STACKED SOLAR-SHADE RADIATOR ARCHITECTURE

Mission Scenario Analysis: Performance Utility Across Lunar Operating Environments

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Executive Summary

The Stacked Solar-Shade Radiator Architecture (SSSRA) collocates a solar array tier above a thermal radiator, using the array structure to shade the radiator face from direct solar flux while a low-emissivity backside coating suppresses IR backradiation from the array underside. The architecture was characterized at lunar south pole conditions (2–6° sun elevation), but its utility varies substantially across mission scenarios.

The central finding of this analysis is counterintuitive: SSSRA's thermal value scales with sun elevation angle. At polar conditions — its design point — unshaded alternatives remain competitive and the architecture's primary value is footprint consolidation and dust resilience. At mid-latitude and equatorial noon conditions — scenarios outside its original characterization — passive shading transitions from an optimization to an operational necessity, and SSSRA becomes the enabling architecture.

Scenario Summary Matrix

Mission Scenario	Sun Elevation	Unshaded Viability	SSSRA Advantage	Verdict
South Pole — Nominal	2–6°	Functional, 444 W/m²	Footprint + dust resilience	STRONG
South Pole — Dust Degraded	2–6°	Degraded, ~363 W/m²	Immune to solar loading	CRITICAL
Mid-Latitude — Dawn/Dusk	5–20°	Functional but declining	Modest thermal, good footprint	STRONG
Mid-Latitude — Midday (45°)	~45°	Severely degraded	Shading essential	CRITICAL
Mid-Latitude — Near Noon (70°+)	70–90°	Net-negative possible	Only viable solution	CRITICAL
Equatorial — Full Lunar Day	0–90°	Unusable at peak hours	Enables continuous ops	CRITICAL
Mobile Platform (any latitude)	Variable	Orientation-dependent	Fixed geometry, robust	CRITICAL
Static Outpost, Constrained Footprint	Variable	Requires separate zone	Collocates power + thermal	STRONG
Static Outpost, Ample Footprint (polar)	2–6°	Fully viable	Marginal benefit	MARGINAL
Permanently Shadowed Region	N/A	Fully viable (no solar)	No benefit	NOT APPLICABLE

Thermal Performance by Sun Elevation Angle

Measured values from parametric analysis at 310 K radiator temperature, low-ε backside coating (ε_back = 0.10), 0.4 m clearance. High sun angle values are extrapolated estimates based on solar loading trends.

Sun Angle	Unshaded Clean (W/m²)	Unshaded Degraded (W/m²)	SSSRA Clean (W/m²)	SSSRA Degraded (W/m²)	SSSRA Net Advantage
2°	455	381	302	255	**+Footprint value**
6°	444	363	302	255	**−141 W/m² (but viable)**
15°	419	305	302	255	**Parity / marginal lead**
45°	~200–250 est.	~100–150 est.	~280–300	~240–260	**Significant lead**
70°+	Net-negative risk	Likely negative	~270–295	~230–250	**Architecture-defining**

Note: High sun angle SSSRA values assume adequate overhang geometry to maintain shadow coverage on the radiator face. Geometry validation required for angles above 30°.

Mission Scenario Analysis

1. South Pole — Nominal Operations (2–6° Sun Elevation)

Operating Environment

The design-point environment. Sun angle is consistently low, typically 2–6° at south polar sites. Thermal environment is relatively benign for radiator performance. Solar flux arrives nearly tangentially to a horizontal radiator surface.

Unshaded Performance

Fully viable. Clean unshaded radiators achieve ~444 W/m² net rejection at 6°, well above the shaded configuration (302 W/m²). Unshaded systems are thermally competitive and mechanically simpler.

SSSRA Performance & Value

SSSRA costs ~141 W/m² relative to an unshaded clean radiator at this angle — requiring roughly 25% more radiator area for equivalent heat load rejection. The architecture earns its complexity premium through footprint consolidation (power and thermal in the same ground patch) and through reduced sensitivity to dust accumulation. Neither benefit is mission-critical in a well-resourced polar outpost with ample apron area and routine maintenance access.

Verdict

STRONG. Architecture is justified for mobile platforms and constrained outpost footprints. Less compelling for static installations with ample real estate and maintenance access. Dust resilience adds long-duration value.

2. South Pole — Dust-Degraded Radiator Coatings

Operating Environment

Same geometry as nominal polar operations, but radiator surface absorptance has increased due to dust deposition, reducing effective net rejection capacity. A realistic long-duration operational scenario.

Unshaded Performance

Meaningfully degraded. Clean unshaded achieves ~444 W/m²; degraded unshaded drops to ~363 W/m² at 6° — an 18% reduction. At higher sun angles the degradation is more severe, as increased absorptance compounds with higher solar flux incidence.

SSSRA Performance & Value

The shaded radiator face is not exposed to direct solar flux. Dust accumulation affects only IR emission (emissivity), not solar absorption. SSSRA degraded performance (255 W/m²) remains stable relative to the clean case, while the unshaded degraded case continues to decline with sun angle and dust load. The architecture provides a degradation floor that unshaded systems cannot match.

Verdict

CRITICAL for long-duration assets where radiator cleaning is infrequent or infeasible. The dust resilience benefit compounds over mission lifetime and becomes the dominant value driver in multi-year surface operations.

3. Mid-Latitude — Dawn / Dusk Operations (5–20° Sun Elevation)

Operating Environment

Mid-latitude sites experience low sun angles at dawn and dusk periods of the lunar day. Thermal conditions are similar to polar nominal, with sun angles comparable to the design-point characterization.

SSSRA Performance & Value

Performance closely mirrors the polar nominal case. Shade benefit is present but the unshaded alternative remains competitive in clean conditions. Primary advantages are footprint consolidation and dust resilience, identical to the polar case. However, mid-latitude assets must also be designed for the full sun elevation range through local noon — an important planning constraint.

Verdict

STRONG. Similar value profile to polar nominal, but the asset’s design must account for much higher sun angles later in the operational day. If the mission operates through lunar noon, the architecture must be sized for that regime, not the dawn/dusk baseline.

4. Mid-Latitude — Midday Operations (30–60° Sun Elevation)

Operating Environment

Sun angles climb substantially at mid-latitudes through local noon. At 45°N/S latitude, noon sun elevation approaches 45°. This represents conditions substantially outside the documented parametric envelope, requiring geometry extrapolation.

Unshaded Performance

Severely degraded. Solar flux now strikes the radiator face at increasingly normal incidence. For dust-degraded surfaces, net rejection capacity may fall below 150 W/m² — less than half the polar clean performance. Thermal management margins erode rapidly, potentially requiring system-level thermal curtailment.

SSSRA Performance & Value

With adequate array overhang geometry (see Section 5), the shaded radiator remains decoupled from solar angle. Rejection capacity holds near the low-sun-angle shaded value (~280–300 W/m² clean). This represents a substantial and growing advantage over unshaded alternatives as sun angle rises.

Geometry Requirement

Overhang sizing becomes non-trivial. At 0.4 m clearance and 45° sun elevation, the sun-facing array edge must extend ~0.4 m beyond the radiator edge to maintain full shadow coverage. This is manageable for a static installation; it adds structural mass and CG height on mobile platforms.

Verdict

CRITICAL. Unshaded thermal management becomes unreliable in this regime. SSSRA transitions from a footprint optimization to a performance-enabling architecture. Array overhang must be explicitly sized for the maximum operational sun angle, not the design-point polar value.

5. Mid-Latitude to Equatorial — Near-Noon High Sun Angles (70–90°)

Operating Environment

Near-zenith solar illumination represents the most thermally hostile lunar surface environment. The sun is nearly overhead, solar flux strikes horizontal surfaces at nearly normal incidence, and surface IR emission from heated regolith adds a secondary thermal load. This is the design-point environment for any equatorial mission.

Unshaded Performance

Potentially non-functional for net thermal rejection. Solar absorption on the radiator face at near-normal incidence, particularly for dust-degraded surfaces, may equal or exceed the radiator's own rejection capacity. Net rejection goes to zero or negative. An unshaded radiator at equatorial noon is a thermal liability, not an asset.

SSSRA Performance & Value

This is the architecture's strongest operating condition. The shade structure is most effective precisely when solar loading is most severe. The radiator operates near its low-sun-angle shaded performance (~270–295 W/m² clean). Simultaneously, the solar array on top is generating maximum power — peak insolation coincides with peak thermal shading effectiveness. Combined power and thermal output per unit ground footprint is maximized.

Combined Yield

A single SSSRA ground patch at noon delivers approximately 200 W electrical/m² (at 20% panel efficiency, 1 kW/m² insolation) plus ~280–300 W thermal rejection/m² — roughly 480–500 W of combined functional output per m². A conventional separated layout in the same footprint provides only one or the other, and the thermal option is non-functional.

Geometry Requirement

Near-zenith sun angles demand substantial overhang at any practical clearance height. At 0.4 m clearance and 80° elevation, overhang requirement exceeds 2 m — impractical for a mobile platform. Equatorial noon operations require either very large array tiers, reduced clearance, or edge baffles/skirts to maintain shadow geometry. This is the primary design challenge for equatorial SSSRA deployment.

Verdict

CRITICAL — architecture-defining. For any equatorial surface asset that must operate through local noon, passive shading of the radiator is not optional. SSSRA is the most mass-efficient method to deliver that shading while recovering power-generation utility from the shade structure. Geometry must be redesigned for this regime.

6. Mobile Platform — Any Latitude

Operating Environment

Mobile platforms (rovers, crew mobility vehicles) face variable sun angles throughout operations, cannot be oriented to minimize solar loading on radiators, and have severe mass and CG constraints. The FLEX rover and similar platforms represent the canonical mobile use case.

SSSRA-Specific Value

Fixed-geometry thermal management is a fundamental mobile platform requirement. A conventional deployable radiator that must be articulated to avoid solar loading adds mass, complexity, and failure modes. SSSRA provides a passive, geometry-independent thermal management solution: the array structure shades the radiator regardless of vehicle heading or sun azimuth (with appropriate horizontal extent), and solar angle variation is accommodated by overhang sizing rather than active control.

The footprint consolidation benefit is most pronounced on mobile platforms, where every structural element must serve multiple functions. An array tier that simultaneously generates power and shades a thermal radiator is a mass-efficient solution that a separated architecture cannot match.

CG Constraint

Clearance height is a gating CG constraint for mobile platforms. Minimum viable clearance (0.3–0.4 m) is preferred, accepting higher F_array values and slightly reduced shade benefit in exchange for lower CG. Overhang for high sun angle coverage must be balanced against cantilevered structural mass.

Verdict

CRITICAL across all latitude operations. Mobile platforms cannot rely on favorable sun angles or radiator articulation. SSSRA's passive robustness and footprint consolidation are mission-enabling rather than merely advantageous.

7. Permanently Shadowed Regions

Operating Environment

Permanently shadowed regions (PSRs) near the lunar poles receive no direct solar illumination. Thermal environment is dominated by IR from surrounding terrain and sky view to deep space.

SSSRA Value

Minimal to none. Solar shading of the radiator is irrelevant when there is no solar flux. The low-ε backside coating may provide marginal benefit by reducing IR backradiation from overhead structures, but the architecture's primary value drivers are absent. Power generation is also not available from the solar array tier, eliminating the combined yield advantage.

Verdict

NOT APPLICABLE. Conventional radiator designs are fully viable and architecturally simpler in PSR environments. SSSRA adds mass and complexity with no thermal return.

Utility Ranking: Most to Least Consequential

Rank	Scenario	Primary Value Driver	Assessment
1	**Equatorial / near-noon (70–90°)**	Enables thermal rejection when unshaded is non-functional; combined power+thermal yield maximized	MISSION-ENABLING
2	**Mobile platform, any latitude**	Passive geometry independence; footprint consolidation; no articulation required	MISSION-ENABLING
3	**Mid-latitude midday (30–60°)**	Growing advantage over unshaded as solar loading increases; overhang geometry tractable	STRONGLY JUSTIFIED
4	**Long-duration surface ops, dust degradation**	Degradation-immune solar loading; performance floor that unshaded cannot sustain	STRONGLY JUSTIFIED
5	**South pole / mid-lat dawn-dusk, constrained footprint**	Collocates power and thermal in same ground patch; design-point characterization	JUSTIFIED
6	**South pole, ample footprint, maintained radiators**	Marginal benefit over simpler unshaded design; complexity premium not fully recovered	MARGINAL
7	**Permanently shadowed regions**	No solar flux, no solar shading benefit, no solar power generation	NOT APPLICABLE

Design Implications

Overhang Sizing Is the Critical Variable

The polar characterization assumed minimal overhang — the array and radiator are approximately co-extensive. For mid-latitude and equatorial deployment, overhang on the sun-facing edge must be explicitly sized for the maximum operational sun elevation. The relationship is: required overhang ≈ clearance × tan(sun elevation). This single parameter determines whether SSSRA maintains its performance advantage at high sun angles or loses it to direct radiator illumination.

The Architecture Needs a Mid-Latitude Parametric Characterization

The documented parametric analysis covers 2–15° sun elevation. Validation of rejection capacity, view factors, and overhang geometry at 30–90° elevation is the highest-priority gap for extending SSSRA to general lunar surface applicability. This would transform the architecture from a polar design with extrapolated benefits to a characterized general solution.

Reframe the Value Proposition

SSSRA is most accurately positioned as a general lunar surface thermal management architecture whose value scales with sun elevation angle, rather than a polar architecture that tolerates other conditions. The south pole use case is the conservative, easy-to-characterize baseline. The equatorial noon case is where the architecture is most necessary and most differentiated. Marketing, proposal development, and technical documentation should lead with the high-sun-angle enabling case.

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