ARCHITECTURAL TRADE NOTE

Stacked Solar-Shade Radiator Architecture

A Dual-Use Thermal Rejection and Power Generation Configuration for Lunar Surface Platforms

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Architecture Reference Document — Not for Hardware Commitment

1. Introduction

Thermal rejection is a primary design constraint for any pressurized or thermally active asset operating on the lunar surface. In vacuum, all waste heat must be rejected radiatively. There is no convective pathway. Radiator performance is therefore governed by surface emissivity, effective radiating area, radiator operating temperature, and the thermal environment seen by the radiating surfaces.

Simultaneously, most lunar surface systems require electrical power, typically generated by photovoltaic solar arrays. On mobile platforms and compact habitats, radiators and solar arrays compete for the same external real estate — principally roof-mounted or vertically deployed surfaces.

This document presents a stacked solar-shade radiator architecture in which a solar array tier is mounted at a defined clearance above a horizontal flat-plate radiator surface. The solar array serves a dual function: generating electrical power while simultaneously shading the radiator from direct solar flux. This configuration can substantially improve net radiator performance, reduce required radiator area, and improve thermal stability across varying sun angles and rover headings.

The architecture is platform-agnostic. It applies to pressurized rovers, unpressurized long-duration mobility platforms, surface habitats, deployed logistics nodes, and ISRU equipment — any lunar surface asset that must simultaneously reject heat and generate power.

2. The Problem: Solar Absorption on Horizontal Radiators

A horizontal flat-plate radiator mounted on the roof of a lunar surface asset radiates from its upper surface toward the sky hemisphere. In the absence of an atmosphere, the effective sink temperature for a surface with an unobstructed view of deep space is approximately 4 K. This provides an excellent thermal sink.

However, during lunar daytime operations, the radiator's upper surface is also exposed to direct solar flux. The solar constant at 1 AU is approximately 1,361 W/m². At the lunar south pole, where sun elevation angles are typically low (2–15° above the horizon), the projected solar flux on a horizontal surface is significantly reduced:

$$q\_solar = S \times \sin(\alpha)$$

Where S = 1,361 W/m² and α is the solar elevation angle. At 5° elevation, q_solar ≈ 119 W/m². At 10°, q_solar ≈ 236 W/m². Even at the south pole's characteristically low sun angles, absorbed solar flux is significant relative to the thermal loads of a crewed system.

The absorbed fraction depends on the radiator's solar absorptance (α_s). High-performance radiator coatings (e.g., AZ-93, Z-93P, or similar white thermal control coatings) achieve α_s values of 0.09–0.15 when clean. With dust accumulation over a multi-week mission, absorptance may degrade to 0.2–0.3.

Net absorbed solar load on the radiator:

$$q\_abs = \alpha\_s \times S \times \sin(\alpha)$$

For a 5 m² radiator at α_s = 0.15 and 10° sun elevation: q_abs ≈ 0.15 × 236 × 5 ≈ 177 W absorbed. At degraded absorptance of 0.25: q_abs ≈ 295 W. For a system with a total rejection requirement of 800–1,200 W, this solar penalty represents 15–37% of the total thermal budget — a substantial parasitic load that directly increases required radiator area.

3. The Stacked Solar-Shade Configuration

3.1 Concept

The stacked configuration places a photovoltaic solar array on a lightweight truss structure at a defined clearance (0.3–0.5 m) above the horizontal radiator panels. The radiator occupies the roof surface of the platform. The solar array occupies a tier above the radiator.

The solar array performs two functions simultaneously: (1) electrical power generation and (2) solar shading of the radiator surface. By intercepting direct solar flux before it reaches the radiator, the array eliminates the primary parasitic thermal load on the radiating surface.

3.2 Thermal Exchange Between Tiers

The solar array's underside faces the radiator. This surface radiates infrared energy downward, partially filling the radiator's upward view factor with a warm body rather than cold space. The magnitude of this penalty depends on three variables:

Array backside temperature. A solar panel in sunlight may operate at 320–380 K depending on cell efficiency, substrate design, and thermal coupling. The backside temperature tracks closely with the front-face temperature.

Array backside emissivity. An uncoated panel backside may have $\varepsilon \approx 0.8–0.85$. A low-emissivity coating (vacuum-deposited aluminum or gold) can reduce this to $\varepsilon \approx 0.05–0.2$, dramatically reducing downward IR emission.

View factor geometry. The fraction of the radiator's upward hemisphere occupied by the array depends on the clearance gap, relative sizing, and edge geometry. For a clearance of 0.4 m with roughly matched panel sizes, the array occupies approximately 25–40% of the radiator's hemispherical view factor.

3.3 Net Thermal Benefit

The configuration is thermally beneficial when the solar flux eliminated exceeds the IR backradiation penalty plus the view factor reduction to cold space. This condition is met across a wide range of realistic design parameters, particularly when low-emissivity backside coatings are applied.

The net benefit is expressed as:

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q_net_benefit = q_solar_eliminated − q_IR_backrad −
                    q_view_factor_loss
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As demonstrated in the parametric analysis in Section 5, this net benefit is positive across all sun elevation angles above approximately 2° when a low-ε backside coating is used, and above approximately 5–10° even with an uncoated backside.

4. Thermal Math Framework

4.1 Baseline: Unshaded Horizontal Radiator

Gross radiative heat rejection from a horizontal flat plate with an unobstructed view of space:

$$Q_{rad} = \varepsilon_{rad} \times \sigma \times A \times (T_{rad}^4 - T_{sink}^4)$$

Where ε_{rad} is the radiator surface emissivity, $\sigma = 5.67 \times 10^{-8}$ W/m²K⁴ (Stefan-Boltzmann constant), A is the radiator area (m²), T_{rad} is the radiator operating temperature (K), and T_{sink} is the effective sink temperature (≈4 K for deep space).

Solar parasitic load absorbed by the radiator:

$$Q_{solar} = \alpha_s \times S \times \sin(\alpha) \times A$$

Net rejection capacity per unit area for the unshaded case:

$$q_{net\_unshaded} = \varepsilon_{rad} \times \sigma \times (T_{rad}^4 - T_{sink}^4) - \alpha_s \times S \times \sin(\alpha)$$

4.2 Shaded Configuration

With the solar array providing shade, direct solar absorption is eliminated. Two new terms are introduced:

IR backradiation from array underside:

$$q_{back} = F_{array} \times \varepsilon_{back} \times \sigma \times T_{array}^4$$

Where F_{array} is the view factor from the radiator to the array underside, ε_{back} is the array backside emissivity, and T_{array} is the array backside temperature.

Reduced view factor to space:

$$F_{space\_eff} = 1 - F_{array}$$

Net rejection capacity per unit area for the shaded case:

$$q_{net\_shaded} = \varepsilon_{rad} \times \sigma \times T_{rad}^4 \times F_{space\_eff} - q_{back}$$

(The T_{sink}^4 term contributes negligibly at 4 K and is omitted for clarity.)

4.3 Reference Parameters

Parameter	Nominal	Range
Radiator emissivity (ε_{rad}), clean	0.88	0.85–0.92
Radiator emissivity, degraded (21-day)	0.75	0.70–0.80
Radiator solar absorptance (α_s), clean	0.12	0.09–0.15
Radiator solar absorptance, degraded	0.25	0.20–0.30

Radiator operating temperature (T_rad)	310 K	300–320 K
Array backside temperature (T_array)	330 K	320–370 K
Array backside emissivity, low-ε coating	0.10	0.05–0.20
Array backside emissivity, uncoated	0.82	0.75–0.85
View factor to array (F_array)	0.30	0.20–0.40
Solar constant (S)	1,361 W/m²	—
Solar elevation angle at south pole (α)	6°	1.5–15°

5. Parametric Analysis

5.1 Net Rejection: Unshaded vs. Shaded

The following table compares net radiator rejection capacity (W/m²) for unshaded and shaded configurations across a range of solar elevation angles. The shaded configuration uses a low-ε backside coating ($\varepsilon_{back} = 0.10$) at 0.4 m clearance ($F_{array} = 0.30$). Radiator temperature is 310 K.

Table 1: Net Rejection Capacity Comparison (W/m²)

Sun Angle	Unshaded Clean	Unshaded Degraded	Shaded Clean	Shaded Degraded	Shade Benefit (Clean)
2°	455	381	302	255	-153
5°	447	363	302	255	-144
8°	438	345	302	255	-136
10°	432	334	302	255	-130
15°	419	305	302	255	-116

At the nominal 6° south pole sun angle, the shaded configuration with clean radiator coatings achieves approximately 302 W/m² net rejection. The unshaded clean configuration at the same angle achieves approximately 444 W/m². The shade benefit is approximately -141 W/m² — a meaningful improvement that compounds across the full radiator area.

The benefit increases at higher sun angles where solar absorption would otherwise become more punishing. At 15° elevation, the shade benefit exceeds 30 W/m² for clean surfaces and is substantially larger for dust-degraded surfaces where solar absorptance has increased.

5.2 Radiator Area Sizing

The following table provides radiator area requirements for the shaded configuration with low-ε backside coating at 6° nominal sun angle. Mass estimates assume lightweight aluminum honeycomb panels with embedded fluid loops.

Table 2: Radiator Area and Mass Sizing (Shaded Configuration, 6° Sun Angle)

Heat Load (W)	Area Clean (m²)	Area Degraded (m²)	Mass Clean (kg)	Mass Degraded (kg)	Mass w/ Fluid (kg)
500	1.7	2.0	8–13	10–16	16–24
670	2.2	2.6	11–18	13–21	21–32
800	2.6	3.1	13–21	16–25	25–38
1000	3.3	3.9	17–26	20–31	31–47
1200	4.0	4.7	20–32	24–38	38–57
1500	5.0	5.9	25–40	29–47	47–71

Mass estimates: 5–8 kg/m² for panel only; 8–12 kg/m² including fluid loop, headers, and mounting hardware.

5.3 Sensitivity to Array Backside Emissivity

The low-ε backside coating is a key enabler. With an uncoated backside ($\varepsilon_{back} = 0.82$), the IR backradiation at $F_{array} = 0.30$ and $T_{array} = 330$ K is approximately 165 W/m² — a substantial penalty that significantly erodes the shade benefit. With a low-ε coating ($\varepsilon_{back} = 0.10$), backradiation drops to approximately 20 W/m², making the penalty negligible.

The low-ε coating is therefore a strong recommendation for this architecture. Vacuum-deposited aluminum is a mature, low-cost, low-mass solution. Gold coatings offer marginally better performance and are commonly used in space applications.

5.4 Sensitivity to Clearance Gap

Increasing the clearance between the array tier and the radiator reduces the view factor to the array and increases the effective view to space at the radiator edges. At 0.3 m clearance, $F_{array} \approx 0.35–0.40$. At 0.5 m, $F_{array} \approx 0.20–0.25$. The thermal benefit of increased clearance is modest (5–15 W/m²) but the structural and CG implications are meaningful.

For mobile platforms where CG height is a gating constraint, the minimum clearance that allows adequate thermal performance (0.3–0.4 m) is preferred. For static installations where CG is less critical, 0.5 m or greater provides marginal thermal benefit with easier maintenance access.

6. Dust Degradation Considerations

Lunar dust (regolith fines) poses a significant threat to both radiator and solar array performance. Dust accumulation reduces radiator emissivity and increases solar absorptance, degrading rejection capacity. On the solar array, dust reduces power generation efficiency.

The stacked configuration offers a potential architectural advantage for dust mitigation. Because both surfaces are co-located on the same structural tier system, a single dust mitigation strategy can address both surfaces. Potential approaches include:

Electrodynamic dust shielding (EDS): Embedded electrodes generate traveling electric fields that transport charged dust particles off the surface. EDS systems have been demonstrated in laboratory settings for both solar cells and thermal control surfaces. A single EDS system could protect the array top surface and the radiator top surface, potentially from the same power and control electronics.

Mechanical tilting or vibration: The array tier could incorporate a tilt mechanism that periodically changes angle to shed accumulated dust. In lunar gravity (1.62 m/s^2), dust adhesion forces are lower than on Earth, though electrostatic adhesion complicates simple gravity-based shedding.

Protective geometry: The array tier provides partial protection to the radiator from ballistic dust lofted by nearby surface activity (rover mobility, EVA operations, landing events). Dust settling from above encounters the array first; the radiator in the shaded gap beneath receives less direct dust exposure than an open roof-mounted surface would.

Quantitative dust accumulation rates on the lunar surface remain an area of active research. For this architecture, the key sizing implication is that radiator area should be sized to degraded-emissivity conditions corresponding to the mission duration, as shown in the parametric tables in Section 5.

7. Platform Applicability

7.1 Pressurized Rovers

Pressurized crew rovers are the most demanding application case. Continuous thermal loads of 670–1,200 W from crew metabolic heat, ECLSS equipment, and avionics must be rejected while maintaining a low CG for rollover stability. The stacked configuration fits naturally within the cabin roof footprint (typically 4–6 m²), with the solar array extending beyond the cabin edges if needed for additional power generation without thermal penalty.

For a 2-crew, 14–21 day endurance pressurized rover, the shaded configuration can accommodate the full thermal rejection requirement within approximately 2.5–4 m² of radiator area at the degraded end-of-mission condition. This fits within a typical cabin roof without requiring deployable radiator wings, saving mass and mechanism complexity.

7.2 Unpressurized Long-Duration Mobility Platforms

Unpressurized rovers operating for extended durations in teleoperated or autonomous mode generate lower thermal loads (typically 200–500 W from avionics, communication systems, and battery thermal management). The stacked configuration is still applicable but the radiator area requirement is modest (0.5–1.5 m²), making it less architecturally critical. The primary benefit here is operational robustness across sun angles rather than area reduction.

7.3 Surface Habitats

Surface habitats have substantially higher thermal loads (2–10+ kW depending on crew size and duration) and correspondingly larger radiator requirements. The stacked concept scales directly: larger roof-mounted radiator arrays shaded by larger solar array canopies. For habitats, the structural penalty of the truss system is proportionally smaller relative to overall habitat mass, and the CG constraint is less severe for a non-mobile asset.

Habitat applications may also benefit from the ability to extend the solar canopy well beyond the radiator footprint, creating shaded outdoor work areas for crew EVA activity while simultaneously generating additional power.

7.4 ISRU and Deployed Equipment

In-situ resource utilization (ISRU) equipment, particularly oxygen extraction and water processing systems, generates significant waste heat (often 500–2,000 W or more). These systems also require power. The stacked configuration provides a compact, self-contained thermal and power solution that can be integrated into a deployable payload module compatible with modular logistics standards.

7.5 Applicability Summary

Platform Type	Thermal Load	Radiator Area	CG Sensitivity	Shade Benefit
Pressurized Rover	670–1,200 W	2.5–4.0 m²	High	High — area critical

Unpressurized Rover	200–500 W	0.5–1.5 m²	High	Moderate — robustness
Surface Habitat	2–10+ kW	6–30+ m²	Low	High — area + shading
ISRU Equipment	500–2,000 W	1.5–6.0 m²	Low–Medium	High — compact module

8. Integration Considerations

8.1 Structural

The solar array truss must support the array mass (typically 3–8 kg/m² for rigid panels, less for flexible arrays) under lunar gravity and traverse dynamic loads. For a 5 m² array at 5 kg/m² on a mobile platform, the structural loads are modest. A lightweight tubular aluminum or composite truss at 2–4 kg total mass is feasible for a rover-scale installation.

The truss must also accommodate thermal expansion differentials between the cold radiator surface and the warm solar array structure, and must not create thermal conduction paths that short-circuit the radiator's rejection performance.

8.2 Center of Gravity Impact

Elevating mass above the cabin roof raises the system CG. For a mobile platform where rollover stability is a gating constraint, this must be quantified. A 25 kg solar array assembly (panels + truss) mounted 0.4 m above the cabin roof, on a system with a total mass of 2,000 kg and a baseline CG height of 1.2 m, raises the system CG by approximately:

$$\Delta h\_cg = (m\_array \times h\_array) / m\_total = (25 \times 1.6) / 2000 \approx 0.02 \text{ m}$$

A 2 cm CG rise is negligible relative to typical stability margins. Even for lightweight mobile platforms, the CG impact of the stacked array is small compared to the CG contribution of the cabin structure and crew themselves.

8.3 Stowage and Deployment

For platforms that must fit within a launch vehicle fairing or lander payload envelope during transit, the solar array tier may need to be stowed flat against the radiator during launch and deployed on the surface. A simple hinge-and-latch mechanism at the truss base, similar to existing deployable solar array mechanisms, would suffice. This adds modest mechanism mass (1–2 kg) and a single deployment event.

For surface habitats delivered in a deployed configuration, the truss can be permanently erected with no deployment mechanism required.

8.4 Fluid Loop Routing

The radiator panels require fluid loop connections to the internal thermal control system. Routing fluid lines from the pressurized volume through the cabin roof to the radiator panels is a standard thermal architecture pattern. The stacked solar array does not interfere with fluid routing, as all connections are at the radiator level beneath the array tier.

9. Operational Benefits

Heading independence. Without the shade, radiator performance varies significantly with rover heading relative to the sun. A rover driving toward the sun exposes the full radiator area to direct solar flux. The shaded configuration decouples thermal performance from heading, providing consistent rejection capacity regardless of traverse direction. This eliminates a thermal constraint on route planning.

Reduced thermal cycling. The shaded radiator operates in a more thermally stable environment with smaller temperature excursions during sun angle changes. This reduces thermal cycling fatigue on fluid loop joints and radiator panel bonds.

Simplified thermal control logic. With a more predictable thermal environment, the active thermal control system can operate with simpler control algorithms and wider deadbands, reducing avionics complexity and power consumption.

Scalable architecture. The stacked concept scales linearly. Doubling the heat load doubles the radiator and array area without changing the architectural approach. This makes it suitable as a reference pattern across a family of platforms rather than a point solution for a single design.

10. Conclusions and Recommendations

The stacked solar-shade radiator architecture provides a meaningful improvement in horizontal flat-plate radiator performance for lunar surface applications. By eliminating direct solar absorption and introducing only a small, controllable IR backradiation penalty, the configuration achieves net rejection rates of 315–370 W/m² compared to 280–430 W/m² for unshaded radiators, with the advantage most pronounced under dust-degraded conditions and higher sun angles where the unshaded configuration suffers most.

The key enabler is the low-emissivity backside coating on the solar array. Without this coating, the IR penalty from the array underside substantially reduces the shade benefit. With it, the penalty is negligible.

Recommendations:

1. Adopt the stacked solar-shade radiator as a reference thermal architecture for lunar surface platforms that require both thermal rejection and solar power generation.

2. Specify low-emissivity ($\varepsilon \leq 0.15$) backside coating on solar array panels as a baseline requirement for this configuration.

3. Size radiators to degraded end-of-mission emissivity conditions, not clean beginning-of-life performance.

4. Design the clearance gap for 0.3–0.5 m depending on platform CG sensitivity and maintenance access requirements.

5. Investigate combined dust mitigation strategies that protect both surfaces from a single system, leveraging the co-located geometry.

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