Effective Annealing of 1 MeV Electron and 3 MeV Proton Damage in Silicon Solar Cells at 65°C and Maximum Power Point Conditions

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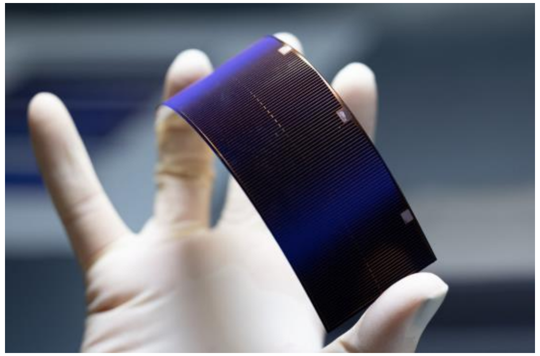
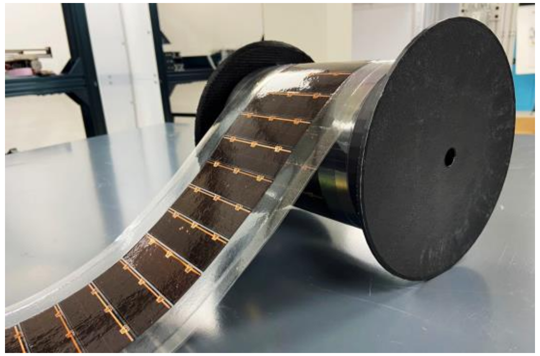
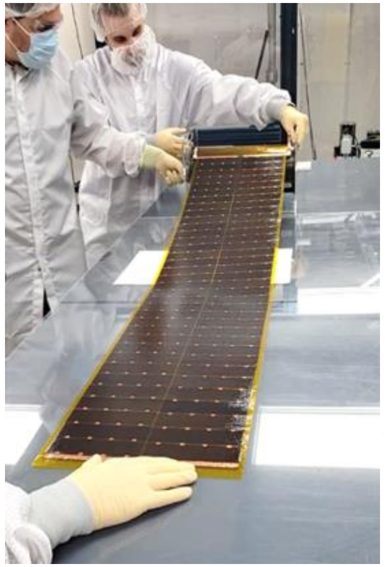
Contents

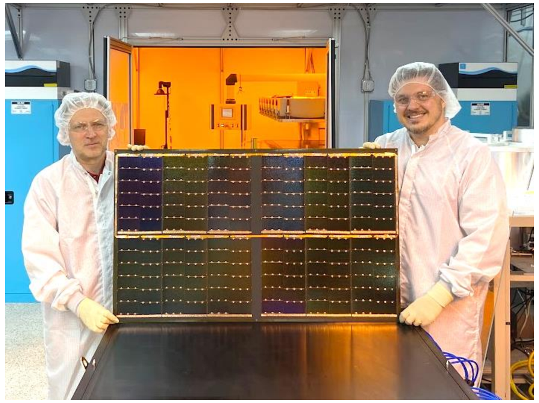
Solestial exists to deliver abundant energy in Space

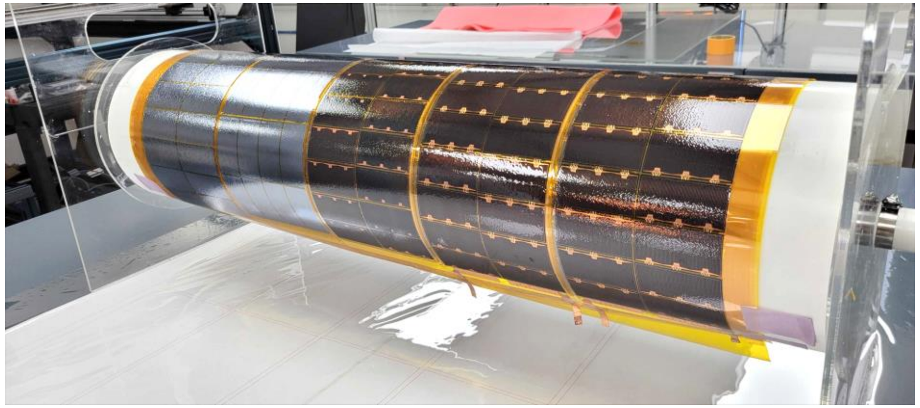
- Silicon solar technology with breakthrough radiation hardening in a light-weight rollable package.
- Company stablished in 2013 and has been serving space missions since 2023.
- Manufacturing facility in Tempe Arizona, with 30,000 sq ft dedicated industrial space for 1 MW production by the end of 2024.
- 38 Employees and growing.
- 10 MW capacity by 2027.


Ultrathin silicon solar cell


Rollable Bifacial Solar Power Module

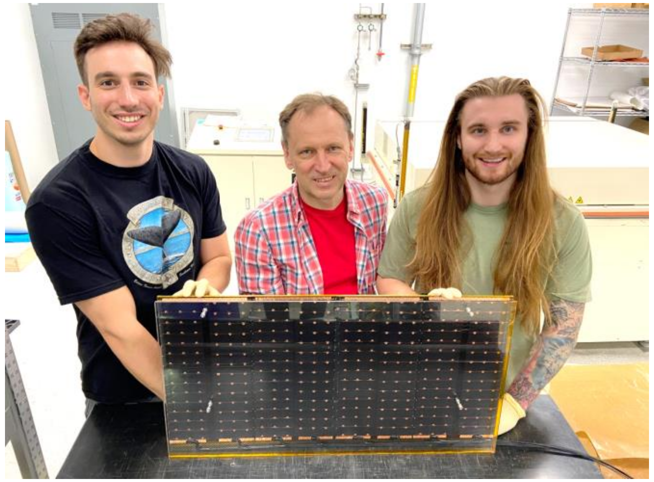

100W Rollable Solar Blanket

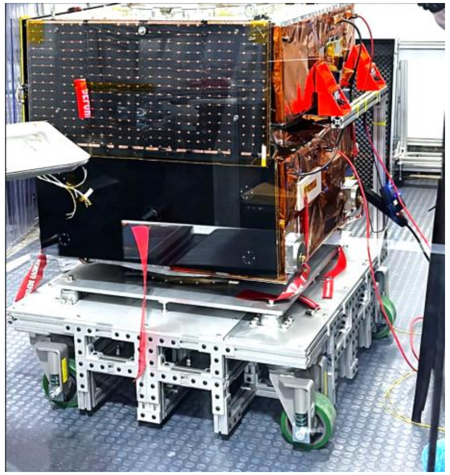

Rigid Panel Solutions, 120W

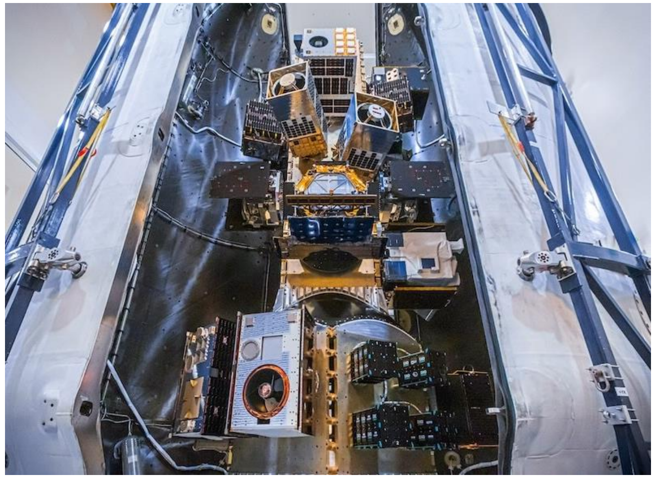

500W Rollable Solar Blanket Prototype, no extra substrate

Space Heritage

- Flew 60W panel with Atomos and 2 x 30W panels with another commercial customer on SpaceX Transporter 10 in March 2024.
- Both spacecraft are nominal in orbit.
- Upcoming 2024 flights:
- 1x ISRO PSLV C59
- 3x Transporter 11
- 2x Transporter 12

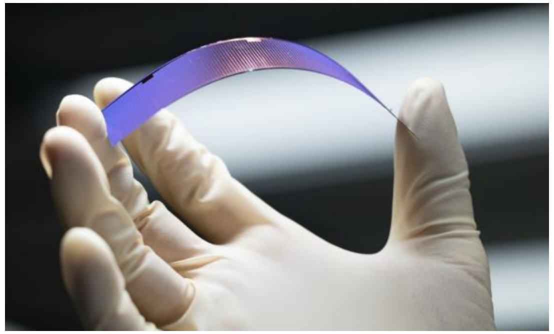






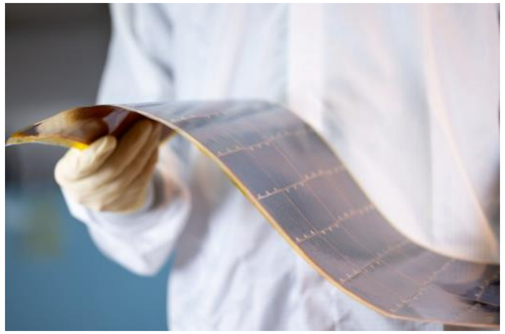
Solestial Products

Rad Hard Silicon Solar Cells – "X-HJT"



- Space-stable silicon solar cells made in the US.
- Self-curing of radiation damage at operational temperatures enabled by defect engineering and 20 microns thickness.
- On demand cell sizing to meet custom electrical requirements with maximum packing density.
- Gen 1: 18.5% BOL AM0 efficiency – delivering today
  Gen 2: 20.0% efficiency – starting end of 2024
  Gen 3: 22-23% efficiency – starting 2027

Flexible Solar Power Modules

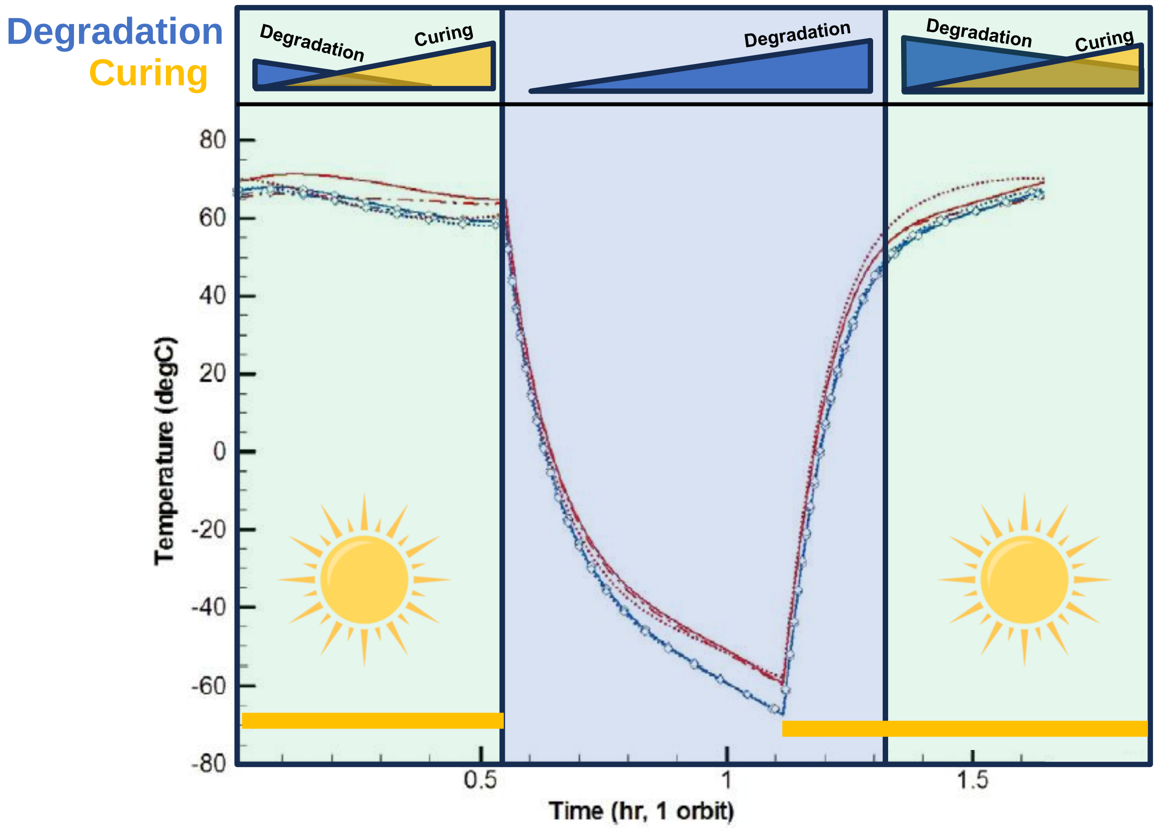


- Circuit integrated packaging with a thin, low-mass polyimide films, silicone encapsulants, and a stack of capping layers serving as a UV filter and AO barrier.
- 5 cm bending radius.
- 400 g/m^2 mass.
- Compatible with flexible or rigid solar array configurations.
- Bifacial cells and modules by default.

Introducing the Concept of a Self-Curing Solar Cell

- Solestial solar cells can anneal radiation damage at operating conditions (1,366 W/m^2 light exposure, 65^{o}C-90^{o}C temperature at maximum power point.
- We expect our solar cells will recover power every time they see the sun and when the cell temperature is >65^{o}C.
- To predict the performance of the system we balance defect formation rate and annealing rate in real time
  - Defect formation rate will be a function of the spacecraft orbit.
  - Annealing rate is be a function of cell temperature

Simulated Solar Cell Temperature Profile for a LEO Mission



Temperature data: Kim, Han, 2010

How to Measure Hourly Defect Formation Rate?

- **Method 1: measure hourly damage**
  - Commonly used accelerators have a very high flux. Annual radiation dose is accumulated within seconds of exposure.
  - One hour in space degradation not measurable due to a high flux.
- **Method 2: interpolate higher damage**
  - Expose a solar cells to 10-years worth of radiation in one minute, as its normally done for space cells qualification. This will also be not be representative of the field conditions due to the cluster defect formation under high fluxes.
- **Compromise:**
  - For this experiment we are targeting 1 year worth of exposure and linearly interpolate to get hourly dose.

Dose Selection for Annealing Experiments

Hourly and Daily Doses	1 Year Dose	10 Years Dose Received in Minutes
Not available due to high flux of available accelerators	Selected for experiments as a results of trade	Additional cluster defects formation not expected for the cells in the field providing annealing works.
1e10 e/cm^2	1e14 e/cm^2	1e15 e/cm^2

Variation of Damage Between Different 1 MeV Electron Sources

- **Background:** Solestial has been comparing reference cell degradation after 1 MeV electrons from several facilities, including recent data from **Mercury Plastics**.
- **Findings:** We observed some variation between different facilities that are probably due to using different fluence measurement methods and beam scanning techniques.
- **Solestial's approach:** we use NIST data as a reference.
- **Degradation rate:** average degradation for 1 MeV 1e14 e/cm^2 is 120 mV. In a typical LEO mission solar cell will receive this dose over one year. So, the degradation rate is 120 mV / 365 / 24 = **0.014 mV/hr.**
- But for example, in MEO solar cells will receive 1e14 e/cm^2 in 1 month. So, degradation rate will be 0.16 mV/hr.

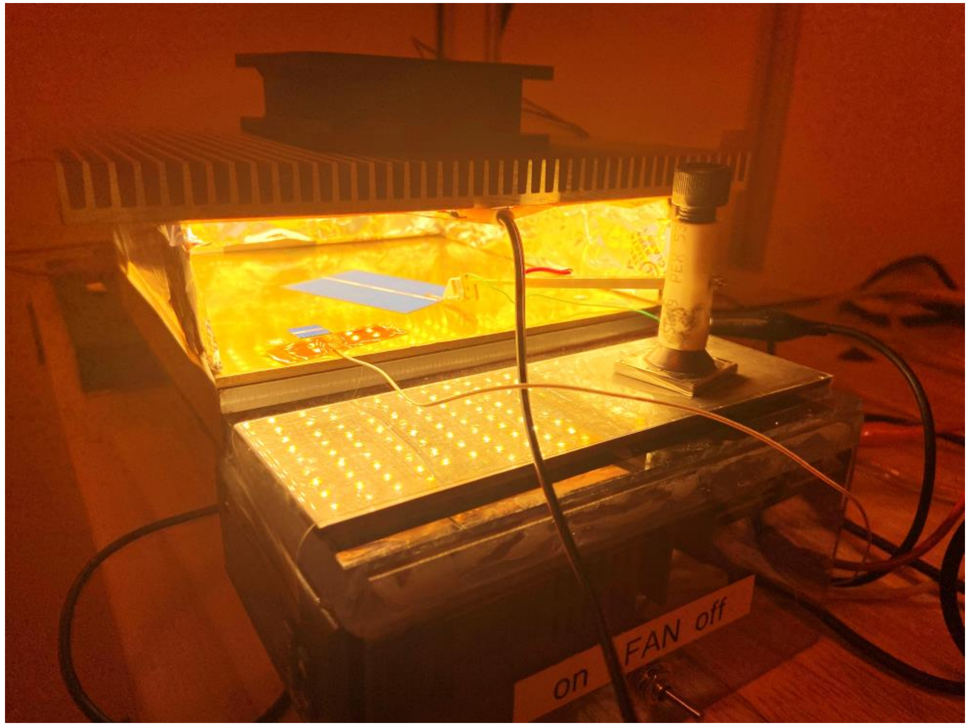
Fluence	Initial Voc	Voc After Irradiation			
		NIST (2019)	FNAL (2021)	CEA (2022)	Mercury Plastics (2023)
(e/cm²)	(mV)	(mV)	(mV)	(mV)	(mV)
1.00E+14	730	653	-	620	615
5.00E+14	730	-	-	580	570
1.00E+15	730	584	600	570	555

NIST – National Institute of Standards and Technology
FNAL – Fermi National Accelerator Laboratory
CEA - French Alternative Energies and Atomic Energy Commission
Mercury Plastics – private company

Annealing Setup

- **Devices**
  - Reference cell: 60 µm SHJ cell of 7x4 cm^2
  - Test device: 20 µm SHJ cells of different dimensions

- **Annealing**
  - Conducted in atmosphere
  - Light source – white LED array, 1366 W/m^2 intensity
  - Solar cell can be at Open Circuit (OC) or Maximum Power Point (MPP) conditions
  - I-V curve swept every 1 min and solar cell set to a new MMP
  - Jsc, Voc, pFF, FF and Efficiency recorded every minute



Annealing Results at Open Circuit

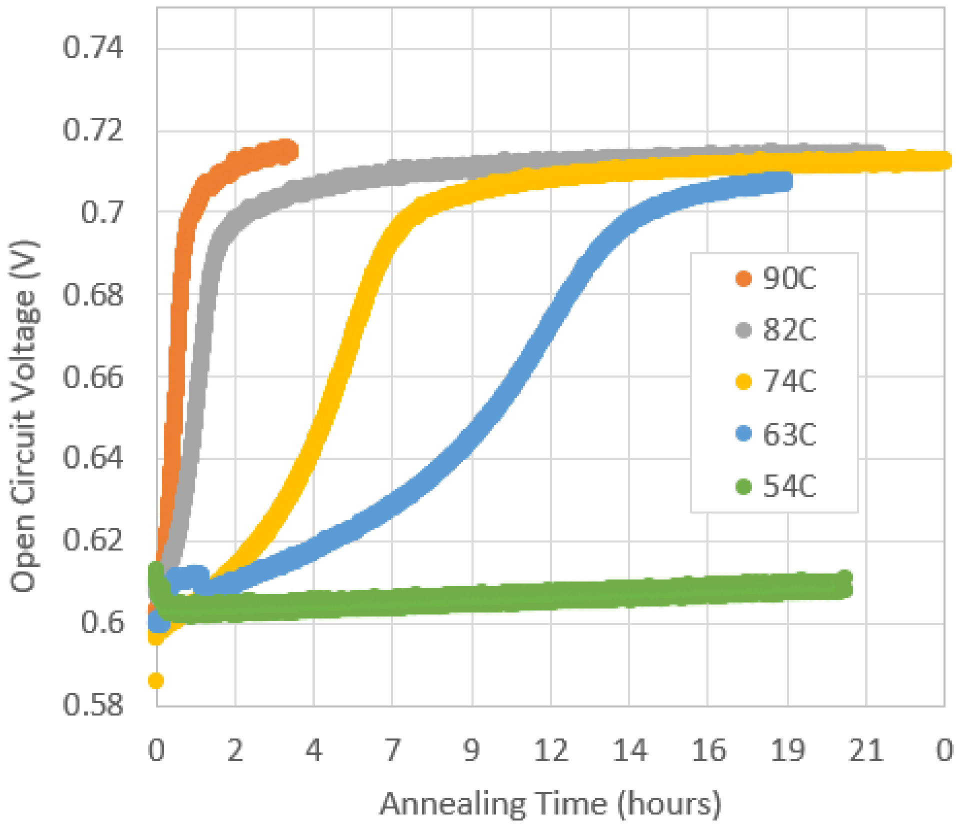
- Achieved full recovery of one year worth of damage (1e14 e/cm² fluence) at **open circuit** under light in less than 2 hours at 90°C, and less than 24 hours at 63°C.

- *Preliminary* average annealing rate for 1 MeV 1e14 e/cm² at open circuit:

Temperature (°C)	Annealing Rate (mV/hr)
90	40
82	15
74	8
63	5
54	0.5

Degradation rate in LEO	0.014

Irradiation: 1 MeV electrons, 1e14 e/cm² fluence
Annealing: at **open circuit** under 1366 W/m² light



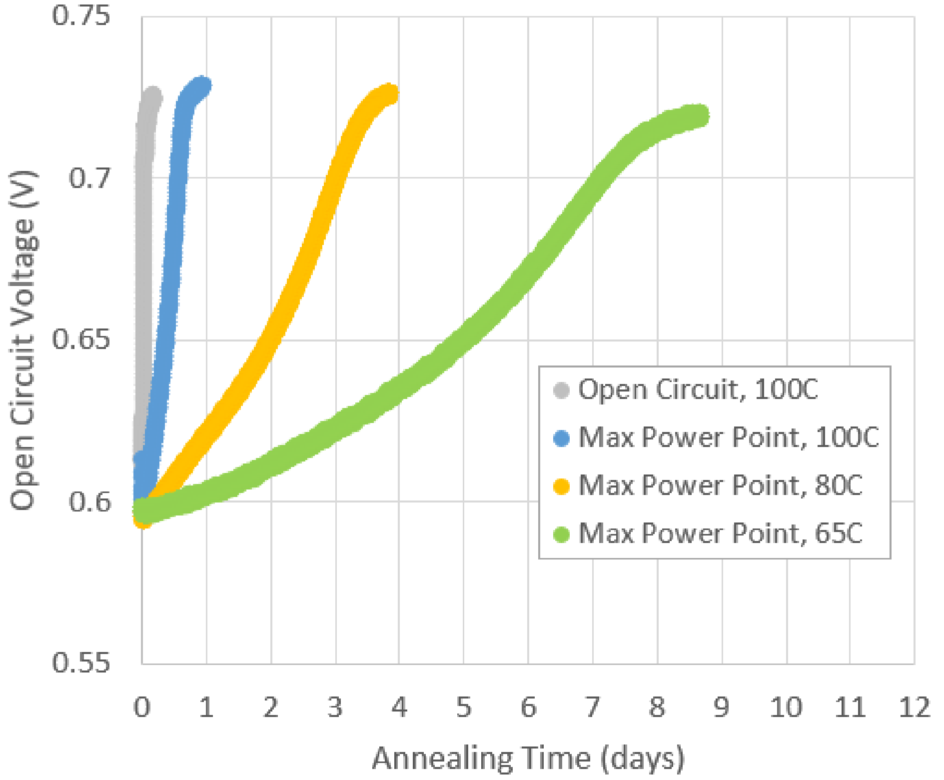
Annealing Results at Maximum Power Point

- Achieved full recovery of one year worth of damage (1e14 e/cm² fluence) at **maximum power point** under light in less than 2 days at 100°C, 4 days at 80°C and 9 days at 65°C.
- Annealing rate at maximum power point is approximately 10 times slower than at open circuit.
- *Preliminary* average annealing rate for 1 MeV 1e14 e/cm² at maximum power point:

Temperature (ºC)	Annealing Rate (mV/hr)
100	5
80	1.3
65	0.5

Degradation rate in LEO	0.014

Irradiation: 1 MeV electrons, 1e14 e/cm² fluence
Annealing: at **maximum power point** under 1366 W/m² light



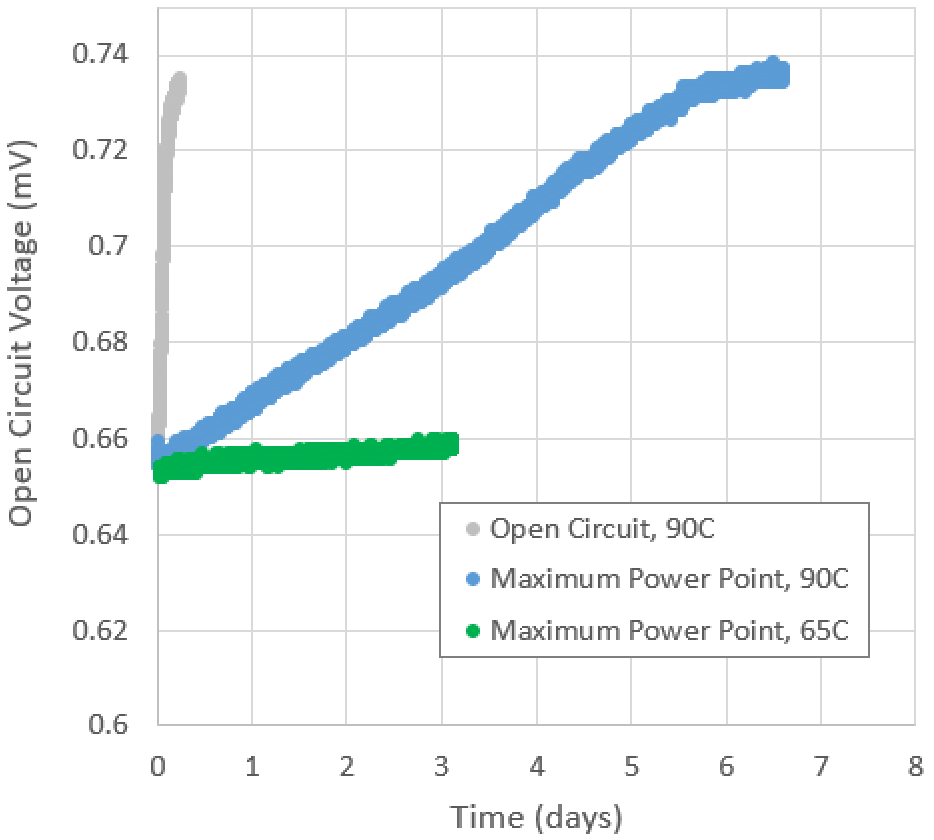
Preliminary Proton Damage Annealing

- **Proton Energy and Fluence:** 3 MeV 1e10 p/cm²
- **Degradation rate:** average degradation for 3 MeV 1e10 p/cm² is 65 mV. In a typical LEO mission solar cell will receive this dose over one month. So, the degradation rate is 65 mV / 30 / 24 = **0.09 mV/hr.**
- Achieved full recovery of one year worth of damage (3 MeV, 1e10 p/cm2 fluence) at **maximum power point** under light in less than 7 days at 90°C.
- *Preliminary* average annealing data for 3 MeV 1e10 p/cm² protons at maximum power point:

Temperature (ºC)	Annealing Rate (mV/hr)
90	0.5
65	0.07

Degradation rate in LEO	0.09

Irradiation: 3 MeV protons, 1e10 e/cm² fluence
Annealing: at **maximum power point** under 1366 W/m² light



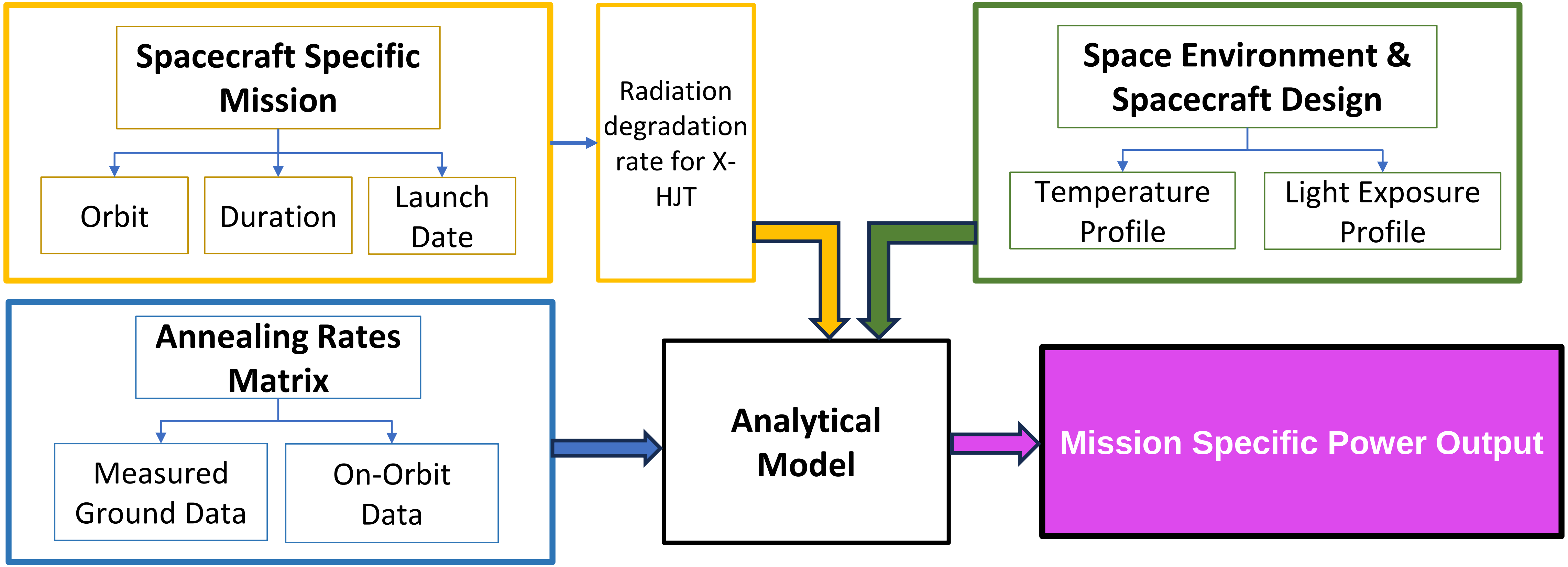
Integrated Solar Array Power Output Modeling

- Multi-Orbit Space Missions and Self-Curing Solar Cells require an innovative way to calculate power output.
- Traditional predicting models do not recreate the real conditions in space.
- Solestial is developing an integrated solar power model to accurately predict the array performance through its dedicated mission.
- Objectives:
  - Design SPMs that maximize the power density and reduce unnecessary mass - remove conservatism from power output predictions.
  - Design mission test campaigns that align with its actual environment - remove conservatism from test requirements, reduce cost and reduce durations on test campaigns.

Solar Array Modeling Output

	Present	Proposed
Radiation damage annealing	Not included	**Included**
Power output	BOL and EOL	At any moment in time
Sizing of the array	Oversizing	Optimized

Integrated Solar Power Modeling

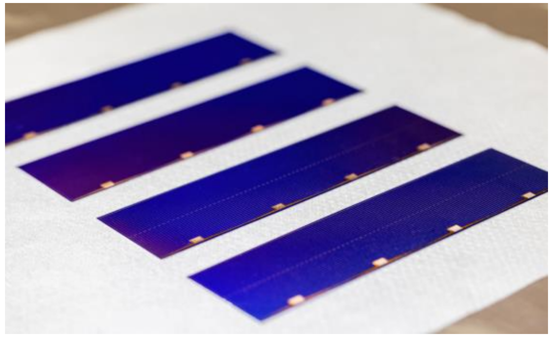


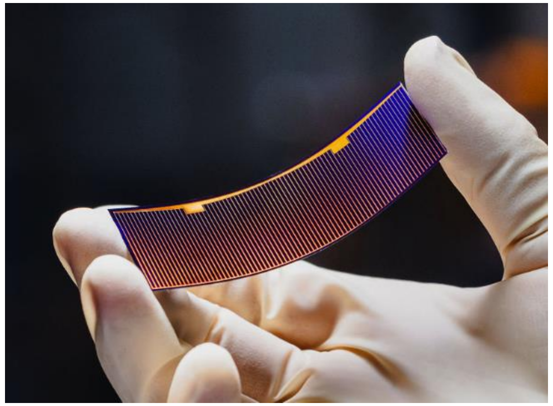
Conclusion

- First time report annealing rate at maximum power point under light which most closely recreates operational conditions in space.
- Data suggests that annealing rate of electron and proton damage at maximum power point even at 65°C is higher than the defect formation rate.
- Developing an integrated power model to predict power output using mission specific radiation dose and solar cell illumination and thermal profiles.

Future Work:

- Collect efficiency data and more proton damage annealing data.
- Completion of the integrated model and validation with on-orbit results.



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