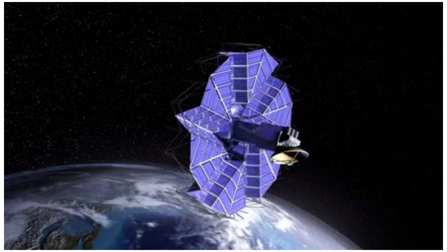
G1:3
Deployable Solar Array Structure



ISYE 4803/Spring 2019

SOL-Mates:

Daniel Bain: Project Manager, Software Lead

Craig Patton: Project Coordinator, Technical Expert

Andrew Tendean: Engineering Manager, Resource Manager

Advisor: Dr. Adeel Khalid

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Problem Statement

- AIAA RFP for Deployable Solar Array Structure
- Spacecraft on a mission to Mars from the Earth needs a supply of electricity
- Design a deployable, folding solar array structure that can withstand the launch forces, vibrations, and the forces/vibrations experienced while deployed

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Design Requirements & Specifications

Size Requirements:

- Deployed radius of 1-1.5m
- Stored volume of 10 cm^3

Performance

- Launch Vibrations: 25G axially, 15G laterally at 100+ Hz
- Deployed Vibrations: 1G in all directions at 1.5 Hz
- 250 kW power output
- Temperature range of –100°C to 100°C
- Continuous functionality after impact from micrometeorite at 25 km/s

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Revised AIAA-RFP

Updated Requirements from Professor Merrett 3.26.19

- 250KW target power output:
  - Achieved by multiple array configuration.
  - Each array limited to 1.5m deployed radius.
  - Each array with a maximum output of 9.5KW.
  - Each array subject to 10 cm^3 volume
- Technology Readiness Level (TRL):
  - TRL 1: Utilizing R&D photovoltaic cells <2um thickness
    - MIT has built and analyzed an experimental proof-of-concept

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Minimum Success Criteria / Solution Proposal

2040 Theoretical Model

- Satisfy volume and surface area constraints
- Projected area on spacecraft to be comparable to recent spacecraft
- Specify technology requirements to meet RFP criteria

2020 Deliverable Model

- Satisfy launch and deployed vibrational analysis
- Volume to be as small as possible for current production solar cell technology
- Ability to continue operation after small impact

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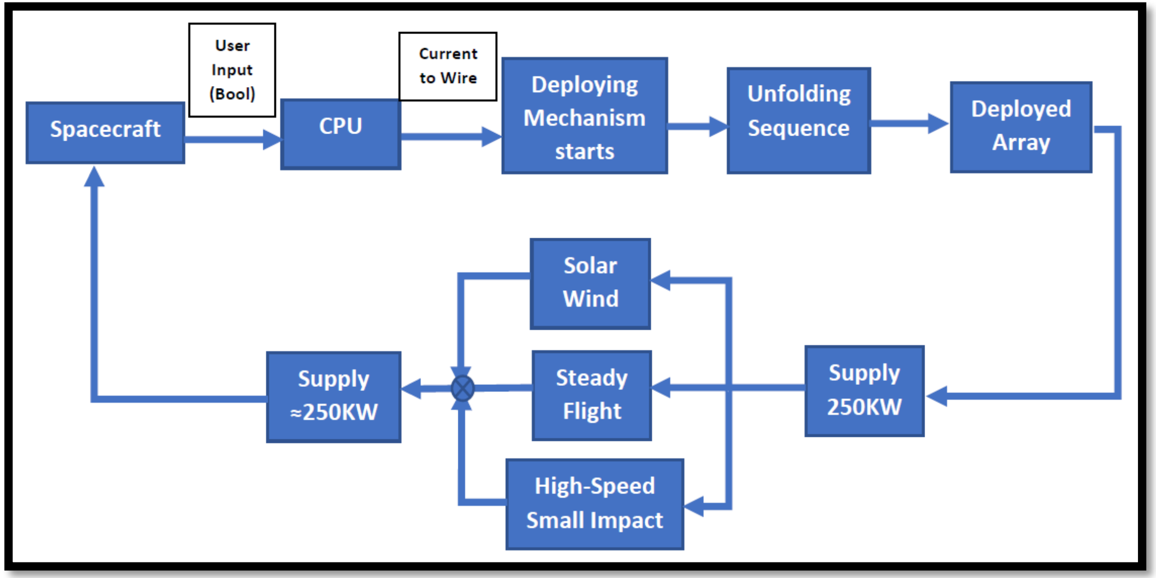
System Block Diagram



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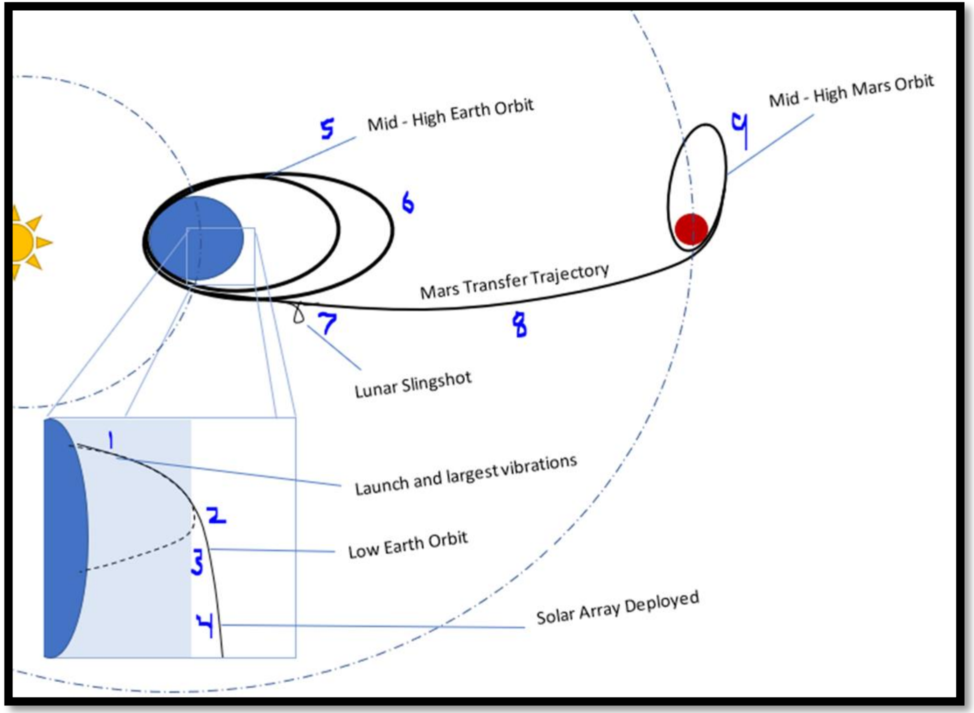
Mission Profile

1. Launch from Earth
2. Travel to low orbit
3. Reached low orbit
4. Solar Array Deployed
5. Reached mid-high Earth orbit
6. Lunar slingshot
7. Second lunar slingshot
8. Mars Trajectory
9. Reached mid-high Mars orbit



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Design Matrices

Decision Matrix	ML	MC	C	S	LM	R	D	EF	SP	AS	Total	Weight	Final Score
Minimal Labor (ML)	-	0.5	0	0	0	0	0	1	1	0	2.5	1.17	2.92
Minimal Cost (MC)	0.5	-	0	0	0	0	0	1	0.5	1	3	1.50	4.50
Compact (C)	1	1	-	1	1	0.5	1	1	1	1	8.5	3.50	29.75
(Integrity) Safety (S)	1	1	0	-	0.5	0	0	1	1	1	5.5	2.50	13.75
Low Maintenance (LM)	1	1	0	0.5	-	0	0.5	1	1	1	6	2.67	16.00
Reliabilitity (R)	1	1	0.5	1	1	-	1	1	1	1	8.5	3.50	29.75
Durability (D)	1	1	0	1	0.5	0	-	1	1	1	6.5	2.83	18.42
Enviromentally Friendly (EF)	0	0	0	0	0	0	0	-	0	0	0	0.00	0.00
Standards Parts (SP)	0	0.5	0	0	0	0	0	1	-	1	2.5	1.17	2.92
Aesthetics (AS)	1	0	0	0	0	0	0	1	0	-	2	0.67	1.33

Personal Rating (Weight)	Craig	Andrew	Daniel	Average
Minimal Labor	0.2	0.2	0.1	0.17
Minimal Cost	0.2	0.1	0.1	0.13
Compact	1	1	1	1.00
(Integrity) Safety	0.9	0.7	0.7	0.77
Low Maintenance	1	1	1	1.00
Reliabilitity	1	1	1	1.00
Durability	0.8	0.9	0.6	0.77
Enviromentally Friendly	0.1	0.1	0	0.07
Standards Parts	0.4	0.6	0.2	0.40
Aesthetics	0.1	0.1	0.4	0.20

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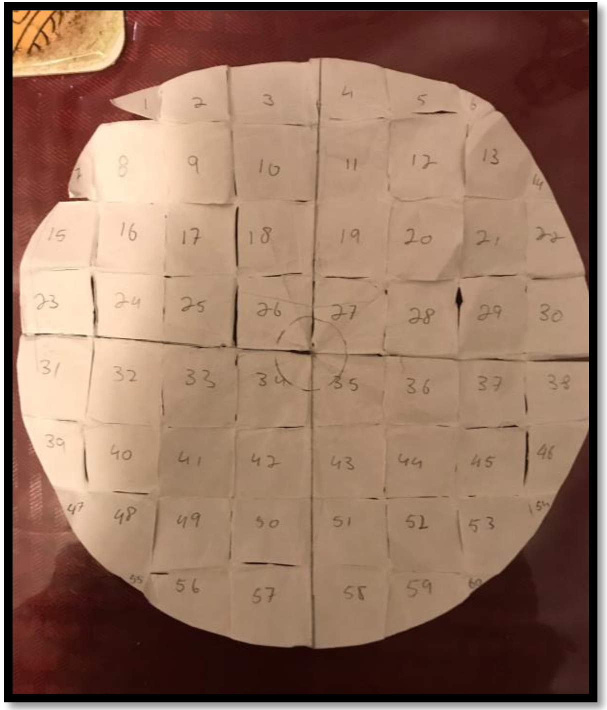
Initial Folding Concepts



- Modularity of each independent cell
- Multiple non-uniform fold pattern
- Slits are created to increase flexibility of the folding crease

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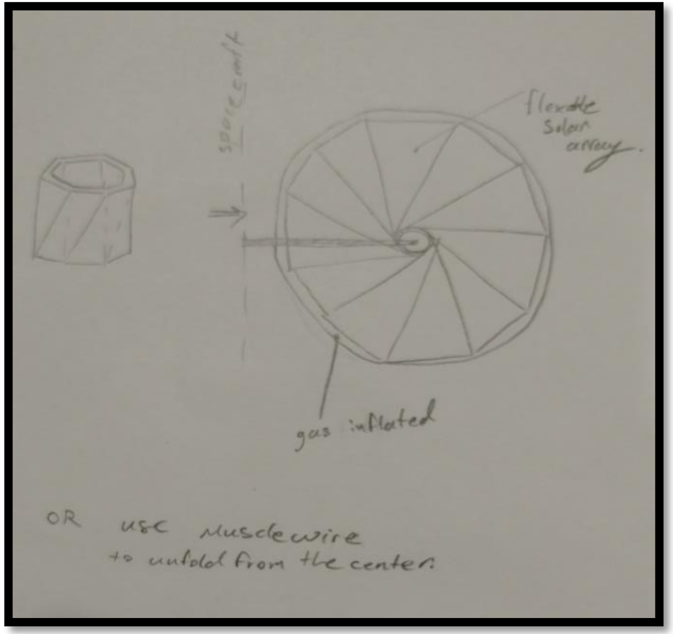
Initial Folding Concepts



- Existing spiral geometry
- Inflatable rim
- Muscle wire

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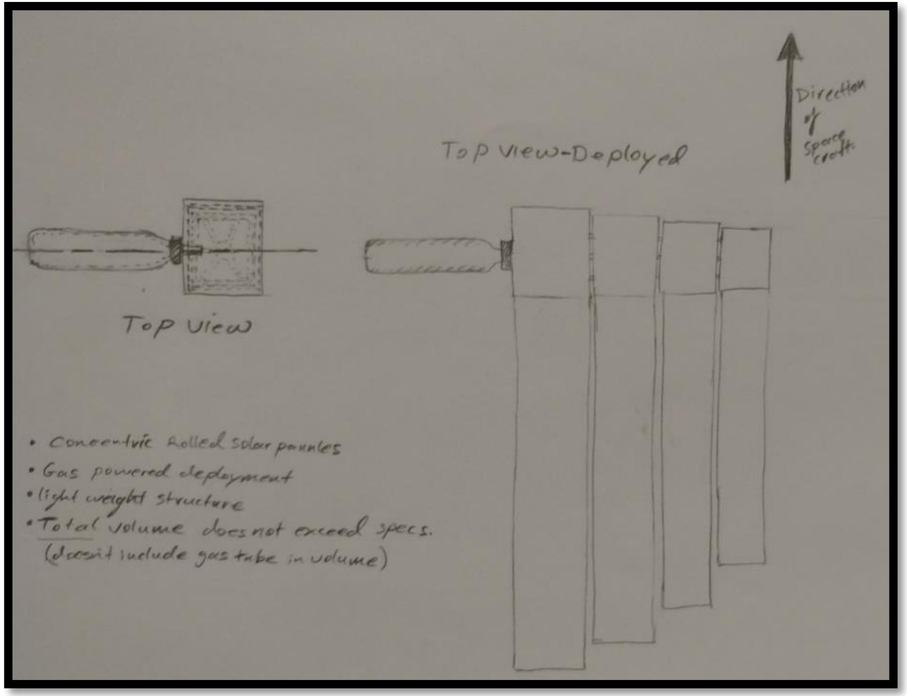
Initial Folding Concepts



- Gas powered
- Concentric solar rolls

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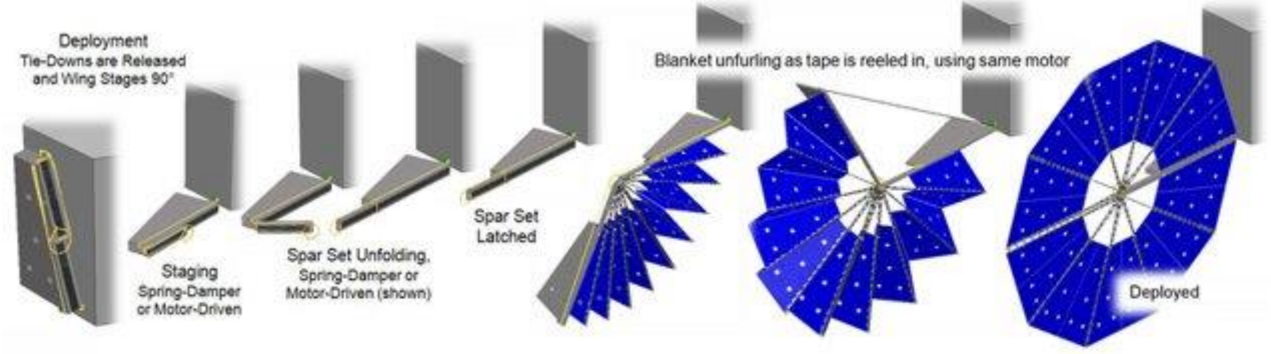
Initial Folding Concepts



Adapt this Mega-Flex solar array to operate without hinges

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Geometric Calculation

- Stored Volume : 10 cm^3 = 10 E $^{-6}m^3$
- Radius: 1-1.5 m
- Area: πr^2= 3.1415m^2 -7.07m^2
- Thickness = 3.2µm (not considering structure)

Common sheet thicknesses:

- Typical Aluminum Foil: 16 µm
- Typical Printing Paper: 24 µm
- Current Production Space Sollar Array: 40-150 µm

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Design Issues

Mission Class	Mission	Destination	Launch Date	Solar Cell Technology	Solar Array Technology	Power Capability at 1 AU (W)
Outer planets	Juno	Jupiter	5-Aug-11	Triple junction	Deployable rigid	14000
Inner planetary systems	Messenger	Mercury	3-Aug-04	Triple junction	Deployable rigid	450
	LCROSS	Moon	18-Jun-09	Triple junction	Body-mounted	600
	Lunar Reconnaissance Orbiter	Moon	18-Jun-09	Triple junction	Deployable rigid	1850
	Grail	Moon	10-Sep-11	Triple junction	Deployable rigid	763
	LADEE	Moon	6-Sep-13	Triple junction	Body-mounted	295
Mars	Mars Global Surveyor	Mars	7-Nov-96	GaAs/Ge and Si	Deployable rigid	2100
	Mars Odyssey	Mars	7-Apr-01	GaAs/Ge	Deployable rigid	2092
	Mars Exploration Rover (2 rovers)	Mars surface	10-Jun-03 7-Jul-03	Triple junction	Deployable rigid	390
	Mars Reconnaissance Orbiter	Mars	12-Aug-05	Triple junction	Deployable rigid	6000
	Phoenix	Mars surface	4-Aug-07	Triple junction	UltraFlex	1255
	MAVEN	Mars	18-Nov-13	Triple junction	Deployable rigid	3165
Asteroids/ comets	Deep Impact/EPOXI	Tempel-1 Hartley-2	12-Jan-05	Triple junction	Body-mounted	620
	Dawn (with solar electric propulsion)	Vesta Ceres	27-Sep-07	Triple junction	Deployable rigid	10300
	OSIRIS-REx	Bennu	8-Sep-16	Triple junction	Deployable rigid	3000

LCROSS—Lunar Crater Observation & Sensing Satellite; LADEE—Lunar Atmosphere Dust & Environment Explorer; MAVEN—Mars Atmosphere & Volatile Evolution; EPOXI—Extrasolar Planet Observation & Characterization Investigation (EPOCh) + Deep Impact Extended Investigation (DIXI)

Dawn Mission: 10.3KW output

- 20m tip to tip Solar Array

- Solar Technology with thickness < 3.2 µm
- 250KW target output :
  - Clarified by Professor. Merret- this is achieved by multiple Arrays with each array output of 9.5KW.

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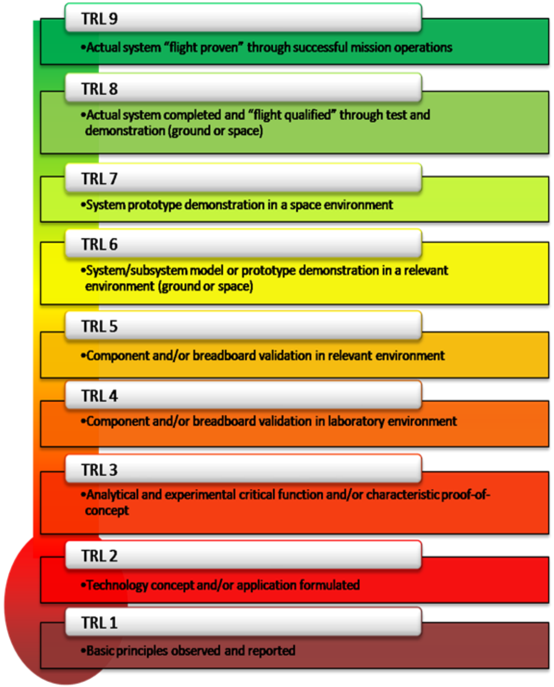
Technology Readiness Level



- Definition of TRL level By NASA:
  - Level 1: Basic Principle observed & Reported.
  - Level 2: Technology concept/ application formulated.
  - Level 3: Analytical and experimental proof of concept.
  - Level 4: Validation in Laboratory environment.
  - Level 5: Validation in relevant environment

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Material Selection

2040 Theoretical Model:

- In Situ Vapor-Deposited Parylene Substrates (1.3 µm)
- Nitinol wire Deploying Mechanism

2020 Deliverable Model:

- MicroLink's epitaxial lift-off (ELO) solar cells (40 µm)
- Nitinol wire Deploying Mechanism

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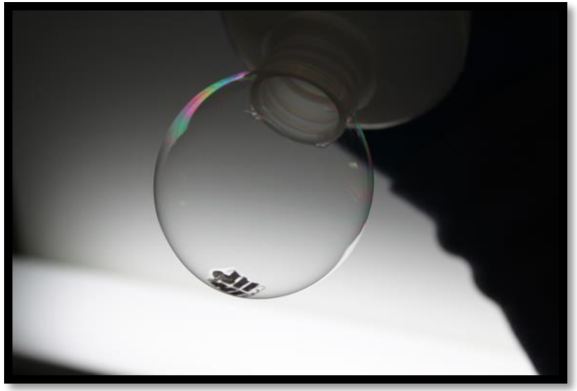
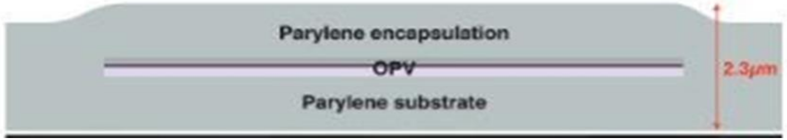
In Situ Vapor-Deposited Parylene Substrates

- Currently experimental at MIT
- Thin polymer flexible film
- Parylene substrate encapsulation
- Organic Photovoltaic Cells
- Thickness PV: <1um
    - Parylene Substrate : 1.3um
    - Mass/unit area: 3.6 g/m2
    - Power Output: 6W/g (21.6 W/m2)





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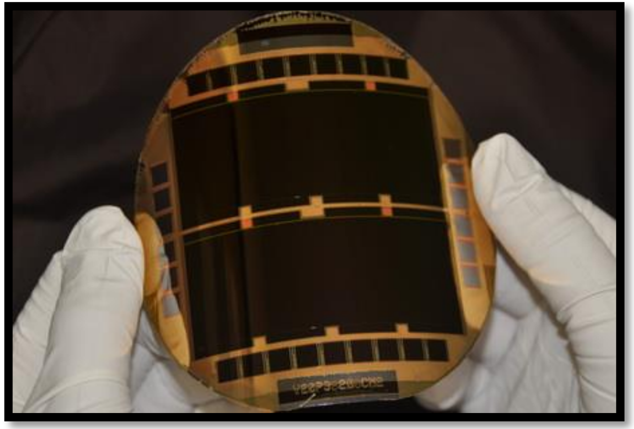
MicroLink's epitaxial lift-off (ELO) solar cells

- Metal Organic Chemical Vapor Deposition
- GaAs Substrate
- Specs:
  - Thickness: <40 um
  - Mass per unit surface area: 250 g/m^2
  - Power output per unit surface area: 250 W/m^2



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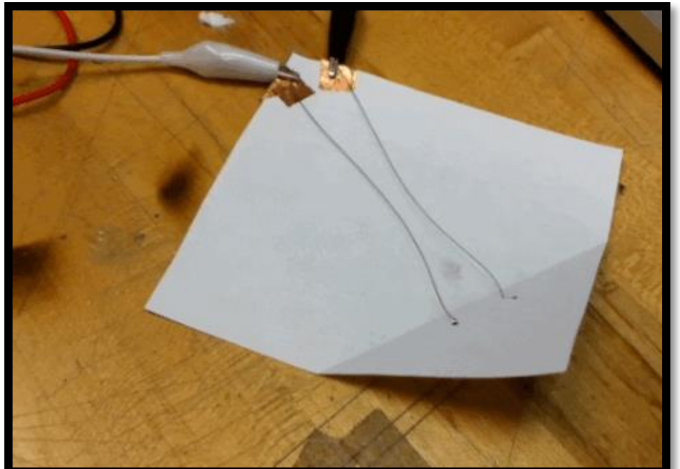
Nitinol Muscle Wire

- Nitinol-Nickle Titanium wire
- The ability to morph to a predefined shape with applied heat/ electric current.

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

* 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



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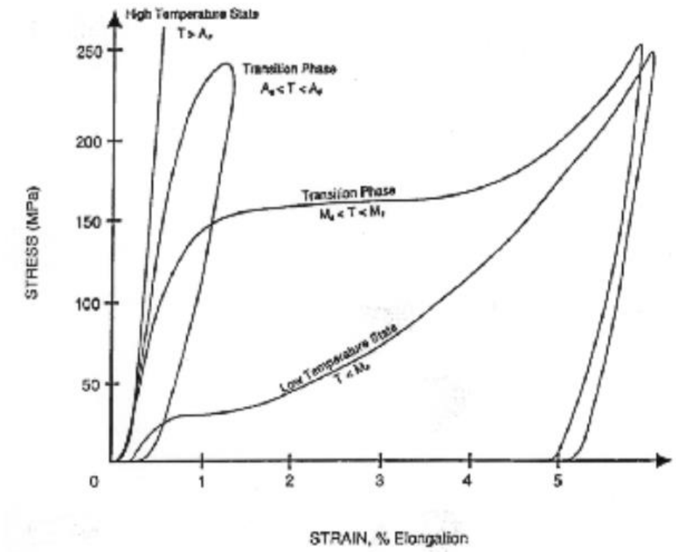
Nitinol Applied Force

- 16 lbs (71 Newtons)
  - (0.02in diameter wire)

Stress-Strain Characteristics of Nitinol at Various Temperatures



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Deploying Sequence

- **Blue:**

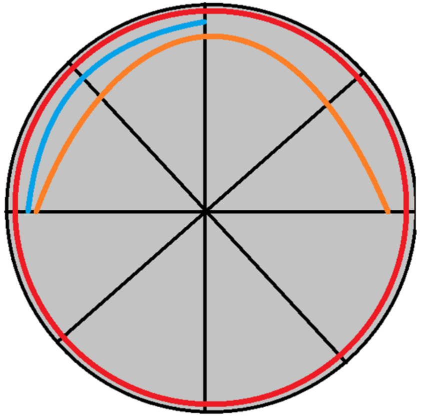
First nitinol loop that will unfold from one "slice" to two

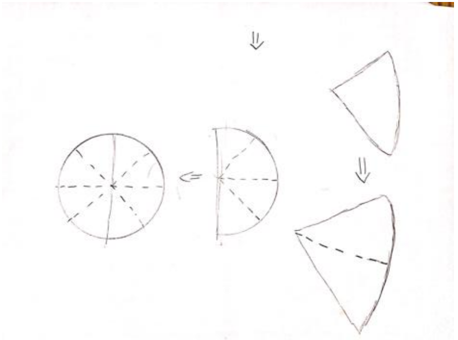
- **Orange:**

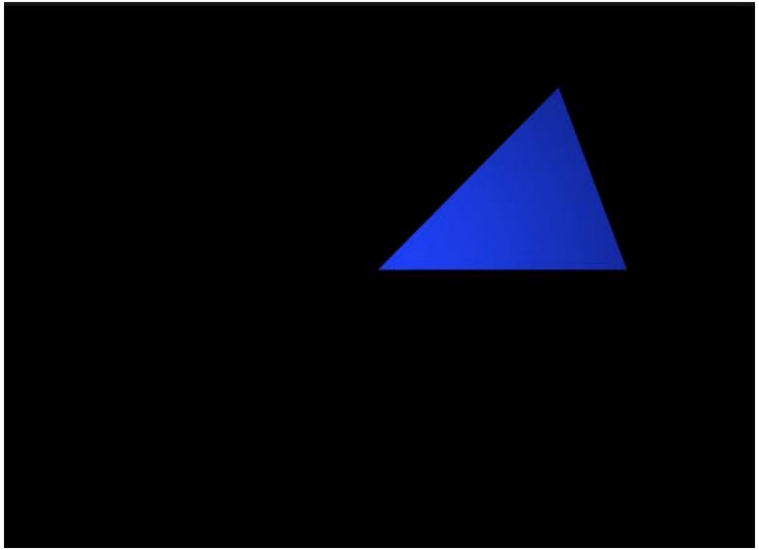
Second nitinol loop that will unfold from two "slices" to four

- **Red:**

Outer nitinol loop that will unfold from four "slices" to eight and keep stability while deployed







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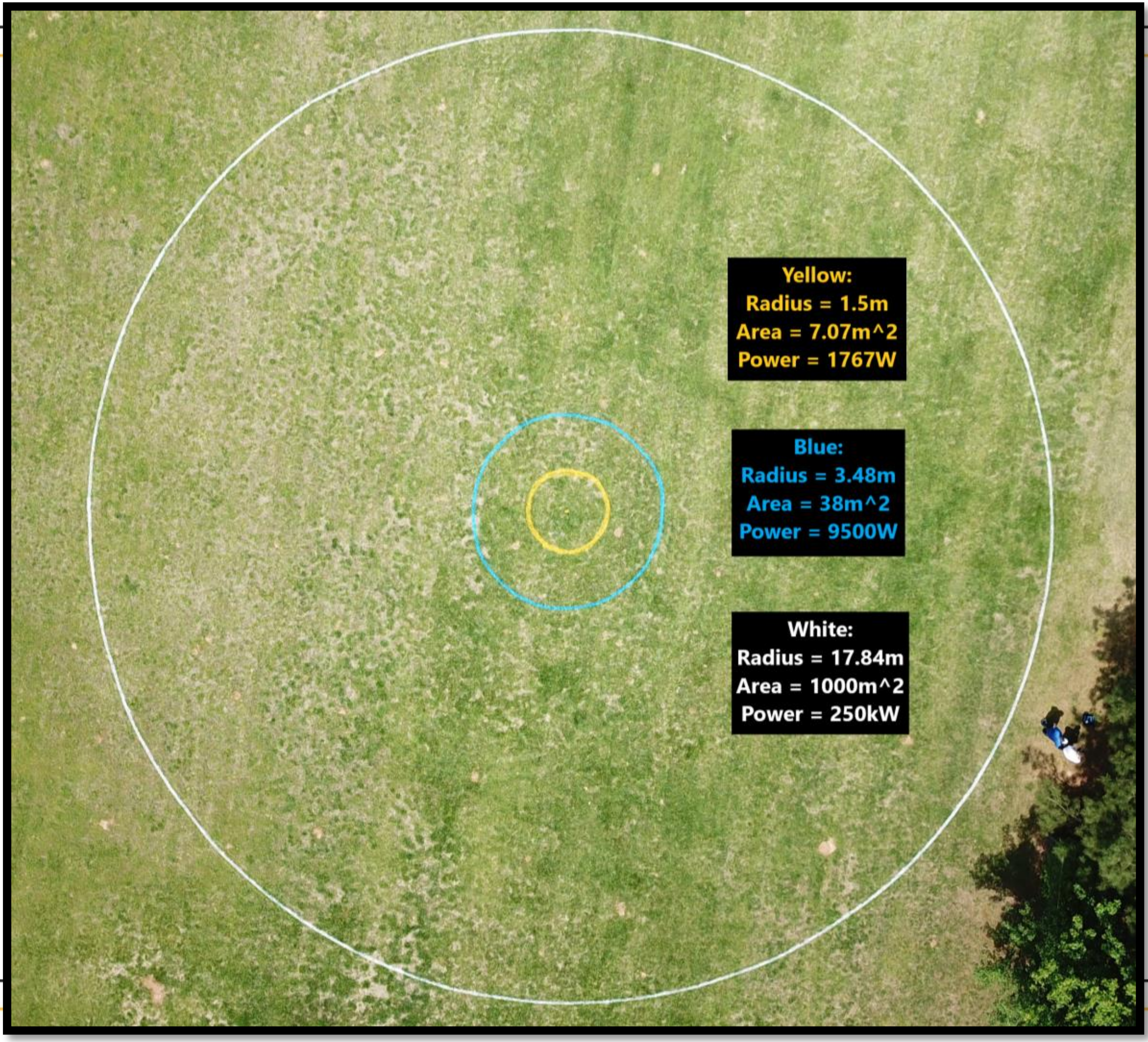

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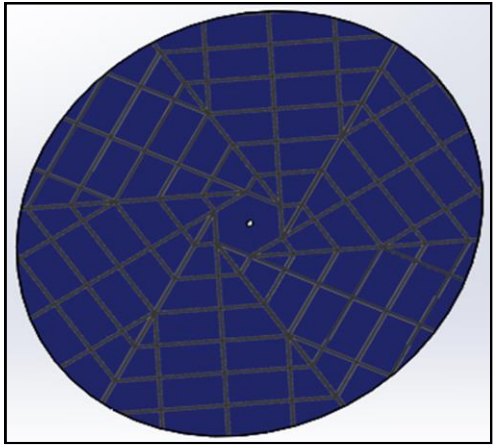
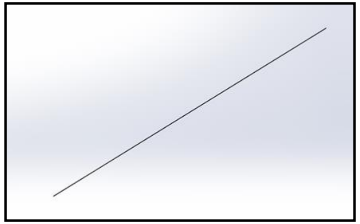
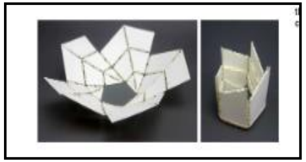
CAD Design: 2040 Theoretical Model

- In Situ Vapor-Deposited Parylene Substrates
- Incorporate Origami Principle to increase compactness
- Applying a non-rigid foldable pattern to a rigid material







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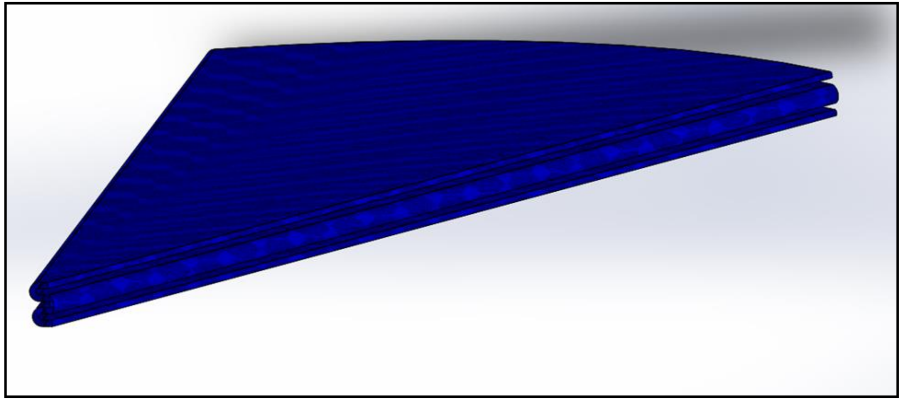
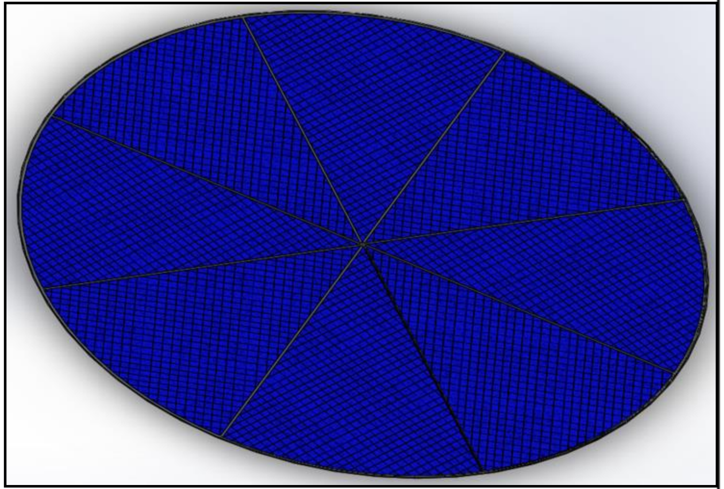
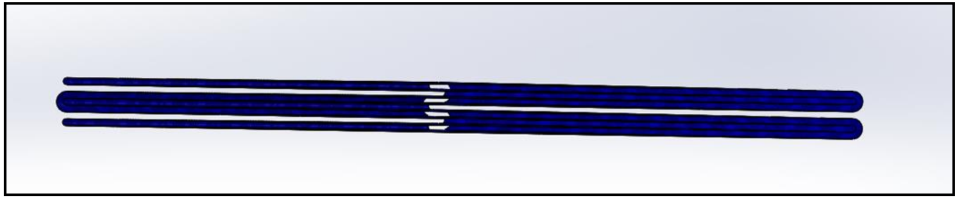
CAD Design: 2020 Deliverable Model







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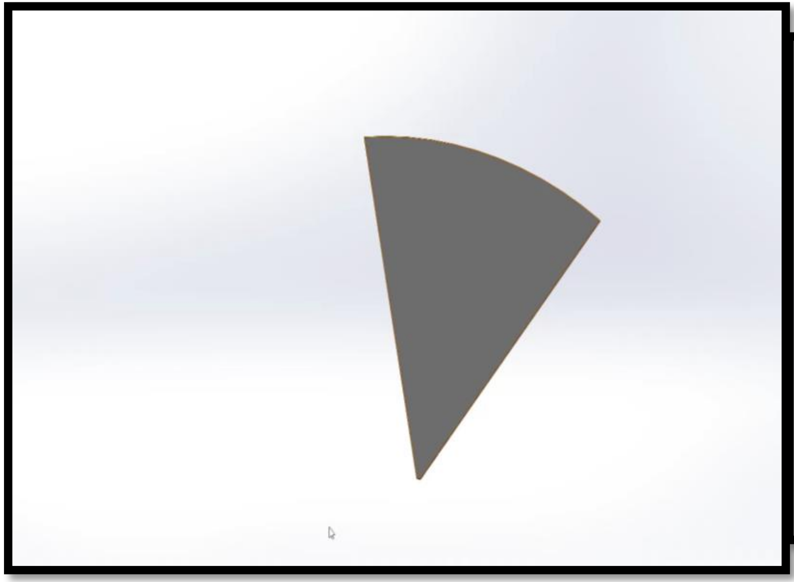
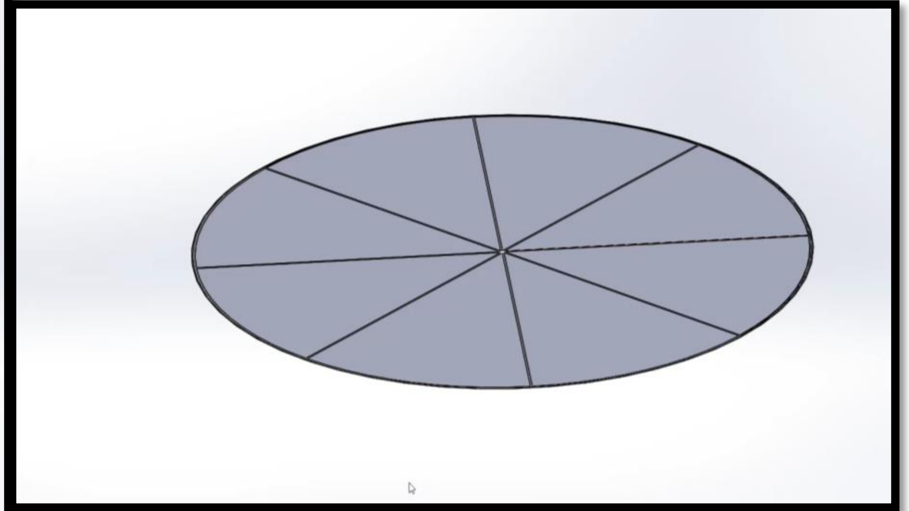
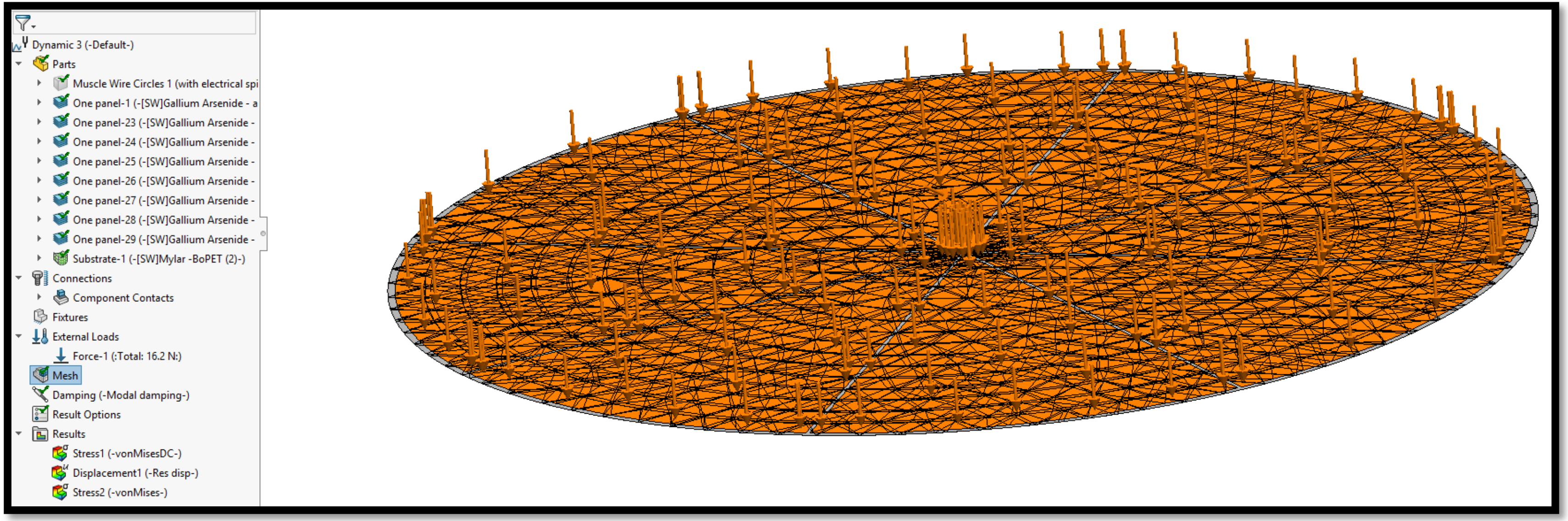
CAD Design: 2020 Deliverable Model





FEA Analysis- Deployed



2020 Model – Dynamic Harmonic Analysis of 1G at 1.5 Hz (Mesh)

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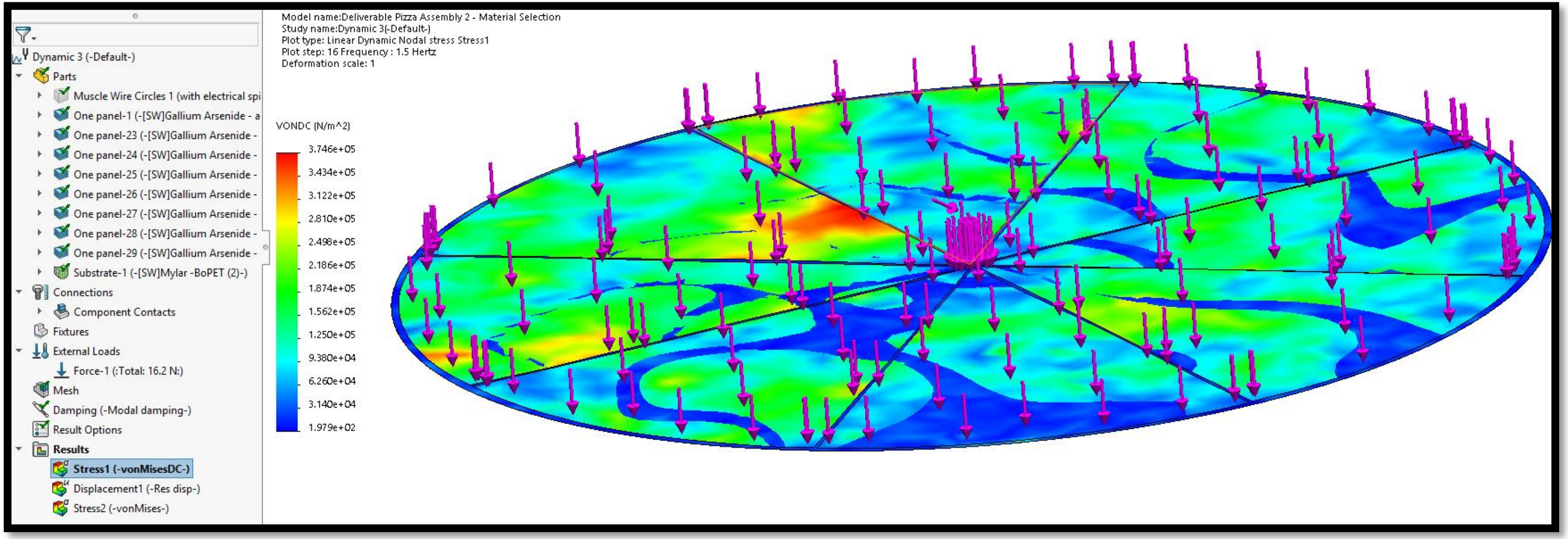
FEA Analysis- Deployed



2020 Model – Dynamic Harmonic Analysis of 1G at 1.5 Hz (Stress)

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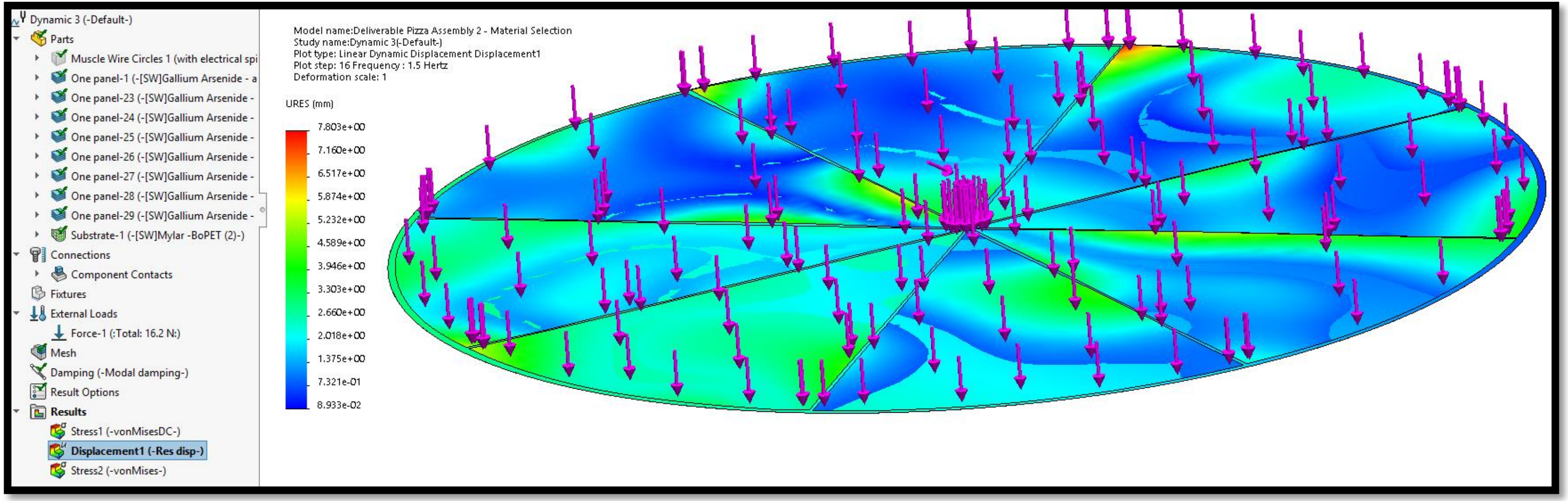
FEA Analysis- Deployed



2020 Model – Dynamic Harmonic Analysis of 1G at 1.5 Hz (Displacement)

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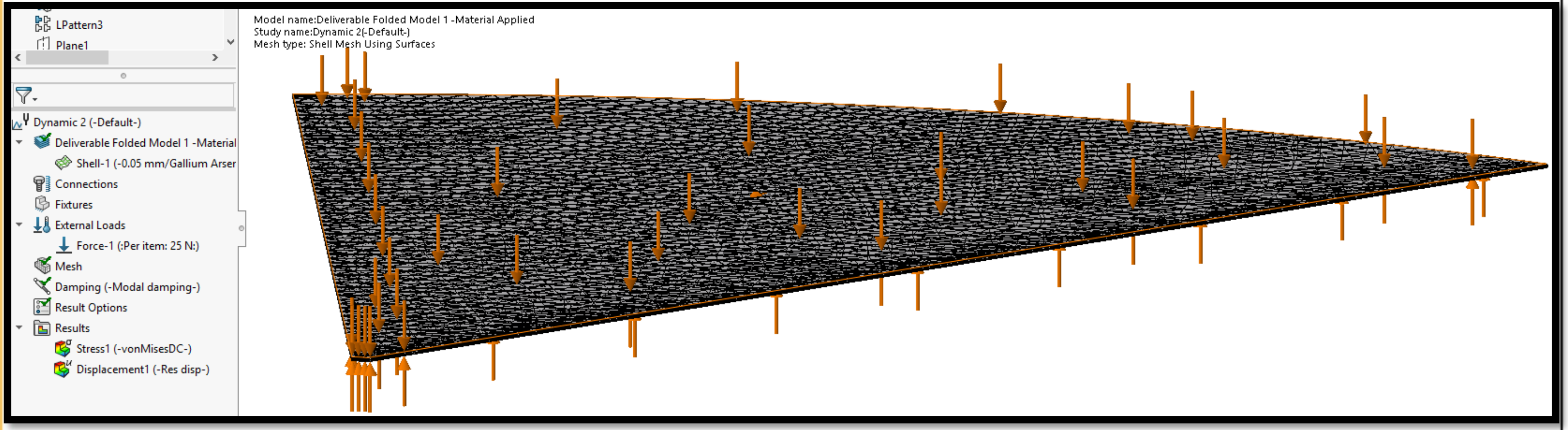
FEA Analysis – Stored Configuration



2020 Model – Dynamic Harmonic Analysis of 15G at 100 Hz (Mesh)

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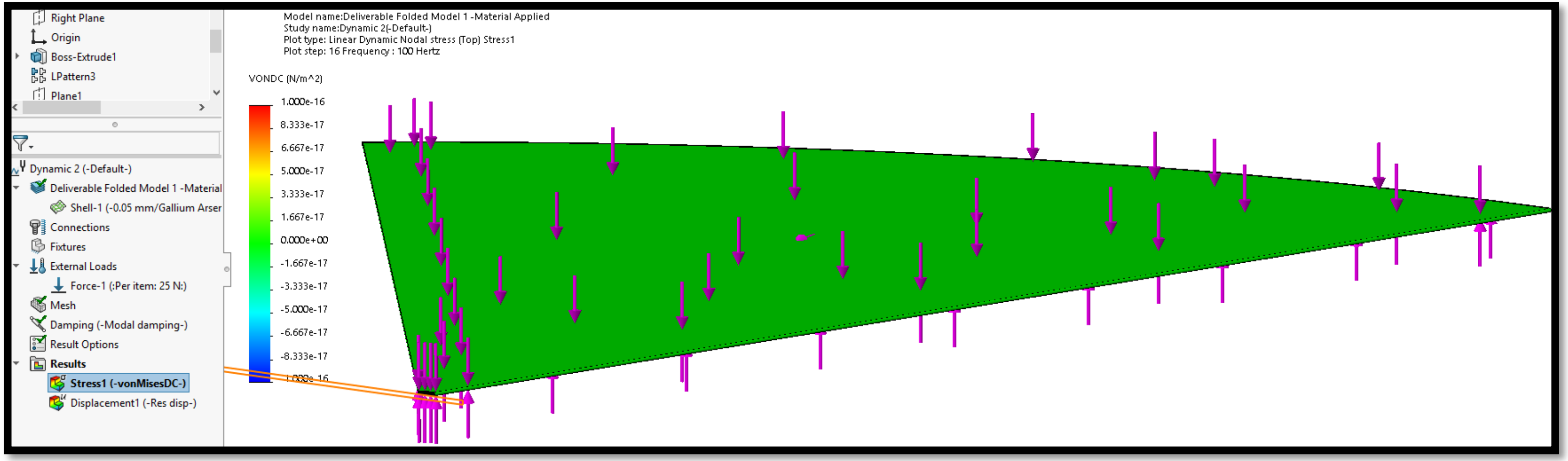
FEA Analysis – Stored Configuration



2020 Model – Dynamic Harmonic Analysis of 15G at 100 Hz (Stress)

Note: No damage because of incomplete SolidWorks material data

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Final Design Metrics

CRITERIA	2040 Theoretical Model	2020 Deliverable Model
Surface Area of 1 Model	7.07 m^2	7.07 m^2
Volume of 1 Model	10 cm^3	375.8 cm^3
Mass of 1 Model	40g	1.65 kg
Power Output of 1 Model	152.7 W	1767.5 W
# Models needed for 250kW	1638	142
SA needed for 9500W	440 m^2	38 m^2
Volume needed for 9500W	623 cm^3	2255 cm^3
SA Needed for 250kW	11,574 m^2	1000 m^2
Volume needed for 250kW	16,372 cm^3	53,363.6 cm^3
Total Mass at 250kW	65.5 kg	234.3 kg
Thickness	2um	53um

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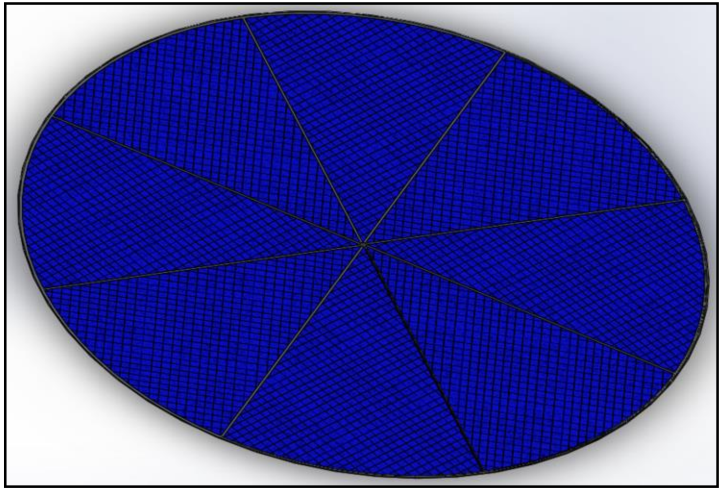
Specs: 2040 Theoretical Model

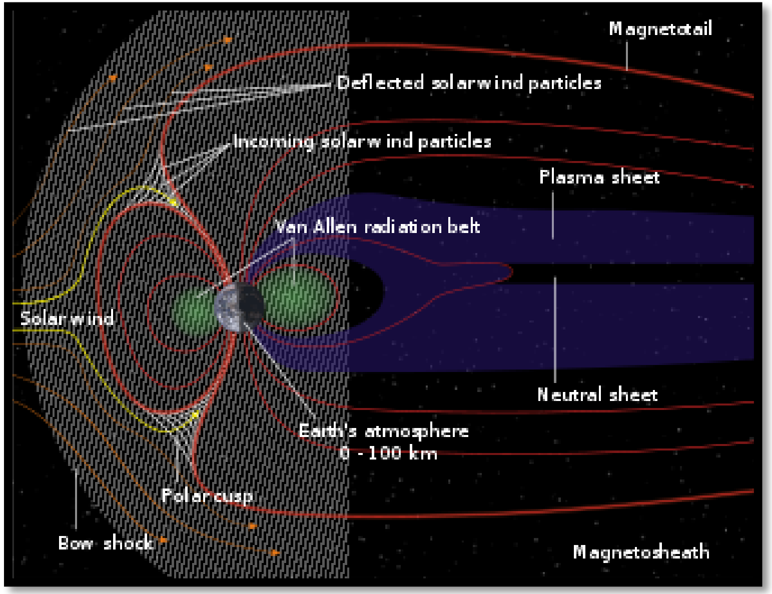
Design Requirements for how to achieve new AIAA RFP (Technology projected in 2040)

- $7.07\ m^2$
- 9500 W output
- $1344\ W/m^2$
- 1 micron thick
- Stress/Strain properties of Nylon



Additional Requirements

- Solar Wind
  - Solar wind's effects are negligible
  - Force = 4.24e-08 N
- Micro-meteorite
  - Solar cells are arranged in parallel, allowing sections and/or whole "slices" to lose power and the remaining structure to continue functionality



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Prototyping 2020-Deliverable Model

- 10 mil plastic = 254 microns

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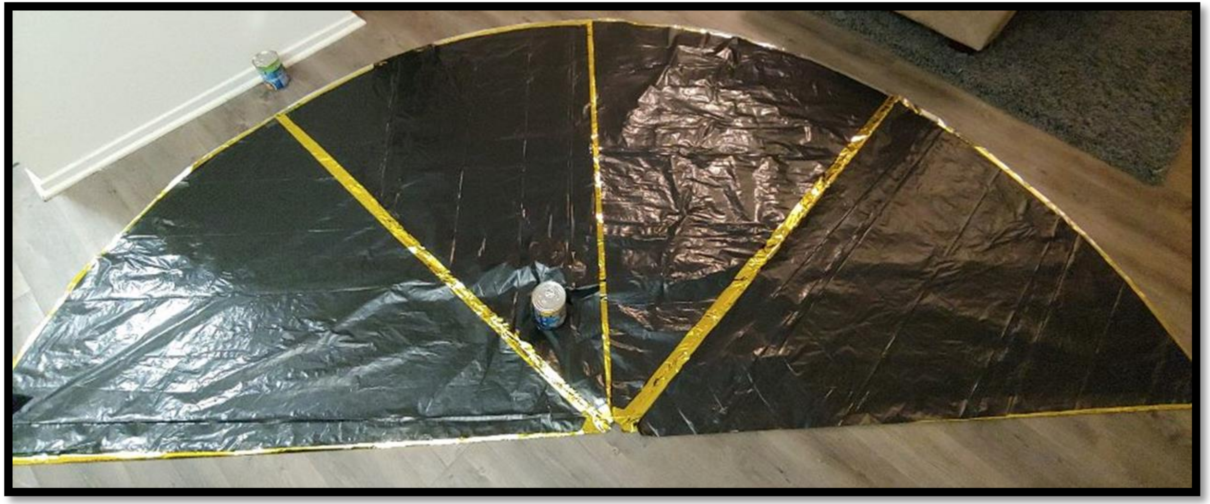
Prototyping 2020-Deliverable Model



- Made with 13 micron Mylar film and 50 micron black plastic sheeting

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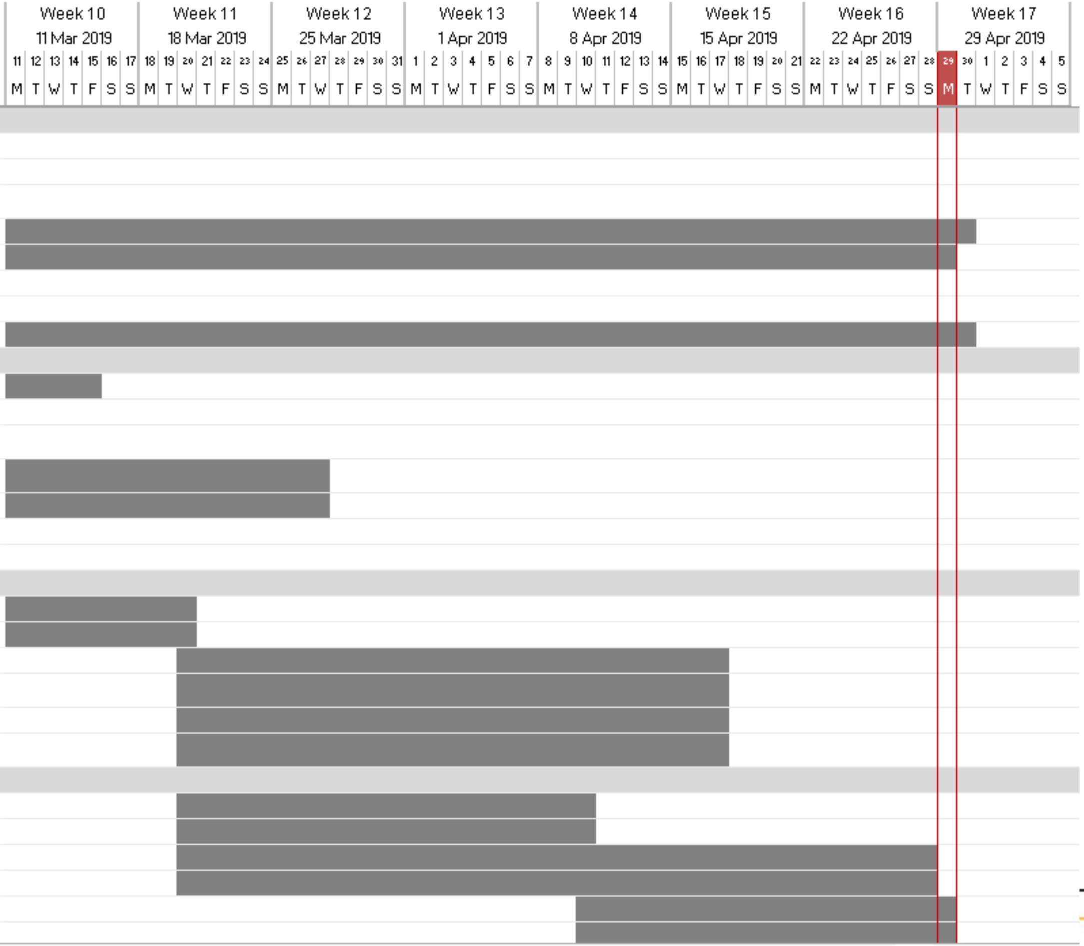
[G1:3 Deployable Solar Array Structure] Project Schedule

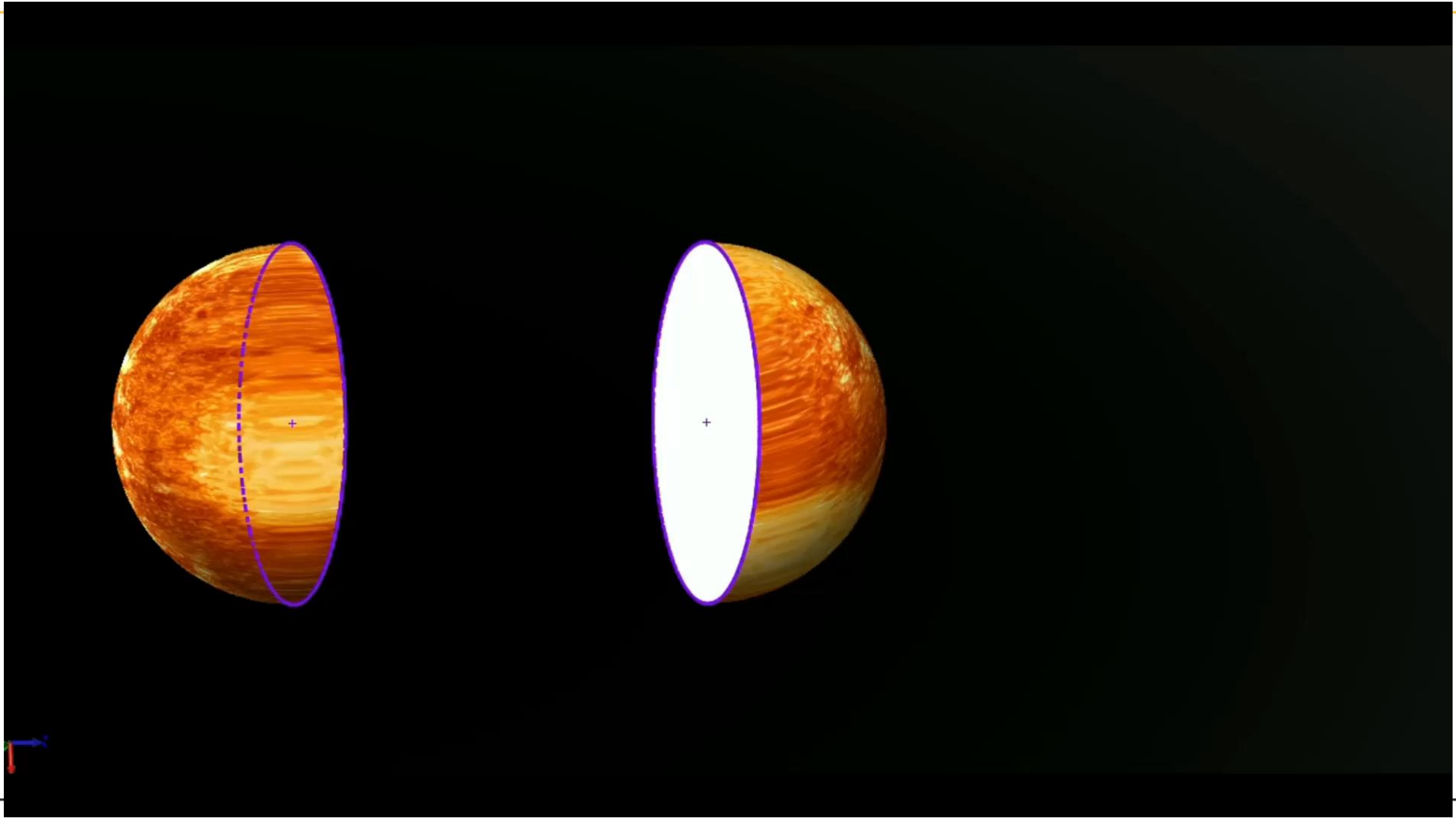
[SOL-MATES]
Daniel Bain, Craig Patton, Andrew Tendean

Project Start Date: 1/9/2019 (Wednesday) | Display Week: 10

Project Lead: Daniel Bain

WBS	TASK	LEAD	START	END	DAYS	% DONE	WORK DAYS
1	**Phase 1**			-			-
1.1	IDR Paper	All	Wed 1/09/19	Wed 1/23/19	5	100%	11
1.2	IDR Presentation	All	Wed 1/09/19	Wed 1/23/19	5	100%	11
1.3	Individual Folding Design Concepts	All	Sat 1/12/19	Wed 1/30/19	4	100%	13
1.4	Individual Activity Logs	All	Wed 1/09/19	Tue 4/30/19	4	100%	80
1.5	Literature Review	All	Wed 1/09/19	Mon 4/29/19	5	100%	79
1.6	Design Matrix	All	Wed 1/16/19	Wed 1/30/19	7	100%	11
1.7	Decision Matrix	All	Wed 1/16/19	Wed 1/30/19	7	100%	11
1.8	Gantt Chart	Craig	Wed 1/16/19	Tue 4/30/19	7	100%	75
2	**Phase 2**			-			-
2.1	Group Design Concept	All	Wed 1/23/19	Fri 3/15/19	4	100%	38
2.2	Material Selection	All	Wed 1/30/19	Fri 3/08/19	3	100%	28
2.3	Folding Mechanism Design	All	Wed 1/23/19	Fri 3/08/19	3	100%	33
2.4	Deploying Mechanism Design	All	Wed 1/30/19	Wed 3/27/19	6	100%	41
2.5	Solidworks Model	All	Wed 1/30/19	Wed 3/27/19	3	100%	41
2.6	PDR Paper	All	Wed 1/23/19	Wed 2/27/19	3	100%	26
2.7	PDR Presentation	All	Wed 1/23/19	Wed 2/27/19	3	100%	26
3	**Phase 3**			-			-
3.1	IPR Paper		Wed 2/20/19	Wed 3/20/19	3	100%	21
3.2	IPR Presentation		Wed 2/20/19	Wed 3/20/19	3	100%	21
3.3	Launch FEA Analysis		Wed 3/20/19	Wed 4/17/19	4	100%	21
3.4	Launch Vibrations Analysis		Wed 3/20/19	Wed 4/17/19	3	100%	21
3.5	Deployed FEA Analysis		Wed 3/20/19	Wed 4/17/19	3	100%	21
3.6	Deployed Vibrations Analysis		Wed 3/20/19	Wed 4/17/19	6	100%	21
4	**Pase 4**			-			-
4.1	CDR Paper		Wed 3/20/19	Wed 4/10/19	1	100%	16
4.2	CDR Presentation		Wed 3/20/19	Wed 4/10/19	1	100%	16
4.3	Prototype Building		Wed 3/20/19	Sun 4/28/19	1	100%	28
4.4	Poster Board		Wed 3/20/19	Sun 4/28/19	1	100%	28
4.5	FDR Paper		Wed 4/10/19	Mon 4/29/19	1	100%	14
4.6	FDR Presentation		Wed 4/10/19	Mon 4/29/19	1	100%	14





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- Friends and Family that support our journey in completing this project.

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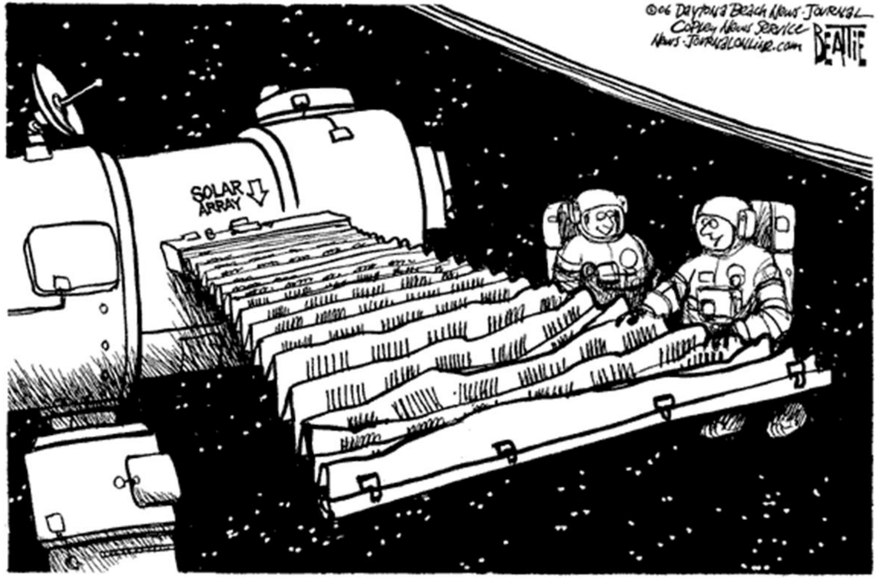
Questions?



"After this, refolding the maps in my car's glove compartment should be a snap!"

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