mPower
TECHNOLOGY

Si-Based Space Solar Cell Qualification and Characterization

Space Power Workshop

April 20, 2021

Acknowledgements

Authors: Kaveh Rouhani, Murat Okandan,
Jason Wilson, Stuart Crosby,
Ian Aeby, Oscar Buitrago

mPower would like to thank AFRL, the Aerospace Corporation,
U.S. Army, NASA, TRAD, TNO, ECN and Texas A&M
for their support and collaboration

Introducing DragonSCALES™

Customizable solar modules composed of singulated high efficiency silicon cells on a flexible substrate

- Enables innovative high-power density designs

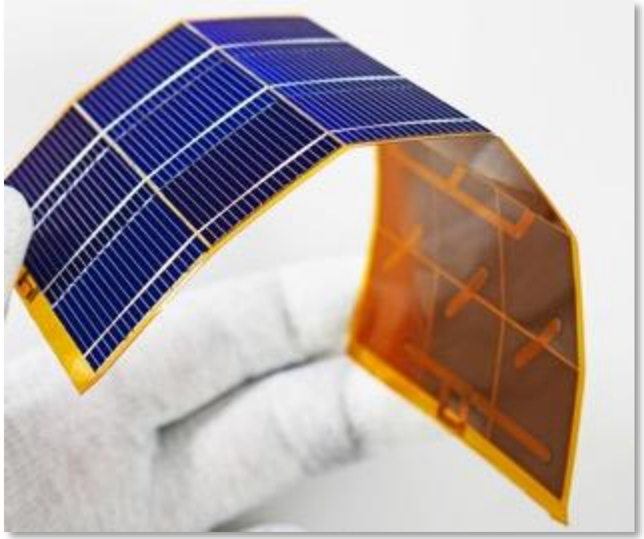
Reduces cost and mass in deployable arrays

- Dramatically reduces touch labor and integration
- Plug-and-play…provides a full solution at connector

In production with semiconductor fabrication partners

- Rapid volume ramp (10+ MW/yr)
- Panel assembly partners qualification in progress

Device-level optimization and mission specific thermal coatings and radiation recovery during operations



DragonSCALES™

mPower TECHNOLOGY

Technology Comparison

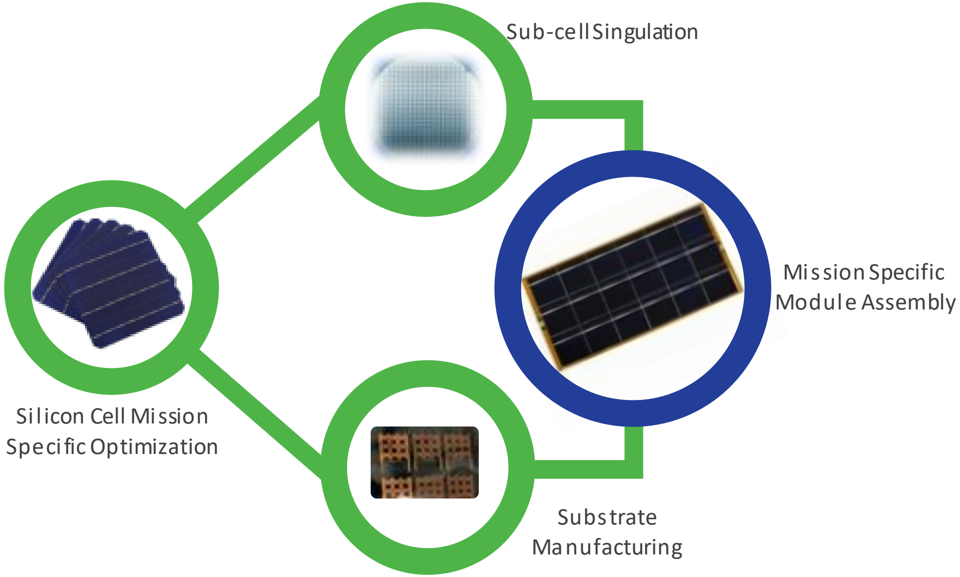
Selection Criteria	Multi-Junction GaAs	DragonSCALES™
Module Cost ($/watt)	$$$$+	$
Beginning of Life Power Density (watts/m^2)	430	271
Density (gram/cm^3)	5.3	2.3
Production Scale	1X	5X-10X
Stowage Volume*	10X	<1X

** Assuming flexible array deployment systems*

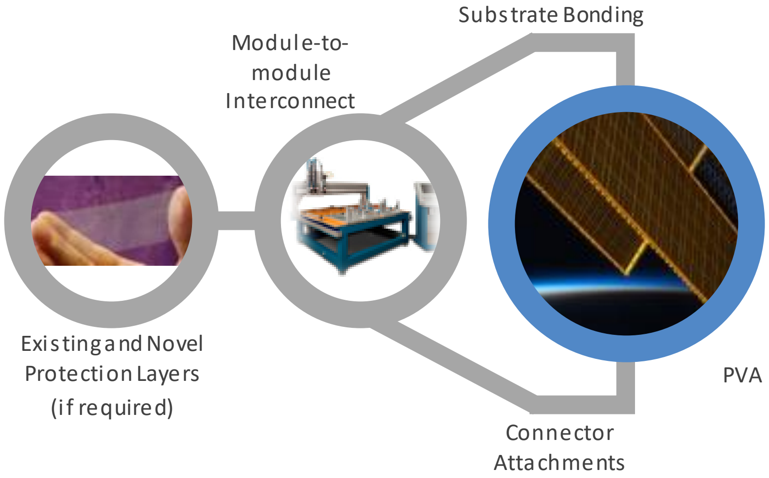
Manufacturing Space Modules

Leverages established Si PV and Semiconductor Processes

Module Manufacturing



PVA Assembly



AIAA S-111 Qualification for DS-100

Characterization

Qualification

Characterization/Qualification	Status
C1 Electron Radiation	In progress; 1MeV electrons completed
C2 Proton Radiation	**Complete**; additional energy levels and new technology testing continues
C3 Bend Test	**Complete**
C4 Mechanical Strength	**Complete**; Not applicable to DragonSCALES; testing for bending around radius and strength testing performed
C5 AM0 Light IV at Temps	In progress; Temperature coefficients for DS-100 after radiation exposure in progress
C6 QE	**Complete**
C7 Dark IV	**Complete**
C8 Capacitance Effects	**Complete**
C9 ESD Human Body	**Complete**
C10 Accelerated Life Test	**Complete** by data and analysis
Q1 Weld and Solder Test	In progress; Not directly applicable to DragonSCALES – additional processes and controls at production stage to ensure survivability
Q2 Solar Cell Integrity Test	In progress; ~1,000 cycles from -120C to +120C complete to date
Q3 Cell Level Humidity Test	In progress; Humidity test

mPower TECHNOLOGY

Electron & Proton Radiation Characterization (C1, C2)

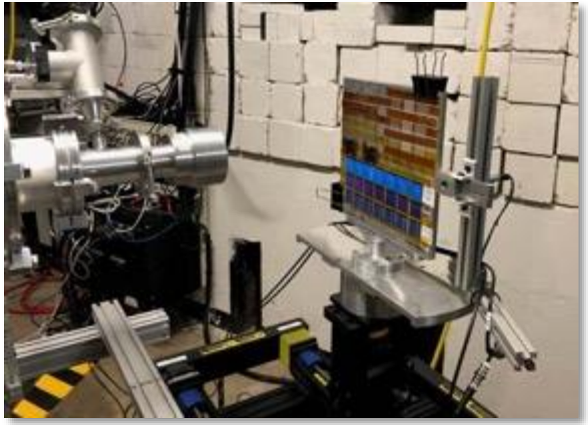
mPower radiation modeling based on the JPL Method complete

- Comparison of DS-100 exposures to historical silicon cell data shows some differences
- Model for relative damage coefficients complete
- Normal- vs omni-incidence conversion model complete

Electron 1MeV and Proton 10 MeV testing are complete

Family of DS-100 cells designed for high- and low-radiation environments

Data is sufficient for accurate EOL power analyses and radiation analyses for most mission types (LEO, MEO, GEO and interplanetary)



Particle	Energy Level (MeV)	Fluence (1MeV)
Proton	10MeV	3.5E13, 8.5E13, 3.5E14, 8.5E14, 3.5E15
Proton	2.8MeV	3.5E13, 3.5E14, 3.5E15
Proton	285KeV	4.5E13, 3.5E15
Electron	1MeV	1E14, 1E15, 5E15, 1E16
Electron	3MeV	1E14, 1E15, 5E15, 1E16

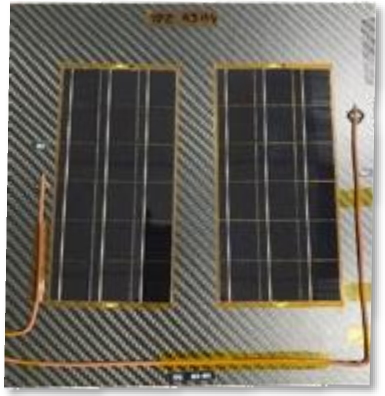
Solar Cell Integrity Test (Q2)

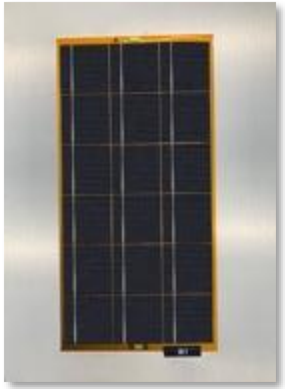
Thermal Cycle at NTS:

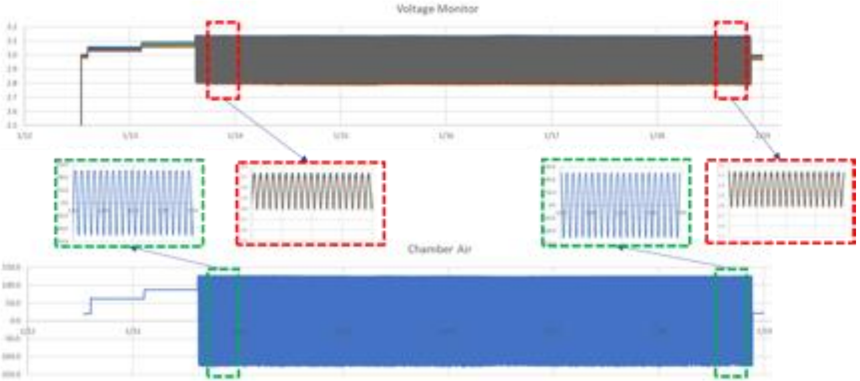
- Full continuity monitoring
- Light IV and EL testing at each break
- Successfully passed 980 cycles
- Thermal range: +120C to -120C

Testing includes modules from 3 suppliers:

- Gen2 module (no glass)
- Gen2 module (glass)
- Gen3 module
- Aluminum and carbon fiber substrates





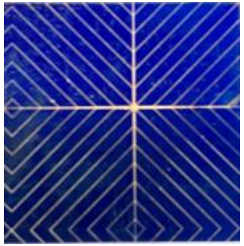


mPower TECHNOLOGY

Beginning of Life – Pre-Radiation Measurements

Wafer 23.4% Datasheet

Supplier A	Isc (A)	Jsc (mA/cm2)	Voc (V)	FF(-)	eta (%)	Impp (A)	Vmpp (V)	max P (mW/cm2)
	10.908	48.48	0.68	0.81	23.4	10.281	0.582	26.58



27 mm die – TNO Measurements AM 1.5

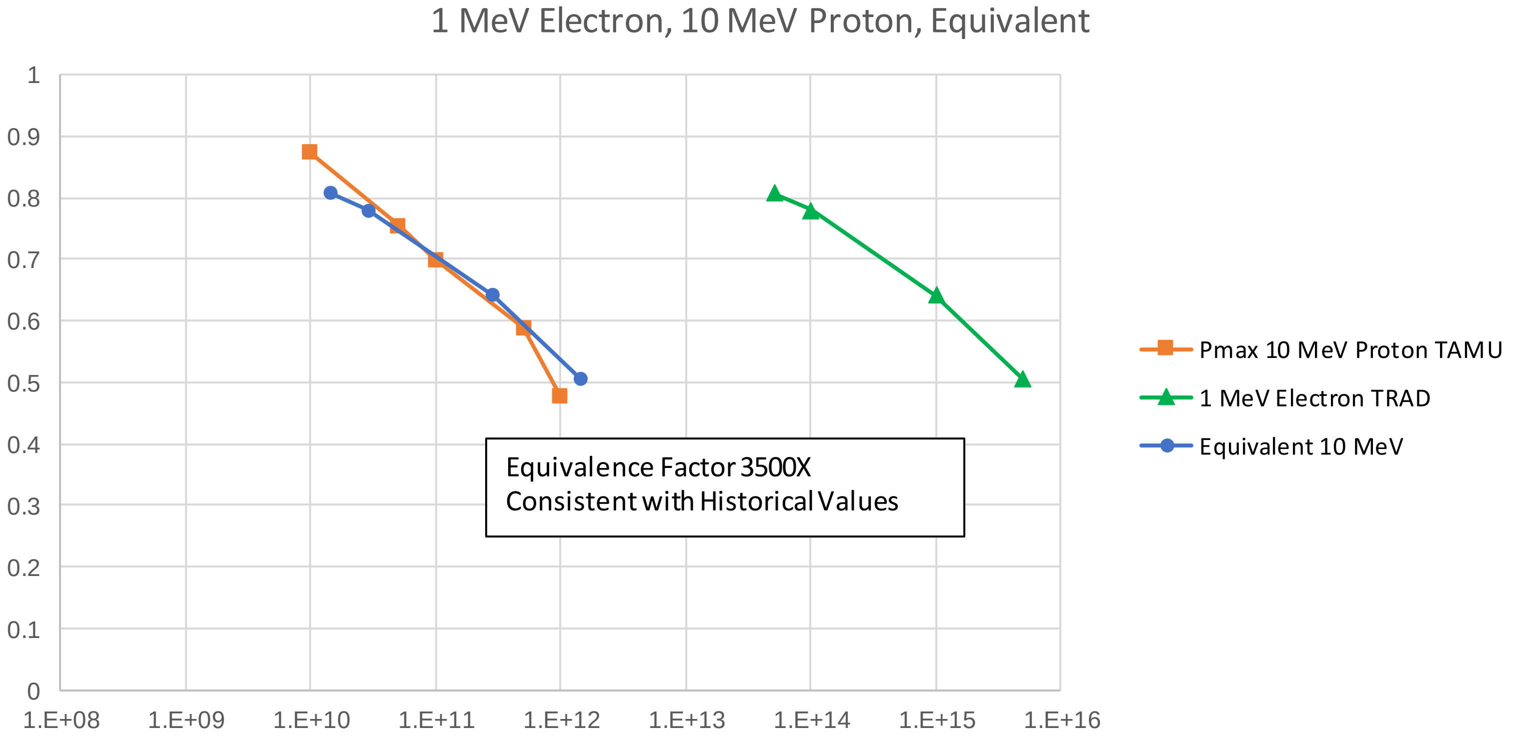
	Isc (A)	Jsc (mA/cm2)	Voc (V)	FF (-)	eta (%)	Impp (A)	Vmpp (V)	max P (mW/cm2)
average	.295	40.526	0.668	0.773	20.917	0.276	0.552	20.92
stdev	0.001	0.168	0.002	0.006	0.178	0.002	0.004	0.18

27 mm die -- AFRL AM0

	Isc (A)	Jsc (mA/cm2)	Voc (V)	FF(-)	eta (%)	Impp (A)	Vmpp (V)	max P (mW/cm2)
average	0.367	50.571	0.669	0.76	18.740	0.343	0.541	25.46
stdev	0.012	0.522	0.003	0.01	0.270	0.013	0.009	0.89

mPower Data for BOL Product Line

Confirm 1 MeV Equivalence



mPower TECHNOLOGY

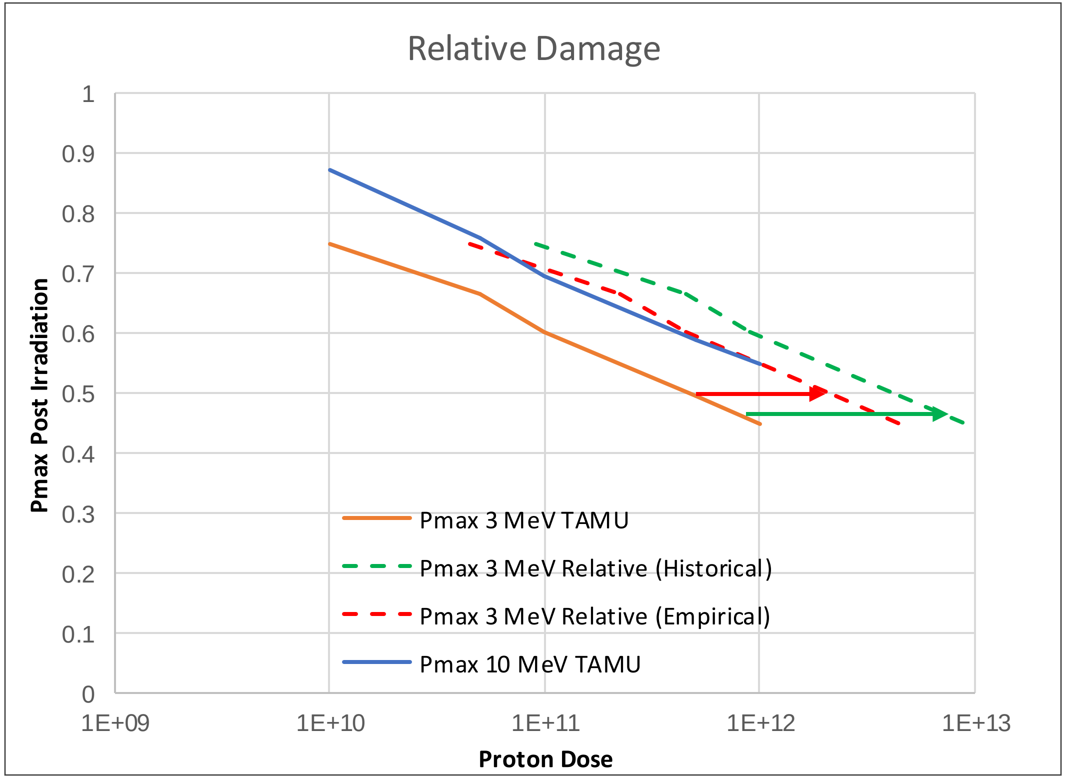
Proton Relative Damage Coefficients

Cells irradiated at 3 and 10 MeV

Historical relative damage coefficients for 3 MeV are 9X the damage at 10 MeV

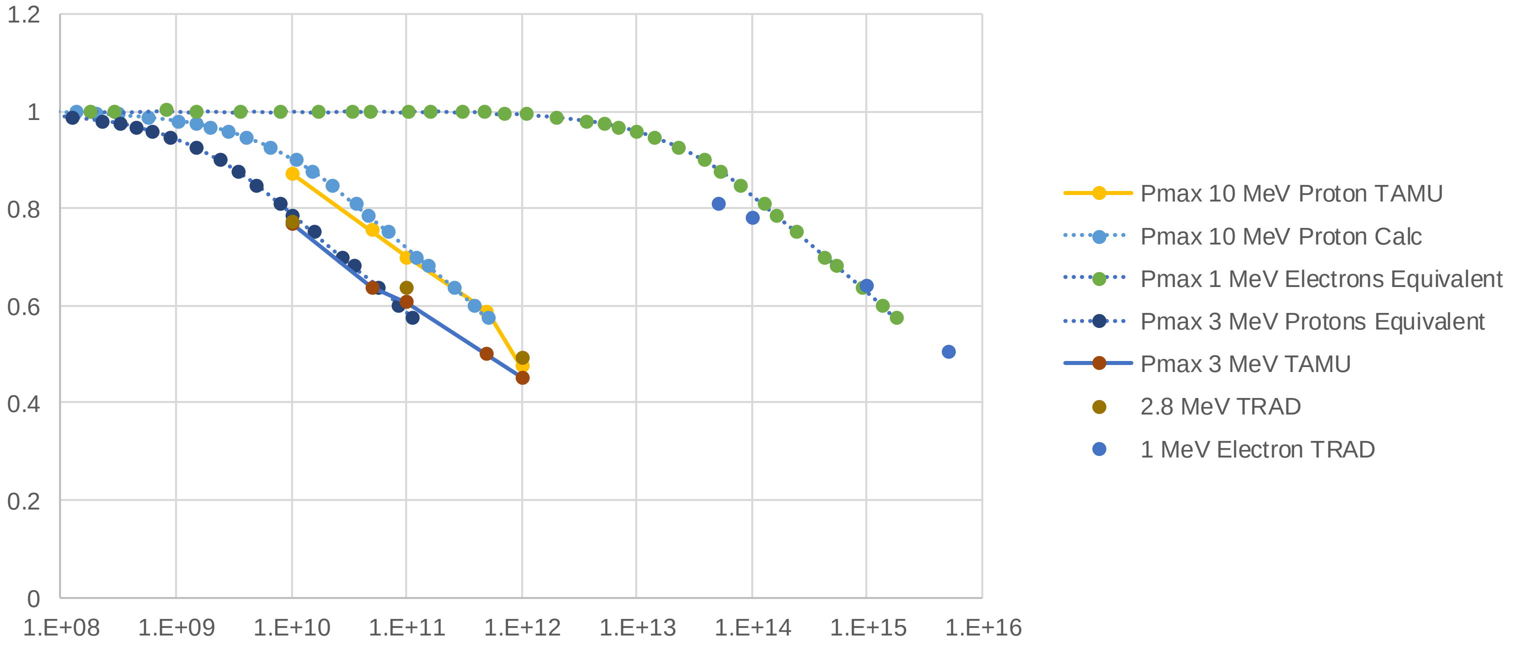
DS-100 relative damage coefficients measured for 3 MeV are 4x the damage at 10 MeV

Significant improvement from historical cells



Model for Relative Damage Coefficients

Using the relative damage coefficient of 3500X for 1 MeV Electrons we can estimate the particle damage for DS-100 as function of fluence (dotted blue lines) – this can be applied to all cell parameters



mPower TECHNOLOGY

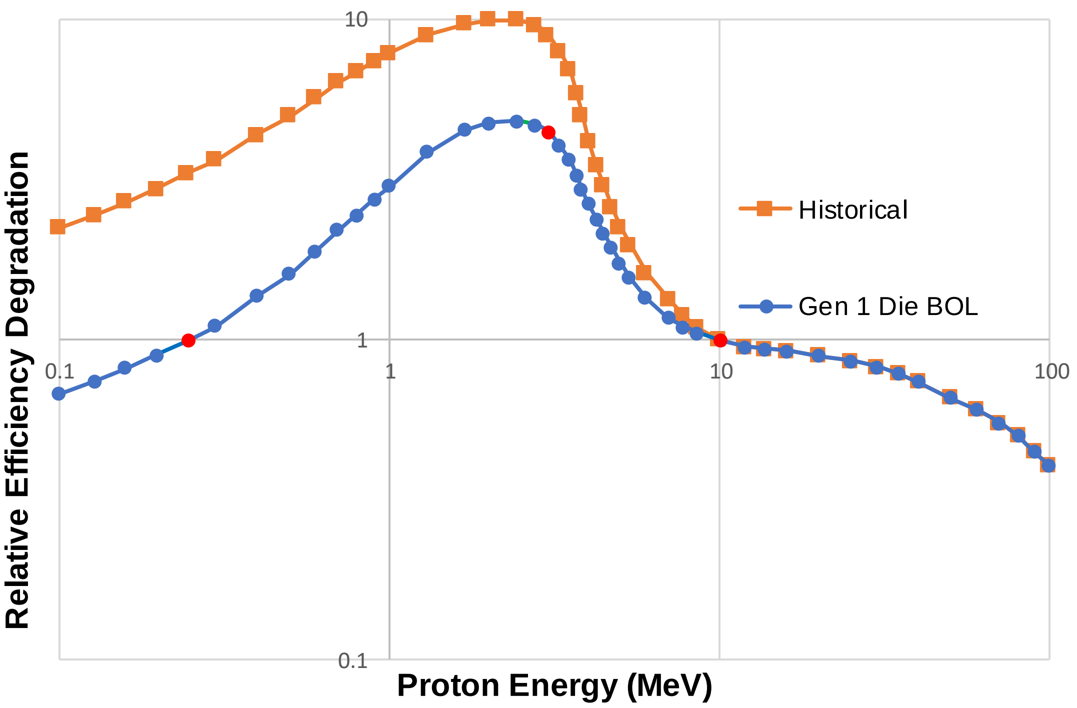
Relative Damage Coefficient Curve

Curve is based on measured data and an estimate of behavior at lower and higher energies

mPower data for DS-100 cells is tracking well vs. historical Si data

DS-100 improve relative damage coefficients vs. earlier space Si cells

Better retention and performance than historical cells (to be refined further)



mPower TECHNOLOGY

DragonSCALES Radiation Protection Options

Glassing Options	Advantages	Disadvantages
Traditional Space Glass (ceria doped borosilicate glass)	• Heritage technology • 4-10% higher w/m2 estimate • Blocks UV from adhesive layer • Minimal darkening under protons • Stable under AO and UV	• Cost • Manufacturing capacity • Availability
Alternative Glass (borosilicate glass, no ceria doping)	• Cost • Manufacturing capacity • Availability • Stable under AO and UV • Great for Si technology (darkens in the blue)	• Darkening under protons mainly under 400nm, not as critical for Si (2-5% relative loss in power) • Passes UV to adhesive layer but again with minimal effects for Si

DragonSCALES is built with all-glass technologies

Manufacturing Capacity

mPower leveraging state-of-the-art manufacturing technologies

- Integrated circuit packaging technology with space solar manufacturing

Current space manufacturing capacity: 50KW/year

Space manufacturing capacity: 1.5MW/year

- Six-month lead time

Readily scalable to tens of MW/year

mPower TECHNOLOGY

DragonSCALES Target Applications

Constellations

Need lower cost solutions

Higher manufacturing throughput

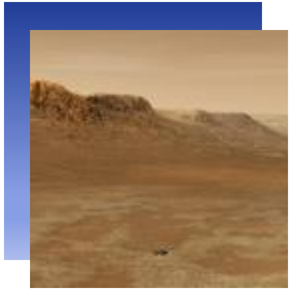
LEO thermal cycling survivability (>50K)

Electric Orbit Raising

Early evaluation indicates high power retention after electric propulsion orbit raising for DS-100 family of cells

Cold Missions

Si temperature coefficients favor cold vs. hot environments



Landed Systems

Lower mass and flexible stowage and deployment capabilities provide favorable solutions for landing missions

LEO Missions

Ideal for large LEO deployments, flexible LEO arrays and body mounted missions

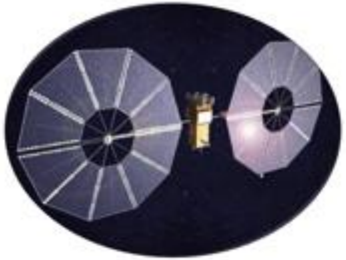
mPower TECHNOLOGY

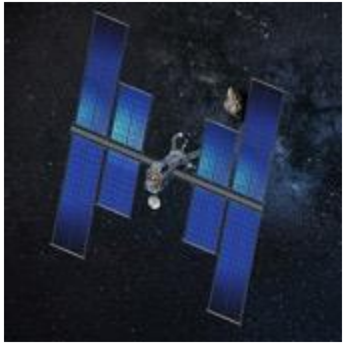
DragonSCALES and New Deployment

Rollable and semi flexible deployment solutions under development

Combining new deployment technologies with unique DragonSCALES features:

- Reduces cost
- Improves mass, deployed area and stowage volume advantages





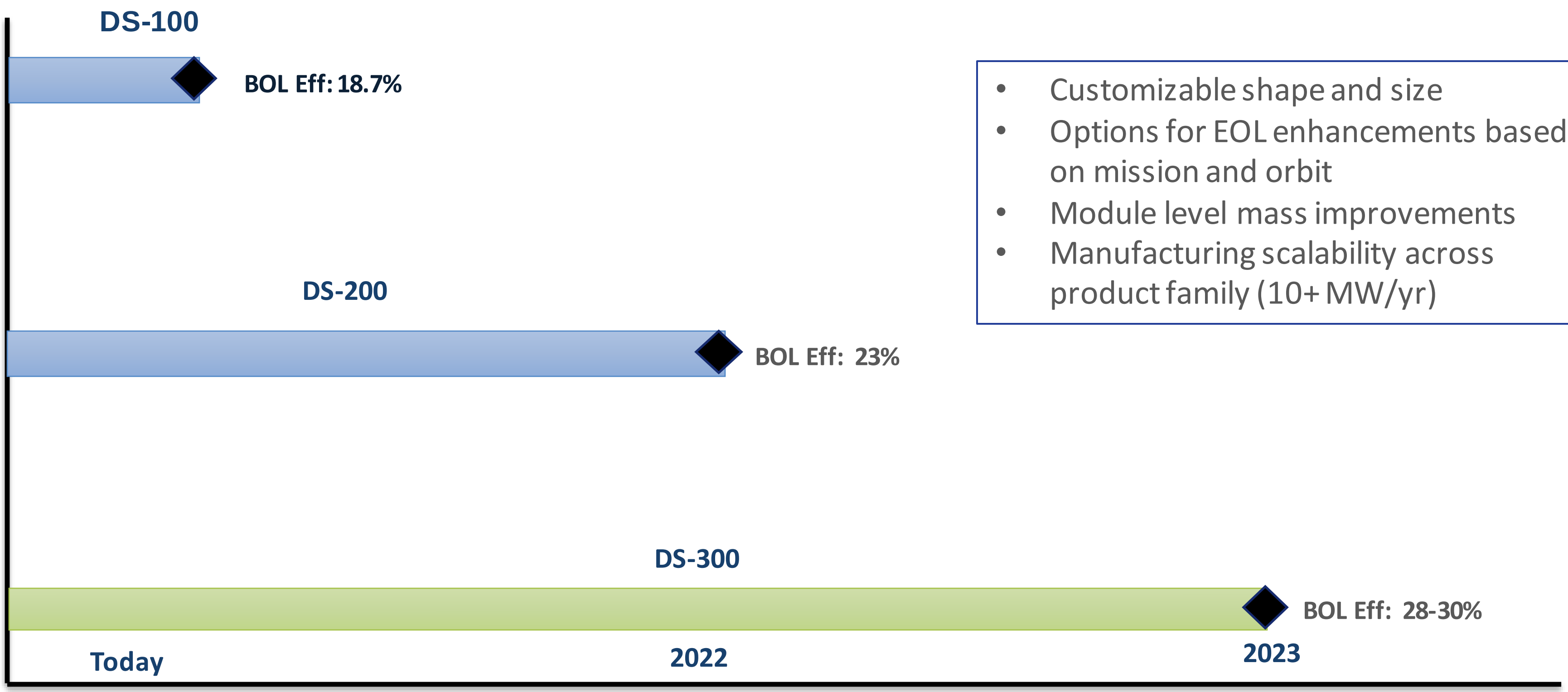
Radiation resiliency and recovering technologies can be combined to improve all key design parameters including cost:

- Electric propulsion transfer orbits
- Other radiation intensive missions

mPower TECHNOLOGY

Technology Roadmap

Lowest System Cost per Watt at EOL



- Customizable shape and size
- Options for EOL enhancements based on mission and orbit
- Module level mass improvements
- Manufacturing scalability across product family (10+ MW/yr)

mPower TECHNOLOGY