Optimization of Thin-Film Solar Cells for Lunar Surface Operations

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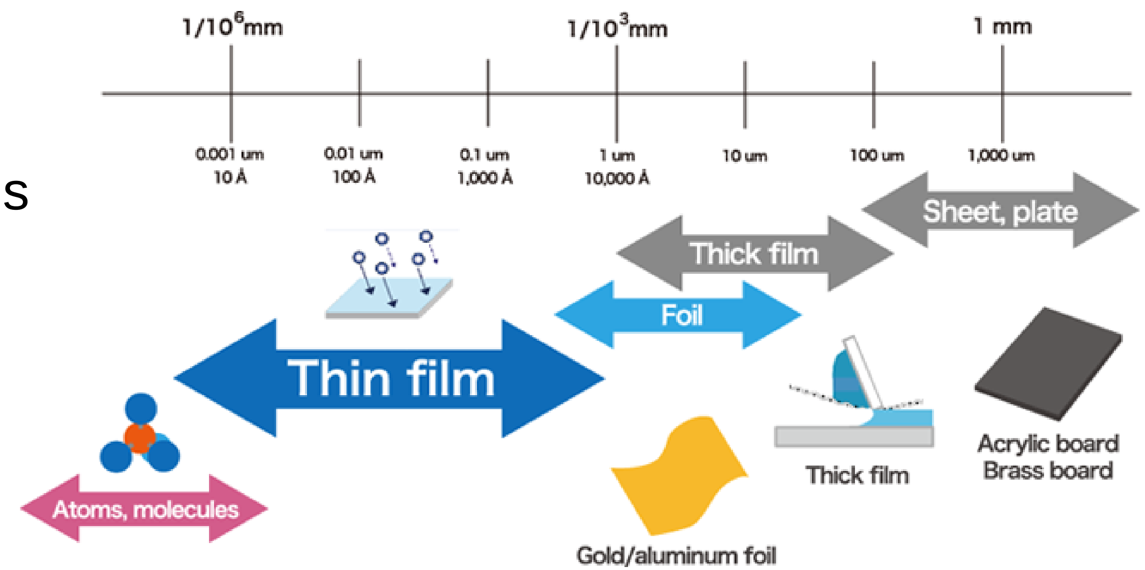
Outline

- Introduction
- LPL Overview
- Driving Requirements
- Thin-Film Solar Cells
  - Design Benefits
  - Design Drawbacks
  - Proposed Design Solution
- Thermal Model
- Testing
- Conclusion

Introduction

- What is a thin-film?
  - General term for material with thickness on the order of nanometers to micrometers
  - Can be single or multiple layers of plastic, metal, or a combination of the two
- What are they used for?
  - Semiconductors
  - Mirrors
  - Hardness coatings
  - Optical coatings
  - Batteries



https://www.susumu.co.jp/_staging/html/usa/tech/know_how_02.php

Lunar Pallet Lander Overview

- Medium payload (300kg) lunar lander
- Primary focus is minimizing cost
  - Using COTS parts as much as possible
  - Simple construction methods and materials
    - Deck is fabricated from riveted sheet aluminum
- Initially designed as lander for the RP rover mission
- Large amount of deck space provides payload flexibility

Baselined configuration with rigid solar arrays

Driving Requirement

- *The lander EPS shall generate electrical power under continuous illumination beginning when the vehicle is pointed to the sun and after launch vehicle separation and ending with the loss of continuous illumination or 336 hours after landing whichever occurs first.*
  - Currently required to generate power during the entire lunar day, which is two earth weeks (~336 hours)

Thin-Film Solar Cells

- Have been in use for decades
  - That small solar cell in calculators is a thin film
- Historically have had low efficiencies, even as low as single digits
- Modern manufacturing and materials science has allowed for efficiencies to become comparable to traditional rigid cells

Modern Thick-Film

Modern Thin-Film

Courtesy of Dr. John Carr, NASA MSFC

Thin-Film Solar Cell Benefits

- Provide significant mass and cost savings
  - Greater than 300% more power per kg
  - Less than 50% of the cost
  - These are both critical areas for any spaceflight mission
- Flexibility inherent to thin-film solar cells allows for different deployment mechanisms to be used
  - Thin-films can be folded and flexed to a smaller volume than rigid panels
  - Booms and other deployment mechanisms become feasible due to the low mass

Thin-Film Solar Cell Issues

- Designed for terrestrial applications
  - Kept cool by natural convection and lower solar load
- Manufacturers did not have data on upper temperature limits
  - Testing was performed to quantify the efficiency loss with increasing temperature
- Keeping the cells cool in space when there is a limited view to space is challenging
  - Cells have low in-plane conductivity and practically zero thermal mass
  - Typical methods, such as decreasing packing factor or adding a high conductivity backer are ineffective or negate some the benefits of thin-films

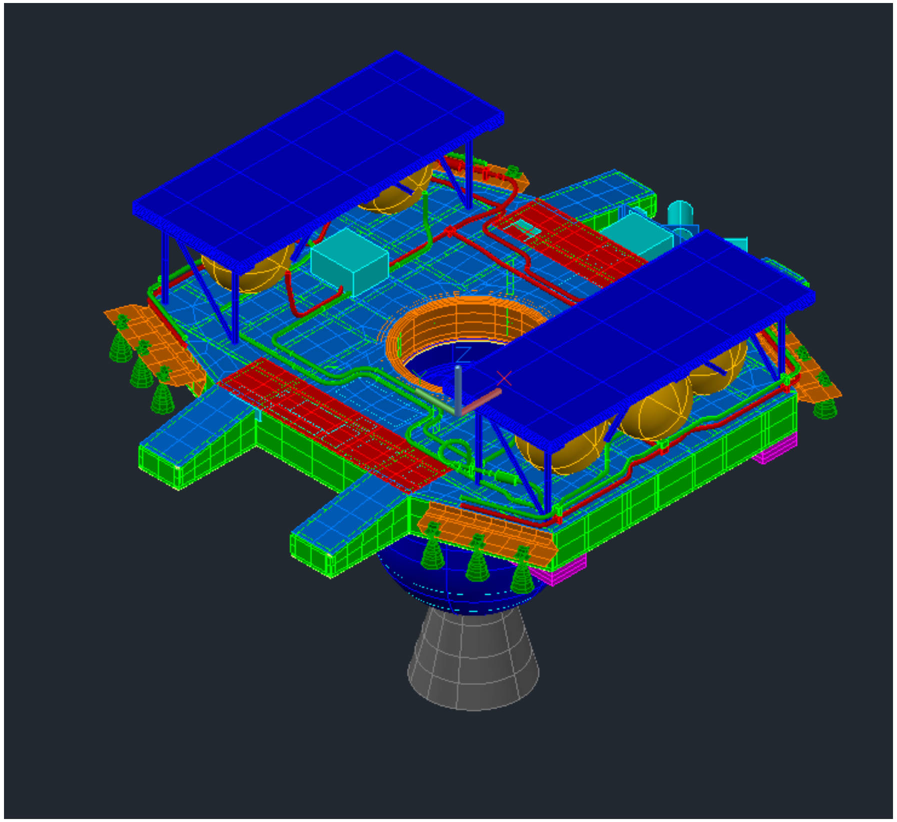
Thermal Model

- C&R Technologies Thermal Desktop and RadCAD are used for modeling
  - Solar cells modeled with surfaces
  - Material properties are polyimide film since exact thermal conductivity us proprietary
    - This serves as a lower bound on thermal conductivity
  - Nodes modeled as arithmetic (zero capacitance)
    - Based on lab observations of cells rapidly changing temperature with environment changes
  - Symbol controlled assemblies allow for easy angle changes without permanently changing the model

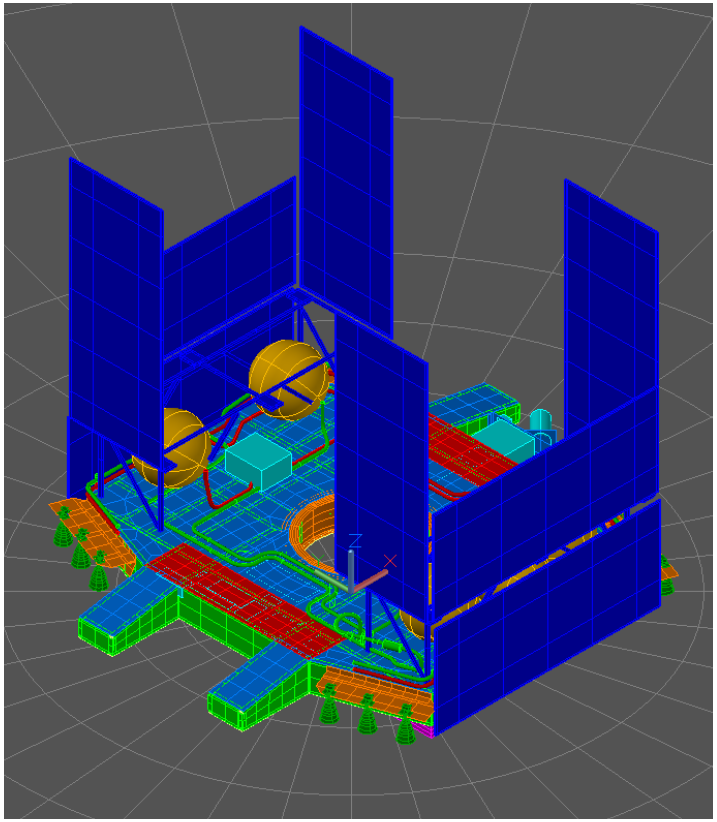
Thermal Model

- Baseline transit and surface configurations shown below

Transit



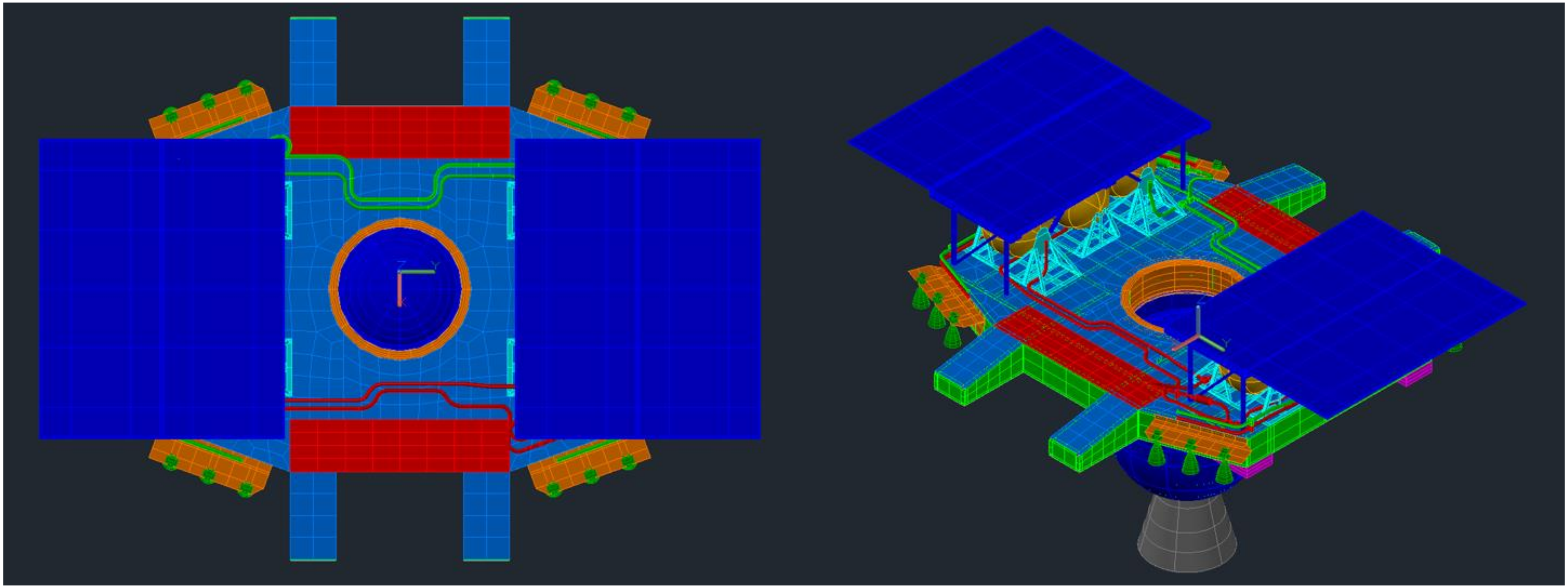
Surface



Proposed Design Solution

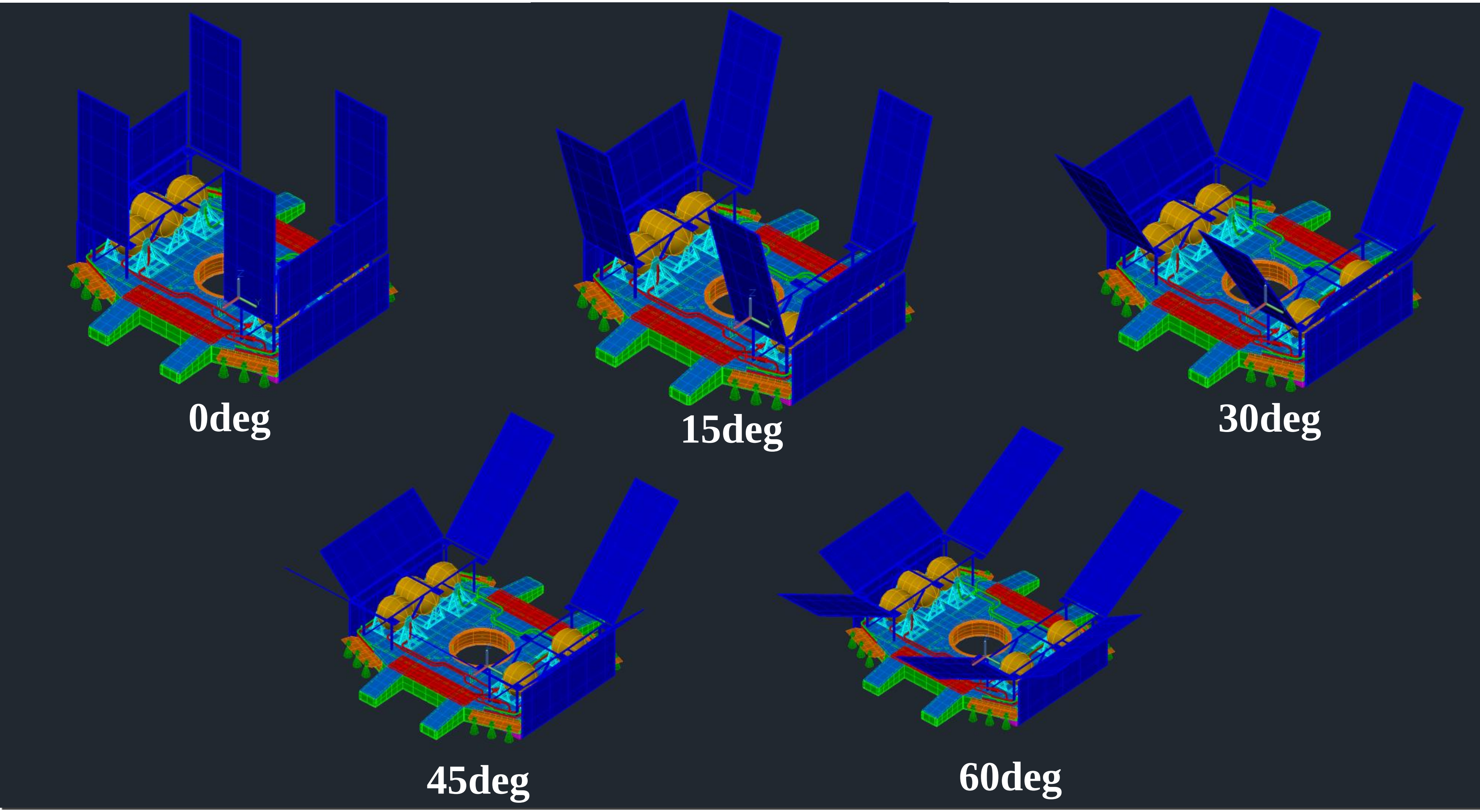
- It is necessary to increase the backside view factor to space
  - Backside is assumed to be high emissivity black optical properties
  - Frontside properties are lower emissivity
- For the transit case:
  - Move from baselined configuration to a single fold deployment
    - Provides view to space for backside of deployed array
    - Baselined configuration views lander structure
- For the lunar surface case:
  - Angle panels downward towards lunar surface
    - This greatly increases the view factor of the backside to space
    - Reduces solar flux on the panel, decreasing temperature, but also decreasing power conversion
  - Optimization needs to be performed that gives best angle for temperature and power

Transit Proposed Design



- Compared to the baseline design shown previously, this configuration gives the backside of the transit panels a clear view to space

Surface Proposed Design



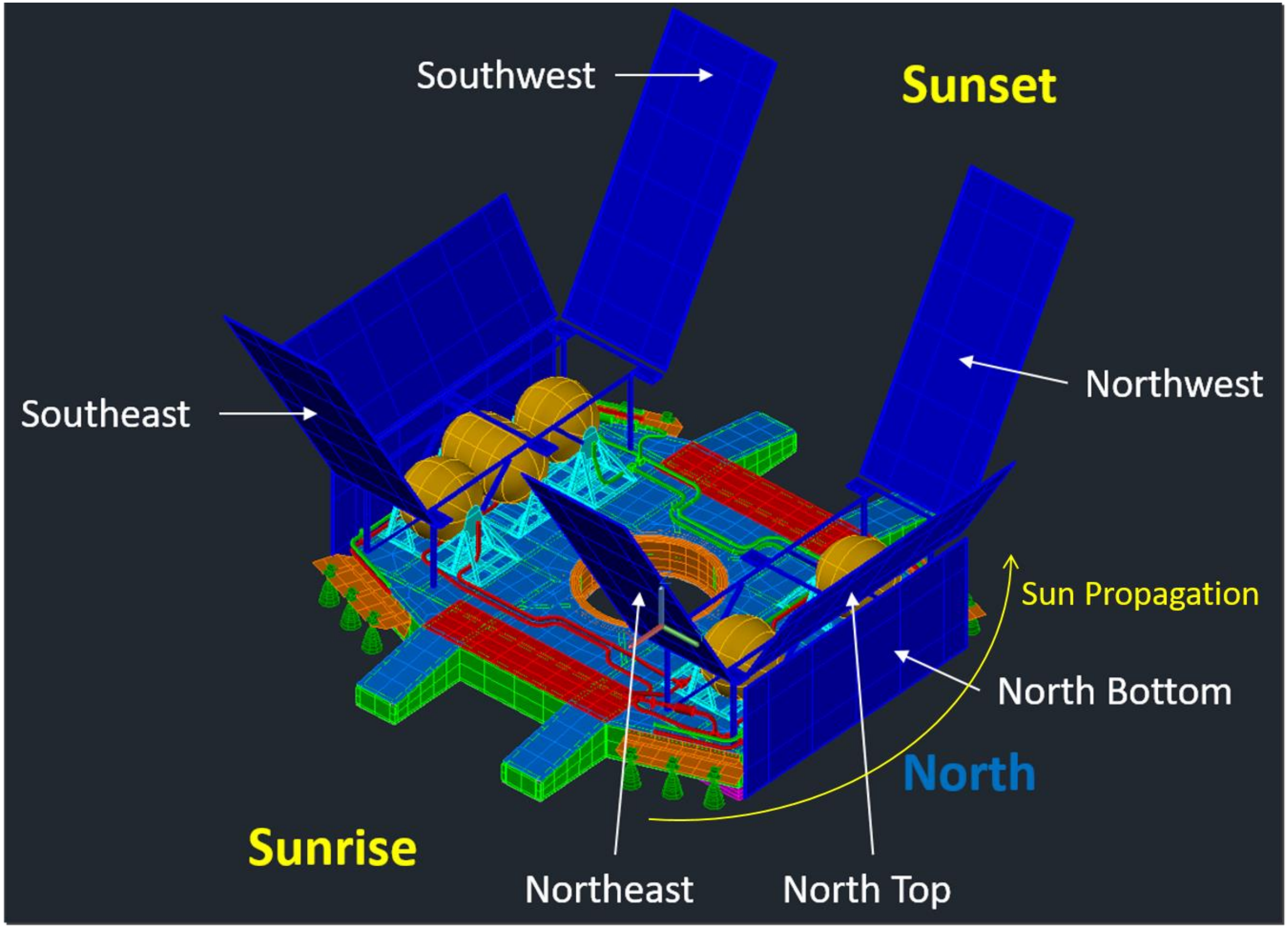
- Lunar surface configurations analyzed

Thermal Model Cases

- Transit
  - Top deck is solar inertial, so the solar arrays are pointed directly at sun
  - Assuming a four day flight to the moon
- Lunar Surface
  - LPL mission was analyzed for a full lunar day (two earth weeks)
  - South pole landing site
- Thin-Film Solar Cell Types analyzed:
  - Inverted Metamorphic Multijunction (IMM)
    - $\varepsilon = 0.81$, $\alpha = 0.897$ (inactive), 0.617 (active)
  - Gallium Arsenide (GaA)
    - $\varepsilon = 0.62$, $\alpha = 0.616$ (inactive), 0.416 (active)
  - Black coating assumed for backside properties
    - $\varepsilon = 0.85$, $\alpha = 0.90$

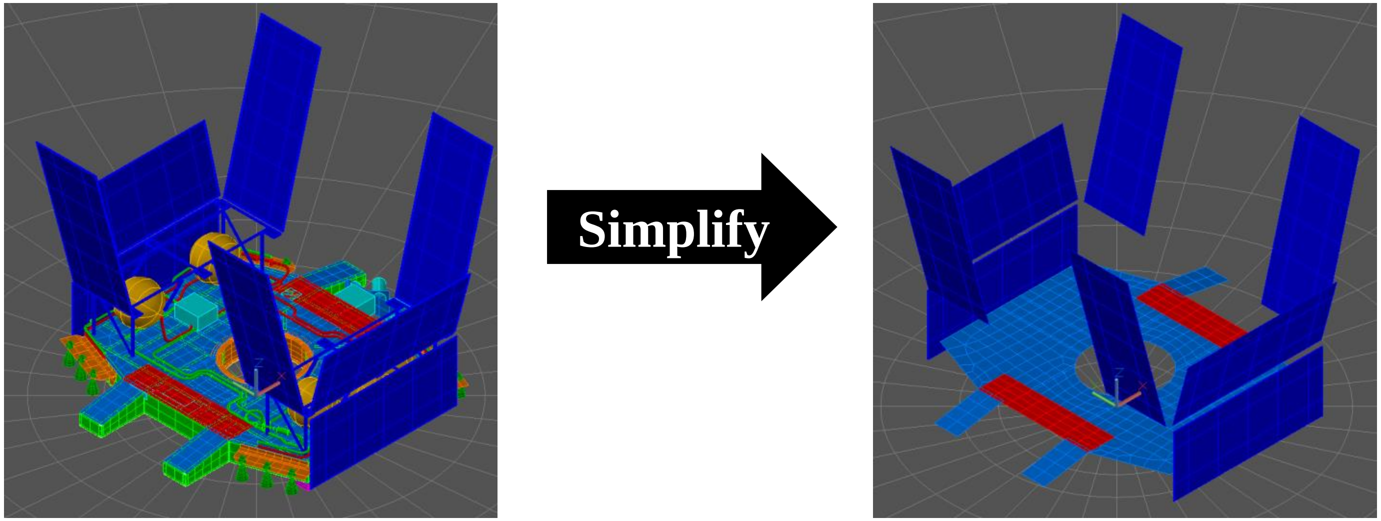
Surface Panel Naming Convention

- The panels are names according to cardinal directions



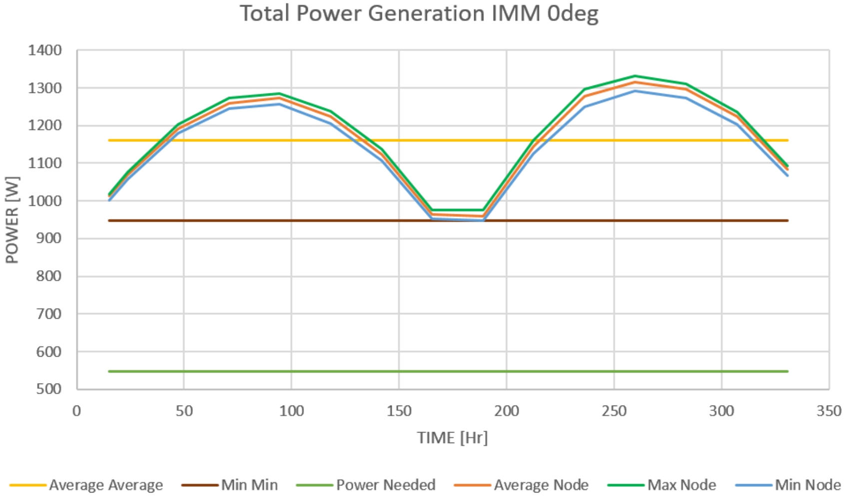
Reduced Order Model for Lunar Surface

- LPL integrated lunar surface model was prohibitive to rapidly performing trade studies
  - Takes approximately 24hrs of runtime to calculate environments and transient temperature solution for the full 336hrs
- Simplified model was created to reduce runtime
  - Only contains the cells, top deck, and lunar surface: the primary radiative interactions with the thin-film solar cells
  - Reduced runtime down to 10 minutes



Power Generation

- Solar cell power generation is a function of solar flux and cell temperature
- Power generation during transit is constant due to constant solar flux
- Power generation on the surface varies since the temperature and flux vary with time
  - Surface power results presented are the minimum power generated during surface operations to be conservative



Transit Model Results for IMM Cell

- 630 Watts of power generation are needed during transit
- Targeting 60 degrees C for the cell temperature
  - Cells are designed for terrestrial application and this is within their normal operating range
- Baseline transit configuration is the solar panels inline with the tanks, as previously shown

Case	Power (W)	Panel 1	Panel 2
Baseline	835.4	94.1	93.7
Deployed	907.9	50.5	53.8

- Both cases provide plenty of power, but only the deployed case is cool enough

Surface Model Results for IMM Cell

- 550 Watts is the maximum power requirement on the lunar surface
- Targeting 60 degrees C
  - Cells are designed for terrestrial application and this is within their normal operating range

Panel Angle	Power (W)	SE (°C)	NE (°C)	NB (°C)	NT (°C)	NW (°C)	SW (°C)
0 degree	962.9	67.5	69.8	72.2	72.2	66.8	69.8
15 degree	912.6	61.8	62.0	66.4	66.4	60.7	63.6
30 degree	805.5	48.8	51.1	57.0	57.0	48.3	50.6
45 degree	641.4	31.1	32.4	45.0	45.0	30.1	33.7
60 degree	428.4	4.69	8.25	29.2	29.2	3.59	9.39

- Only the 60 degree angle does not produce enough power
- The 0 and 15 degree are borderline on temperature

Transit Model Results for GaA Cell

- 630 Watts of power generation are needed during transit
- Targeting 60 degrees C for the cell temperature
  - Cells are designed for terrestrial application and this is within their normal operating range
- Baseline transit configuration is the solar panels inline with the tanks, as previously shown

Case	Power (W)	Panel 1	Panel 2
Baseline	613.8	82.4	83.5
Deployed	641.4	36.3	34.8

- The baseline case is both under the power requirement and over the temperature target
- The deployed case is well within the temperature target but is borderline for power

Surface Model Results for GaA Cell

- 550 Watts is the maximum power requirement on the lunar surface
- Targeting 60 degrees C
  - Cells are designed for terrestrial application and this is within their normal operating range

Panel Angle	Power (W)	SE (°C)	NE (°C)	NB (°C)	NT (°C)	NW (°C)	SW (°C)
0 degree	694.3	53.5	52.6	55.4	55.4	50.1	56.8
15 degree	656.6	45.9	44.2	48.1	48.1	42.9	47.5
30 degree	575.8	32.1	32.0	38.4	38.4	29.8	33.7
45 degree	454.5	14.0	14.7	27.5	27.5	11.8	15.5

- The 45 degree does not generate enough power, and the 30 degree leaves little margin
- All of the cases are within the temperature limit
  - This is due to the lower absorptivity compared to IMM cells

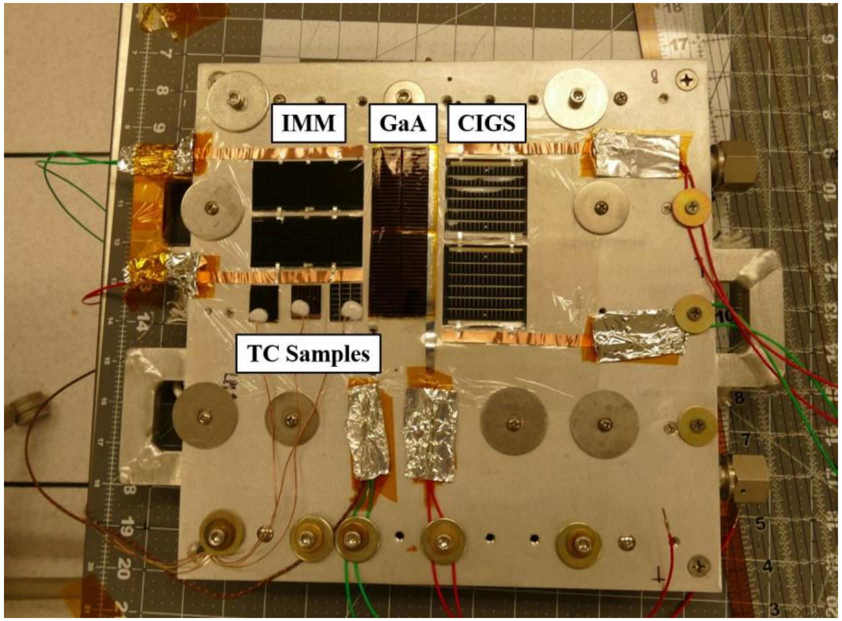
Thermal Testing

- Manufacturers do not have good data on how the thin-film cells react at high temperatures
- Testing was performed to quantify temperature produced degradation and failure points
- Three types of cells were tested:
  - Copper Indium Gallium Diselenide (CIGS)
  - Gallium Arsenide (GaA)
  - Inverted Metamorphic Multijunction (IMM)
- Test coupons were made that contained a sample of each cell type on a common backer
  - Coupons also included small piece of inactive material for each cell to serve as TC locations

Cell Coupon and Test Apparatus

- Coupon was placed in a vacuum chamber and illuminated by a solar simulator
- Multiple tests were run at differing durations and temperatures

Test Coupon

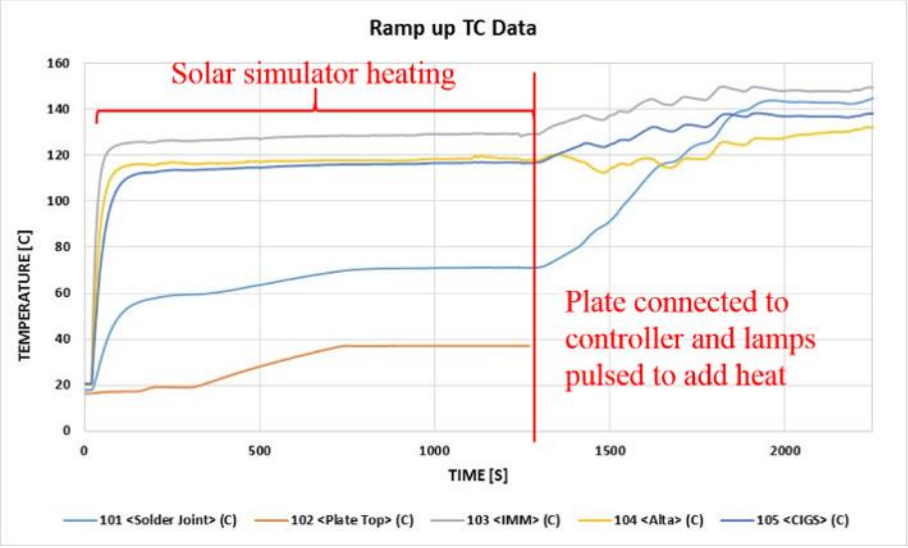


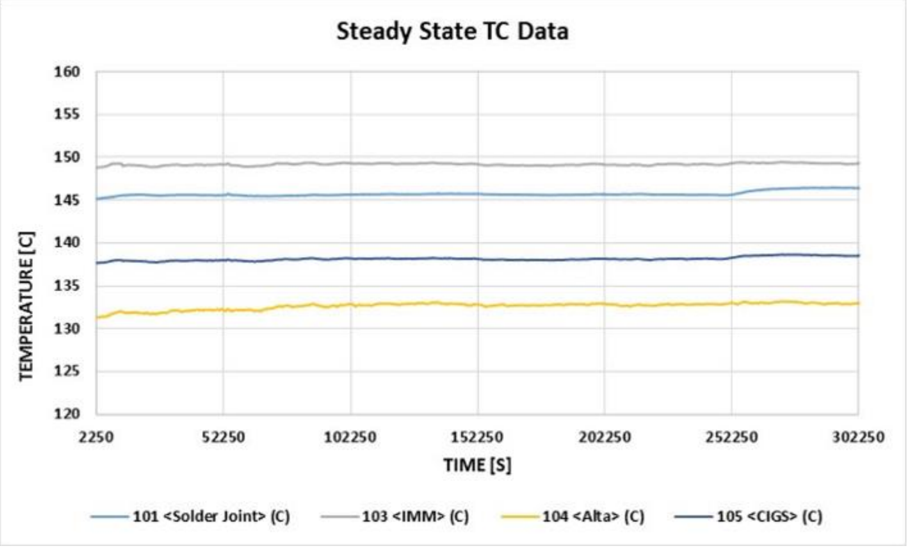
Coupon in Chamber

Courtesy of Dr. John Carr, NASA MSFC

Test 1 Temperature Issue

- The solar simulator provided the majority of the heat load, but IR lamps placed behind the sample were used as needed to raise the temperature
- The results from the first test did not match the pre-test prediction
  - This prompted a discussion about how the control temperature was being measured





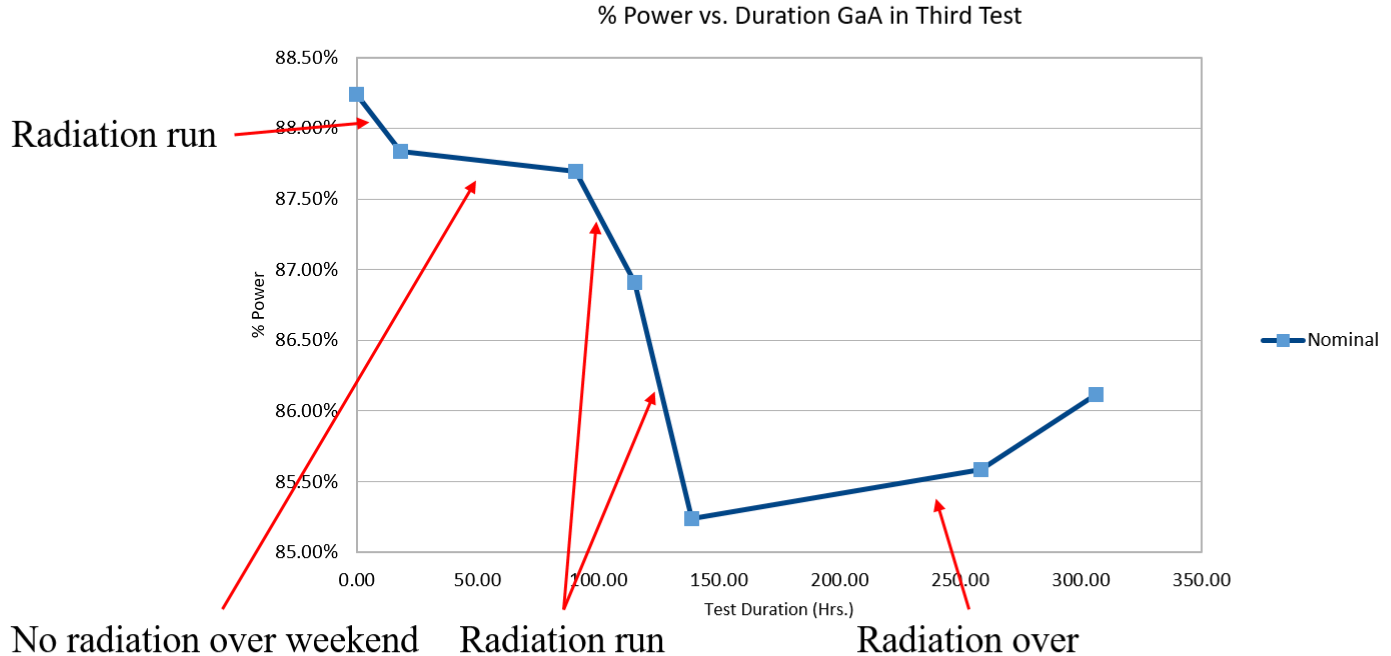
Courtesy of Dr. John Carr, NASA MSFC

Test 1 Temperature Issue

- It was thought that the test reached a higher temperature than measured
  - Additional thermocouples were added to supplement the three on the inactive cell samples
- After retesting it was found that test 1 was over the desired temperature by anywhere from 17-37 degrees C

Radiation Issue

- During a third test it was discovered that there was a radiation leak from an adjacent test chamber
  - It can be seen below that during known periods of radiation leakage there was accelerated cell degradation
  - It is speculated that this could have caused some of the issues in the first two tests



Courtesy of Dr. John Carr, NASA MSFC

Testing Results

- The results for the first four tests are shown below
  - The fourth test showed promise after all the kinks were worked out of the system
- A fifth test will be conducted using a full coupon that simulates the entire mission profile

Test Number	Sample(s)	Temperature	Runtime	EOL Performance	Notes
1	Full Coupon	>>140.6C	213hrs	CIGS @ 4.20% IMM @11.5% GaA @ 51.20%	Real temp as high as 180°C
2	Full Coupon	125C	75.8hrs	CIGS @ 34.72% IMM @ 31.03% GaA @ 6.11%	GaA shorted out during test
3	GaA	100-110C	306hrs	81.97%	Radiation exposure from adjacent test
4	GaA	110-112C	168hrs	88.22%	No radiation exposure from adjacent test

Conclusion

- Thin-film solar cells are a promising technology for space applications
  - They provide large mass and cost savings which is beneficial to any project
  - Flexibility allows for new deployment mechanisms to be designed
- They are not without issues and provide an interesting thermal challenge
  - The only viable way found so far is to increase the view factor to space
  - This can be challenging for surface missions with tight power requirements