuming all arrays have SOF triple junction cells

### 1.6 Problem Statement

The challenges for solving this problem are the geometric constraint given and power output requirement. These two parameters are directly related, and therefore they are the driving factors of the design. To generate 250 kW of power output, a large surface area of the solar array is required, while also contending with the geometry constraint of 10cm³ stowed volumes.

The next step of the challenge is a structure which must be hinge-less and autonomously deployed. Utilizing origami principles was encouraged; this and other principles will be explored
to increase the compactness of the design. Therefore, material selection and research of available technology is a priority in this project.

During the process of adapting available technologies to fit the design requirements, several other challenges have presented themselves. Most notably is that there is not currently a design that can hold up to the power requirements while fitting into the volumetric constraints described. We are exploring possible compromises to this dilemma, with favoritism toward volumetric constraints for logistical purposes.

The AIAA representative Professor Merrett clarified a few ambiguities in the RFP. The target output of 250KW is achieved using multiple arrays with each array subjected and limited to 1.5m radius. The updated proposal is to achieve 9.5 KW for each of the array with a flower-like configuration. However, the general trendline of the evolutionary space solar technology are improving overtime and therefore the 2040 model will use future photovoltaic technology.
2 LITERATURE REVIEW

2.1 Photovoltaic cells evolution

Photovoltaic technology has advanced tremendously in the past two decades, it started with cell efficiencies <10% using a single crystal silicone solar cells to a multi-junction cells with efficiency that is >30%. However, there is room for improvement in advanced studies in the sector of a higher power output, high intensity/high temperature environment, low intensity/low temperature environment for missions that heading toward/away the sun.

According to NASA-JPL at the beginning of the space age, solar cells were only capable to produce 15W/kg with efficiency of 10%. (NASA-JPL 2017) Single Crystal silicon cells were used in all space satellites throughout the 1950s. The advancement of solar technology begins with single crystal silicon to a single junction GaAs cells to a dual junction III-V compound semiconductor to a triple junction III-V compound semiconductor.

The current productions of solar array for space mission are produced by three major companies, which are Azure Space, Sol Aero Technology, and Spectrolab. The current space triple-junction space solar arrays can reach 29.8% to 30.7% efficiency at 28°C with assumption solar irradiance of 135 mW/cm². (NASA-JPL 2017)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Status</th>
<th>Silicon</th>
<th>High Efficiency Silicon</th>
<th>Single Junction Ga-As</th>
<th>Dual Junction</th>
<th>Triple Junction</th>
</tr>
</thead>
<tbody>
<tr>
<td>STC Efficiency (%)</td>
<td>Obsolete</td>
<td>12.7 - 14.8</td>
<td>16.6</td>
<td>19</td>
<td>22</td>
<td>26.8</td>
</tr>
<tr>
<td>STC Operating Voltage (V)</td>
<td>Obsolete</td>
<td>0.5</td>
<td>0.53</td>
<td>0.90</td>
<td>2.05</td>
<td>2.26</td>
</tr>
<tr>
<td>Cell Weight (mg/cm²)</td>
<td>Nearly Obsolete</td>
<td>80 - 100</td>
<td>80-100</td>
<td>80-100</td>
<td>80-100</td>
<td></td>
</tr>
<tr>
<td>Temp Coefficient at 28°C (%)</td>
<td>Obsolete</td>
<td>-0.0055%</td>
<td>-0.0021%</td>
<td>-0.0019%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cell Thickness (μm)</td>
<td>Obsolete</td>
<td>50 - 200</td>
<td>76</td>
<td>140 to 175</td>
<td>140 to 175</td>
<td>140 to 175</td>
</tr>
<tr>
<td>Radiation Tolerance (%)</td>
<td>Obsolete</td>
<td>0.66 - 0.77</td>
<td>0.75</td>
<td>0.80</td>
<td>0.84</td>
<td></td>
</tr>
<tr>
<td>Absorptance</td>
<td>Obsolete</td>
<td>0.75</td>
<td>0.89</td>
<td>0.91</td>
<td>0.92</td>
<td></td>
</tr>
<tr>
<td>Vendors</td>
<td>Spectrolab,</td>
<td>ASE, Sharp</td>
<td>Spectrolab,</td>
<td>Spectrolab,</td>
<td>Spectrolab,</td>
<td>Emcore, Spectrolab,</td>
</tr>
</tbody>
</table>

(*) Fractional output after exposure to $10^5$ 1 MeV electrons per cm².

Table 3 Summary of Space Solar Cell Performance

Note: Reprinted from Solar Cell and Array Technology for future Space Mission pg.05
2.2 Space mission solar array designs

The current solar array can be divided into six categories which include: Body-Mounted Array, Rigid Panel Planar Arrays, Flexible Panel Array, Flexible Roll-Out Arrays, Concentrator Arrays, High Temperature / Intensity arrays, and Electrostatically Clean Arrays. Each of the six had their own advantages and disadvantages as listed below:

- Body Mounted Array: This is the early model design of solar array that is designed for spherical satellite and spin cylindrical satellite that uses silicone as the solar cells structured in the honeycomb panels that mounted on the side of the spacecraft body. This type of array is reliable and used in a short planetary rover mission. (NASA-JPL 2017)

![Body Mounter Array](image1)

---

- Rigid Panel Planar Array: A rigid commercial array with specific power output 40-60 W/kg and mainly used in earth orbiting mission. (NASA-JPL 2017)

![Rigid Panel Planar Array](image2)

---

- Flexible Panel Array: Flexible fold-out array that has a very high packaging efficiency (stowed volume) with high specific power output. Array will be deployed in space and stowed in the fairing of the spacecraft during launch sequence. (NASA-JPL 2017)

![Flexible Panel Array](image3)
• The Flexible Roll-Out Array: Similar concept with accordion type solar array except the flexible substrate is rolled into a cylinder before the array is deployed. The array deployed by tubular, extendable boom (Bi-STEM) deployment system. (NASA-JPL 2017)

• Concentrator Array: This type of array is using a refractive optics to concentrate the sunlight onto an active cell area. The concentrator method able to increase the power output 7.5x concentration ratio, such as SCARLET array that are used in DS-1 mission. (NASA-JPL 2017)
• High Temperature/ Intensity Array: These arrays are used in the inner planetary mission and using a modified rigid panel array by replacing the Si cells with mirrors to cool down the array. This type of array is not mass efficient and unable to operate in condition >200°C. (NASA-JPL 2017)
• Electrostatically Clean Array: The solar cells are coated with a conductor such as indium tin oxide. These types of array do not allow voltage to distort the plasma. (NASA-JPL 2017)

2.3 The Epitaxial lift-off (ELO) Solar Cells by MicroLink

The Epitaxial Lift-off is a process technique that enable thin epitaxial layer grown on GaAs substrate to be peeled off from the host substrate and then transferred onto a different substrate that are thin, flexible, lightweight, and with a higher thermal conductivity material. The fabricating method is called Metal Organic Chemical Vapor Deposition (MOCVD). The Epitaxial Lift- Off Process are shown in figure 2.3-1. (Epitaxial Lift Off n.d.)
2.4 In Situ Vapor-Deposited Parylene-C Substrates with Organic Photovoltaic Cells

Most common substrate material that is utilized in solar panel industry are glass, which provides protection to the sensitive material from exposure to foreign material and water vapor. It is also provided a smooth, flat and robust surface for the solar cells. However, glass substrates are heavy and add a considerable amount of thickness to the solar array. Typical glass substrate thickness ~3mm in thickness and weights~8kg/m\(^2\), therefore, glass or plastic substrate are not ideal for space mission solar array.

Eni-MIT- Solar Frontier Center developed a new substrate that demonstrate lightweight and flexible using methodology growing in situ thin polymer film as a substrate and as encapsulation of organic photovoltaic cells fabricated in between as shown in figure 2.4-1. The solar cell consists of vapor-deposited metal oxide, molecular organic film, and metal electrodes. This state-of-the-art technology are the thinnest and the lightest among the solar cell industries with the thickness <1 μm and weight factor of 3.6g/m\(^2\) and power output per unit area of 21.6 w/m\(^2\). (Jean, Wang and Bulović 2016)

![Figure 2.4-1 Parylene Substrate Encapsulation](image)

2.5 Nitinol Muscle Wires

Nickle Titanium wire was selected for the deployment actuation mechanism. Given that the deployment of the solar array takes place outside of the noticeable effects of Earth’s gravity, there is no need for structural support beyond a passive tension to resist small changes in inertia.
as the space craft maneuvers smoothly throughout its mission. Nickle Titanium has been studied for many years NASA has examined its unique properties as early as the 1960s.

The appeal of Nitinol is that when heat or an electric current is applied to the wire the wire will morph into a predefined shape. This shape is programmed into the wire by holding the wire in the desired shape and heating the wire to temperatures in excess of 1000 degrees Fahrenheit for a defined period. The forces required to unfold the solar array are small enough that with the application of an electric current to the wire in the designed sequence will unfold the solar array from a sector shape to a fully deployed circle.

<table>
<thead>
<tr>
<th>Wire Name</th>
<th>Wire Diameter (microns)</th>
<th>Linear Resistance (Ω/m)</th>
<th>Typical Current (mA)</th>
<th>Deform. Weight** (grams)</th>
<th>Recovery Weight** (grams)</th>
<th>Typical Rate** (LT/HT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexinol 025</td>
<td>025</td>
<td>1770</td>
<td>20</td>
<td>2</td>
<td>7</td>
<td>55/na</td>
</tr>
<tr>
<td>Flexinol 037</td>
<td>037</td>
<td>860</td>
<td>30</td>
<td>4</td>
<td>17</td>
<td>52/68</td>
</tr>
<tr>
<td>Flexinol 050</td>
<td>050</td>
<td>510</td>
<td>50</td>
<td>8</td>
<td>35</td>
<td>46/67</td>
</tr>
<tr>
<td>Flexinol 075</td>
<td>075</td>
<td>200</td>
<td>100</td>
<td>16</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td>Flexinol 100</td>
<td>100</td>
<td>150</td>
<td>180</td>
<td>28</td>
<td>150</td>
<td>33/50</td>
</tr>
<tr>
<td>Flexinol 125</td>
<td>125</td>
<td>70</td>
<td>250</td>
<td>45</td>
<td>230</td>
<td></td>
</tr>
<tr>
<td>Flexinol 150</td>
<td>150</td>
<td>50</td>
<td>400</td>
<td>62</td>
<td>330</td>
<td>20/30</td>
</tr>
<tr>
<td>Flexinol 200</td>
<td>200</td>
<td>32</td>
<td>610</td>
<td>116</td>
<td>590</td>
<td></td>
</tr>
<tr>
<td>Flexinol 250</td>
<td>250</td>
<td>20</td>
<td>1000</td>
<td>172</td>
<td>930</td>
<td>9/13</td>
</tr>
<tr>
<td>Flexinol 300</td>
<td>300</td>
<td>13</td>
<td>1750</td>
<td>245</td>
<td>1250</td>
<td>7/9</td>
</tr>
<tr>
<td>Flexinol 375</td>
<td>375</td>
<td>8</td>
<td>2750</td>
<td>393</td>
<td>2000</td>
<td>4/5</td>
</tr>
</tbody>
</table>

* Multiply by 0.0098 to get force in Newtons
** Cycles per minute, in still air, at 20 Centigrade
LT = low temp 70°C, HT high temp 90°C

Table 4 Flexinol Specification
3 DESIGN APPROACH

3.1 Problem Solving Approach

The ultra-thin solar array is still in research and development stage and therefore in commitment to completing the project, the team decided to break the project into two sections which are 2040 theoretical ideal model and 2020 deliverable model. The 2040 theoretical ideal model is a model that will satisfy the geometric constraint without sufficient power output for the onboard equipment. The technology for the proposed model is still undergoing research and development stage, and not available for production yet. The 2020 deliverable model is be the model that the prototype will be based on with available production solar cell that insinuate the given output requirement with an attempt to comply with stowage volume constraint.

3.2 System Requirements

The preliminary geometric calculation indicates that the thickness of the solar array must be between 3.2 μm and 6 μm depends on the radius selection of 1 to 1.5 m to satisfy 10cm³ stored volume constraint. The power output of 9.5kW is a primary criterion that must be sought for. The correlation between power output and the area of the array are proportional due to the effective efficiency of the array to capture solar energy.

<table>
<thead>
<tr>
<th>Category</th>
<th>Priority</th>
<th>Description</th>
<th>Value</th>
<th>Comment/Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometry and Dimensions</td>
<td>8</td>
<td>Deployed Radius</td>
<td>1m to 1.5m</td>
<td>Research Phase</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>Stored Volume</td>
<td>10 cm³</td>
<td>Research Phase</td>
</tr>
<tr>
<td>Vibration</td>
<td>7</td>
<td>Launch Vibration Launch Direction</td>
<td>25g</td>
<td>Research Trade Study</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>Launch Vibration Lateral Direction</td>
<td>15g</td>
<td>Research Trade Study</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>Launch Vibration Frequency</td>
<td>100Hz</td>
<td>Research Trade Study</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>Deployed Vibration Magnitude All Direction</td>
<td>1 g</td>
<td>Research Trade Study</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>Deployed Vibration Frequency</td>
<td>1.5 Hz</td>
<td>Research Trade Study</td>
</tr>
<tr>
<td>Temperature Operation</td>
<td>9</td>
<td>Minimum Temperature for Deployment</td>
<td>-100 Celcius</td>
<td>Research Trade Study</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>Maximum Temperature for Deployment</td>
<td>100 Celcius</td>
<td>Research Trade Study</td>
</tr>
<tr>
<td>Performance and Functionality</td>
<td>7</td>
<td>Power Output</td>
<td>250kW</td>
<td>Research Trade Study</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>Micrometeorite Impact Functionality of 100mg @ specific gravity 8 and 25 km/s</td>
<td>Yes</td>
<td>Research Trade Study</td>
</tr>
</tbody>
</table>

Table 5 System Requirement
3.3 Mission Profile

The Mission Profile for this project can be seen below in figure 3.3-1. The mission is divided into 9 sections, which includes mission launch to arrival in high Mars orbit. The RFP specifies the requirement to withstand strong vibrations of 25Gs at 100hz, this vibration would be felt between the 0th and 2nd point on the mission profile while the solar array is folded and onboard the launch rocket. Deployment of the solar array will occur at point 3 when the spacecraft is free from the rocket and has just entered low earth orbit. Once deployed the solar array will experience vibrations of 1G in all directions as it makes its way through the rest of the flight.

Points 5 and 6 may vary as the spacecraft awaits the system checks before leaving orbit for point 7, the lunar slingshot, to save fuel on the trip to Mars. The longest leg and smoothest segment of the flight by far is point 8, the Mars Transfer Trajectory. Once the trip from Earth’s orbit to Mars Orbit is complete Point 9 marks the entry to Mid to High Mars orbit and the mission for the Solar Array is complete.
3.4 Technology Readiness Level

Technology Readiness Level is a NASA measurement system to assess the maturity level of a particular technology. The measurement system is evaluating the given requirement parameter of the project based on the progression of the particular project. The technologies are subjected to analytical validation and experimental validation. The new technology also needs to be demonstrated the functionality in the environment where technology will be operated.

At this time the technology readiness level of the theoretical device is at approximately level one. Meanwhile the technology readiness level for the deliverable model is at approximately level three.
3.6 Design Matrices

Design Matrix is created to give guidance on which design parameter is important to the project and which finalize design as the primary design. The design matrix showed that...
compactness, reliability and low maintenance as a primary parameter to our designs. The secondary parameters to incorporate into our design will be durability and integrity.

![Design Matrix](image)

Figure 3.6-1 Design Matrix

![Weighted Matrix](image)

Figure 3.6-2 Weighted Matrix
3.7 Project Management

This project is coordinated by Craig Patton as project coordinator and weekly meeting is conducted with Andrew Tendean as resource manager and Engineering manager and Daniel Bain as project manager and software leads. Gantt Chart are employed as our guideline to meet the deadlines for each phase of the project. Each team member is involved in each phase of the project and correlates with their specific roles. Each team member has an open channel communication throughout the duration of the project, where any available data are shared in a common cloud-based drive.

3.7.1 Responsibilities
Discuss the roles each team member had in the research, design, analysis, management, and execution for all of the project components.

Ideation and research are conducted as a team and each team members played their role throughout the project. The list below showed each team member responsibilities:

- Craig Patton- Coordinate, research, ideation, analysis, prototyping, calculation, primary editor, purchasing liaison, video production, block diagram.
- Daniel Bain- CAD modeling and assembly, research, design, ideation, prototyping, graphics and video production, mission profile, calculation, first-iteration block diagram, material properties input for analysis.
- Andrew Tendean- Technical writer, ideation, research, calculation, editor, prototyping, purchasing liaison, production of design alternatives and MISC additional visual aids, technology historian.
3.8 Resources Available

The primary advisor for this project is Dr. Adeel Khalid of Kennesaw State University and Professor Craig Merrett as an AIAA representative. The Kennesaw State University library department also assist conducting researched and attaining required literature reviews to study past projects and existing new technologies.

The prototype is built to be as closed as the 2020 model specification as possible. CNC cutting machine is used to cut 10 mil plastic which is 254 μm thickness on the first round of prototype. As a final model prototype, 13 μm thickness are used as substrate and 50 μm plastic as PV cells.
4 DESIGN CONCEPTS

4.1 The 2040 Model (Origami B-Roll Solar Array)

This design is inspired by origami-based design that was researched by MIT students in the past. The goal of this design is to be able to compactly fold the array without repeating of the same fold line, which may cause to break a circuitry if multiple folds were occurred. Origami is considered as a compliant mechanism which eliminates the use of hinge joint which reduced the weight associated with the design.

Other advantages of compliant mechanisms applied in aerospace structures are eliminates required lubricants, motorization, reduced friction wear, and ease of miniaturization with pre-defined folds. The simultaneous folds allowed for the structured to compactly folded with a high ratio between stowed and deployed area. This is very advantageous in space missions due the limiting factor in a spacecraft.

![Theoretical Origami Model](image_url)
4.2 The 2020 Model (Foldable Sector Array)

The 2020 model is utilizing sector array with 3 folds and totaling 8 sectors. The simplicity of the design is to prevent repetitive folding on the same crease line which can break the circuitry of the system. The Nitinol wire will be embedded on the perimeter of the array and to deploy the array, a current will run on the Nitinol wire causing the effect of the wire to contract/expand to the predefined shape, in this case, it will the shape of deployed array.
4.3 Photovoltaic Cells Selection

4.3.1 Theoretical Models 2040

The theoretical model will satisfy the volumetric constraints given in the request-for-proposal (RFP), by using experimental solar cell technology in situ vapor deposited Parylene-C substrate. This is an organic material solar cell that has a thickness of 1.3 μm which satisfy the volumetric constraint of 3.2 cm$^3$ with room for deployment structure (Total of 10 cm$^3$). The Nano technology is still under further research and development with potential improvement in efficiency and power output.

The proposed solution for 2040 models is to combine the flexible thin film array with concentrator array, specifically the SLA. The concentrator array can increase the output of the in-situ vapor deposited Parylene-C by 8.5x from the original power output per unit area of 21.6w/m$^2$ to 183.6 w/m$^2$. With the surface area of 7.07m$^2$, the power output can significantly increase from 153 watts to 1.29 KW for each of the array.

4.3.2 Deliverable Models 2020

The 2020 deliverable model will utilize ELO photovoltaic cells by MicroLink, along with the same Nitinol wire deploying mechanism as the 2040 theoretical model. This model will satisfy the power output (as close as current technology can be) as well as the launch and deployed vibrational loads.
4.4 Deploying Mechanism Material Selection

Nitinol is Nickle -Titanium alloy that exhibits unique properties under heat and electric current. With the application of either of these a wire made of this material will revert back to its originally “programmed” shape regardless of the configuration that it is in at the time that the current is applied.

Nitinol with a diameter of approximately 0.020 inches is capable of lifting 16 lbs. (about 71 Newtons). Since the deployment of the solar array will take place outside of the noticeable effects of earth’s gravity, this force is adequate for the task. In the figure below, you can see the stress strain diagrams with respect to temperature.

Stress-Strain Characteristics of Nitinol at Various Temperatures

Figure 4.4-1: Stress-Strain of Nitinol

4.5 Solar Wind

Our design will deploy in an environment devoid of an atmosphere. The Earth’s atmosphere is responsible for shielding the surface from radiation phenomena. One of these phenomena’s is Solar Wind. Solar wind has been considered as a propulsion method for large solar sails. With this fact in mind, our team investigated the pressure and resultant force on the structure of our 2020 deliverable solar panels. We found that the resulting force exerted on the solar array
is approximately 4.24e-08 Newtons. This has a negligible effect on the performance and dynamics of the array.

![Solar Wind Diagram](https://en.wikipedia.org/wiki/Solar_wind)

**Figure 4.5-1: Solar Wind**

5 ENGINEERING ANALYSIS

In this section we will be talking about the analysis done on the 2020 Deliverable model. The first three tables below show a linear dynamic harmonic analysis done on the deployed configuration of the 2020 deliverable model.

Figure 5-1: 2020 Deployed Mesh

Figure 5-1 above shows the mesh done on the model. Because this model is so thin, we used the shell mesh feature in order to simulate all of these analyses. This simulation has the deployed model subjected to 1G in all directions at a frequency of 1.5 Hz. The stress curve is shown below. The max stress experienced by the ELO solar array is 3.75e+05 Pa, located in the center.

Figure 5-2: 2020 Deployed Stress
The max displacement is 7.8 mm, also located in the center. You can clearly see that the gallium-arsenide (GaAs) ELO solar cells by MicroLink can handle this load and frequency.

The two figures below are simulations done on the folded configuration 2020 deliverable model using GaAs ELO solar cells. These have been subjected to 15G’s laterally at a frequency of 100 Hz. Below is the mesh of the model, again using surface shell meshing.
The figure above, Figure 5-5 shows the results of this simulation. There is zero damage done to the GaAs solar structure. We are concluding that this is from either a) incomplete material property data for SolidWorks to compute from, or b) the model is too fragile at that frequency, and SolidWorks refuses to compute it. Either way, we know from these simulations that gallium-arsenide ELO solar cells are not strong enough to satisfy the RFP requirements set forth from AIAA.
6 RESULTS AND DISCUSSIONS

As shown in the analysis section above, gallium-arsenide ELO solar cells will not be sufficient to withstand the 15G/25G at 100Hz set forth in the RFP. Table 6-1 shows the basic metrics of the two models. The 2040 model column shows the output of the MIT parylene solar cells constrained to the dimensions of the RFP. The 2020 model column shows the output of the ELO solar cells at the same surface area.

<table>
<thead>
<tr>
<th>CRITERIA</th>
<th>2040 Theoretical Model</th>
<th>2020 Deliverable Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Area of 1 Model</td>
<td>7.07 m²</td>
<td>7.07 m²</td>
</tr>
<tr>
<td>Volume of 1 Model</td>
<td>10 cm³</td>
<td>375.8 cm³</td>
</tr>
<tr>
<td>Mass of 1 Model</td>
<td>40g</td>
<td>1.65 kg</td>
</tr>
<tr>
<td>Power Output of 1 Model</td>
<td>152.7 W</td>
<td>1767.5 W</td>
</tr>
<tr>
<td># Models needed for 250kW</td>
<td>1638</td>
<td>142</td>
</tr>
<tr>
<td>SA needed for 9500W</td>
<td>440 m²</td>
<td>38 m²</td>
</tr>
<tr>
<td>Volume needed for 9500W</td>
<td>623 cm³</td>
<td>2255 cm³</td>
</tr>
<tr>
<td>SA Needed for 250kW</td>
<td>11,574 m²</td>
<td>1000 m²</td>
</tr>
<tr>
<td>Volume needed for 250kW</td>
<td>16,372 cm³</td>
<td>53,363.6 cm³</td>
</tr>
<tr>
<td>Total Mass at 250kW</td>
<td>65.5 kg</td>
<td>234.3 kg</td>
</tr>
<tr>
<td>Thickness</td>
<td>2 µm</td>
<td>53µm</td>
</tr>
</tbody>
</table>

Table 6-1: Final Design Results

You can see that our 2020 model (today’s technology capabilities) produces a solar array that is 376cm³ and outputs 1768W. In order for the 2040 Theoretical model to satisfy the new RFP requirements, the technology has to be as such to accomplish the following:

- **Surface Area:** 7.07 m²
- **Volume:** 10 cm³
- **Thickness:** 1 um or less
- **Power Output:** 9500 W
- **Specific Power Output:** 1344 W/m²
- **Material Stress/Strain:** Roughly equivalent to Nylon (plastic)
In summary, the team has researched and analyzed the current solar cell technology of April 2019 and found it lacking to the performance standards required by this AIAA RFP. The team has specified the technology and material property requirements necessary for such constraints to be met, and we have successfully attained/met our minimum success criteria.
Given the current state-of-the-art technologies commercially available, our 2020 deliverable model is capable of producing 1767.5 Watts while remaining relatively compact with a volume of 375.8 cubic centimeters. This is significantly higher than the RFP’s desired 10 cubic centimeter constraint. It should be noted that this power output is above what most spacecraft have historically drawn from solar panels. Our designs are state-of-the-art yet fall short of fully satisfying the RFP criteria at this time.

The outlook for the technologies being developed for our 2040 design are favorable for the specifications dictated in the RFP. Even so, the power output is still less than desired at 152.7 Watts. The volume constraint is, however, satisfied in the 2040 design with the use of significantly thinner material. This material is currently under development at the Massachusetts Institute of Technology.

With improvements in manufacturing techniques and with the advent of new materials and technologies the scale and availability of ultra-thin solar cell technology will become more prevalent. The key to the fulfillment of all the design criteria for this project lies in the power density, flexibility, and compactness of the material. Materials such as Gallium Arsenide will serve a bridge between these technologies and will eventually be replaced with materials that are more flexible when folded. While there is much left to be desired of existing solar energy harnessing technologies, our team remains optimistic that further developments will eventually render the entire scope of this project a probable energy solution for missions from Earth to Mars and beyond.
REFERENCES


9 APPENDICES

9.1 Appendix A: Acknowledgement

We would like to express our appreciation to Dr. Adeel Khalid as our Aerospace Engineering Advisor and Department of Industrial and System Engineering of Kennesaw State University to give us guidance and resources to complete our project. We are also would like to express our gratitude to other faculty members of Kennesaw State of University that played part in our education and completing this project. We are also would like to say thank you to friends and family that have given us support and inspiration in our journey in continuing education.

9.2 Appendix B: Contact Information

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9.3 Appendix C: Geometry Calculation

9.3.1 Deliverable Model

Figure 9.3-1: Deliverable Model Geometry Calculation
9.4 Appendix D: Past Executive Summaries

The contents of this paper serve as the report for team SOL-MATES and their deployable solar array structure, the G1:3. This report is written up through the Preliminary Design Review, and as such, is only partially complete.

For this capstone project, the team is tackling the AIAA Spacecraft Structures project, which is a deployable solar array structure for a spacecraft on a mission from the Moon to Mars. The quantitative and qualitative requirements of this mission are outlined in Table 3.2-1. The reason this project is a priority for AIAA, we believe, is because the industry of solar panels and solar arrays is on the precipice of a breakthrough. This breakthrough will provide the means for mankind will step onto another planet, most likely Mars, in the next 5-10 years.

As was discussed in the presentation, the approach the SOL-MATES will be using to accomplish this goal is as follows. The team will construct and analyze two different solar array structures. The first, called the Theoretical Model, will satisfy the volumetric constraints given in the request-for-proposal (RFP). It will do this by using experimental solar cell technology that is currently being researched by the solar lab at MIT. The second model, called the Deliverable Model, will satisfy the power output, as well as the launch and cruise vibrational requirements. We will accomplish this by using the thinnest currently commercially available solar cell technology, which is the Epitaxial lift-off (ELO) solar cells being produced by MicroLink. We will discuss in chapter two of this paper the literature review, and why this two-part delivery was chosen.

Since the IDR presentation, the team has done hours and hours of literature review searching for the materials that would make this project possible. The team also constructed several different folding models, all of which would depend on the material choice, because of cell thickness. The team has also found more resources on campus relevant and beneficial to this project, including two different professors specializing in solar cell research.

For the final paper, this executive summary will be rewritten. This section currently serves as the Design Review update section.
The contents of this paper serve as the report for team SOL-MATES and their deployable solar array structure, the G1:3. This report is written up through the In-Progress Review, and as such, is only partially complete.

Since the PDR presentation, the team has done more research and literature review, and found more justification to our approach. We’ve found papers from NASA’s JPL describing past and current spacecraft, the solar cell technology we have used, are using, and will be using in near future missions. They describe the efficiencies, specific weights, specific power outputs, material composition, and cell thicknesses of all the currently available solar cell technology branches.

The team has also begun preliminary CAD work, including modeling the theoretical model in deployed and folded configurations, as well as the deliverable model in deployed and folded configurations. The team is currently working on the modelling of the Nitinol wire structure in its folded and deployed configurations for each model. After these structures are meshed with their frames, simulations will be done in SOLIDWORKS. These simulations will be FEA, drop test, vibrational analysis, and fatigue.

The challenges faced in the last couple weeks were the same ones as before the PDR presentation. We have reached out to the AIAA contact for this assignment about clarification on materials since we couldn’t find material that would satisfy all requirements. We will continue in this split-deliverable approach unless we hear back from Professor Merret again. Our goal has been, and will continue to be, to produce our best work with materials we can gather information on. The budget for this project is quite abstract since the theoretical model is experimental material. However, for the deliverable model, the team has requested quoted on materials from suppliers. The team is on schedule to have analysis done in two-to-three weeks, and prototyping is already underway.

For the final paper, this executive summary will be rewritten. This section currently serves as the Design Review update section.
The contents of this paper serve as the report for team SOL-MATES and their deployable solar array structure, the G1:3. This report is written up through the Critical Design Review, and as such, is only partially complete.

Since the In-Progress Design Review presentation, the team received confirmation through Professor Merrett regarding ambiguity in the RFP. With the clarification on the RFP, which indicates the target power output are achieved via multiple array configuration with petal-flower like configuration and each petal are subjected to 1.5 m radius with target output of 9.5KW for each of the array. Thus, the clarification helped the team getting closer to the power output criterion, however the photovoltaic cells technology to meet the stowed volume of 10cm³ is still being researched and development. The photovoltaic cells technology had improved significantly overtime and following the trendline, the trajectory on technology to be available for production will put the theoretical model to the “2040 Model”

The meeting with Dr. Khalid also helped the team to understand further regarding the Technology Readiness Level Chart that is created by NASA to rate the level of technology to be “flight proven technology”, where a complete system is proven with validation via analytical and experimental as well demonstration at the environment the system will be operating. The extensive researched that is conducted by the team has put the project at TRL level 1 with a target after completing this project will put the project to TRL level 2, where technology concept and application are formulated.

The team also successfully prototype the deliverable model with the required parameter as close as possible to the thickness of “The 2020 Model”. Although, the 2040 theoretical model are very similar to the 2020 model, the team haven’t abandoned the idea to incorporate origami principle to add compactness to the design. The second prototype is also underway to understand how origami principles behave and will add value to the project.

For the final paper, this executive summary will be rewritten. This section currently serves as the Design Review update section
Figure 9.5-1: CAD Dimensions
Figure 9.5-2: CAD Dimensions 2

Figure 9.5-3: CAD Dimensions 3
The prototype model was constructed using 50-micron thick black plastic sheeting taped onto 12.3-micron gold mylar sheeting. This gave the 2020 deliverable model prototype an overall thickness of 62.3 microns, compared to the CAD model of 52.3 microns. This is really close. The surface area and diameter are the same as the CAD model.