Passive daytime radiative cooling-inspired technologies for space thermal management: Principles, limits, and prospects

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Citation: Chin. Phys. B. 35, 104401 (2026). DOI: 10.1088/1674-1056/aeac0f | CSTR: 32038.14.CPB.aeac0f
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TOPICAL REVIEW — A 40th Anniversary Celebration: Physics Research and Innovation at Ningbo University

Passive daytime radiative cooling-inspired technologies for space thermal management: Principles, limits, and prospects

Wansheng Wu(吴万生)[1], Tian Dai(戴天)[1], Hanzhuo Shao(邵翰卓)[2], Xiaoli Huang(黄晓莉)[1], Hua Xu(徐华)[1,†], Weijie Song(宋伟杰)[2], and Yuehui Lu(鲁越晖)[1,‡]

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(Received 24 May 2026; revised manuscript received 19 September 2026; accepted manuscript online 24 September 2026)

Passive daytime radiative cooling (PDRC) has emerged as a zero-energy thermal-management strategy on Earth, where its performance is governed by the atmospheric window, solar absorption, convective heat exchange, and terrestrial background radiation. Radiative thermal control, however, has long been used in spacecraft through technologies such as optical solar reflectors, second-surface mirrors, and white paints. Recent advances in terrestrial PDRC materials, particularly in achieving very low solar absorptance and high infrared emittance, provide new inspiration for further improving these established space thermal-control technologies. In this perspective, we compare the common physical basis and key environmental differences between terrestrial PDRC and PDRC-inspired space radiative cooling, discuss how PDRC-derived material and photonic strategies can be adapted for space applications, and analyze theoretical limits, ground-simulation constraints, on-orbit validation, and mission-specific applications. We argue that future PDRC-inspired technologies should evolve from material-level optimization toward integrated thermal-management strategies for spacecraft, satellites, lunar facilities, and deep-space exploration.

Keywords: passive daytime radiative cooling, terrestrial, space, extraterrestrial, thermal control

PACS: 44.40.+a, 78.20.Ci, 07.87.+v

DOI: 10.1088/1674-1056/aeac0f **CSTR:** 32038.14.CPB.aeac0f

1. Introduction

Passive daytime radiative cooling (PDRC) enables a surface to reject heat to the cold universe through thermal radiation while minimizing solar absorption, offering a passive route for thermal management under sunlight.[1] The key to terrestrial PDRC lies in designing materials that can simultaneously achieve high solar reflectance and high thermal-infrared emissivity under ambient conditions. Researchers have successively developed various high-performance materials, such as doped composite materials and photonic structured films, capable of achieving high solar reflectance and high thermal infrared emissivity.[2] With the continuous optimization of manufacturing processes, PDRC materials are gradually evolving towards lightweight, miniaturized, and highly durable designs.[3] The potential applications of terrestrial PDRC have been extensively investigated in practical scenarios including building thermal management and photovoltaic efficiency enhancement.[4]

Radiative cooling has long been used in aerospace exploration to achieve thermal management. Optical solar reflectors (OSRs) reduce solar heat input through low solar absorptance while maintaining high infrared emissivity to reject heat to deep space, and have been extensively applied to the thermal control of spacecraft exterior surfaces and radiators. In addition, publications edited by Gilmore *et al.* classify second-surface mirrors, white paints, and related coatings as typical thermal-control surfaces. These technologies show that low solar absorption, infrared heat rejection, orbital boundary conditions, and long-term environmental reliability have long been central considerations in spacecraft radiative thermal control.[5] For example, the Venus Express spacecraft employed a predominantly passive thermal-control architecture, with heat rejected to space through radiators located on several spacecraft panels.[6] Figure 1(a) shows the Venus Express spacecraft during integration, and Fig. 1(b) shows a schematic cross-sectional view of a flexible optical solar reflector (F-OSR).[7] Shi *et al.* developed a flexible microcrystalline glass radiative cooling coating, which has been validated for 24 months on low Earth orbit satellites. The maximum temperature of the satellite shell reached only 13.1 °C, addressing the issues of conventional space radiative cooling coatings being thick, having low reflectivity, and poor stability.[8] Figure 1(c) is a schematic diagram of the on-orbit temperature measurement scheme. In addition, researchers have gradually established space testing platforms to conduct studies on the thermal control performance of coatings. The Materials on Inter-

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national Space Station Experiment Flight Facility (MISSE-FF) is currently located on the Expedite the Processing of Experiments to the Space Station Logistics Carrier (ELC-2) on the International Space Station. Experiments installed in MISSE Sample Carriers (MSC) are launched on commercial cargo missions, then are robotically deployed onto the MISSE-FF platform. Using the International Space Station MISSE low-orbit platform, space environment exposure experiments have already been carried out.[9] Figure 1(d) shows the actual installation location of the experimental platform. Despite the long history and engineering maturity of spacecraft radiative thermal control, the achievable thermal performance remains strongly dependent on the solar absorptance and infrared emittance of the thermal-control surface.

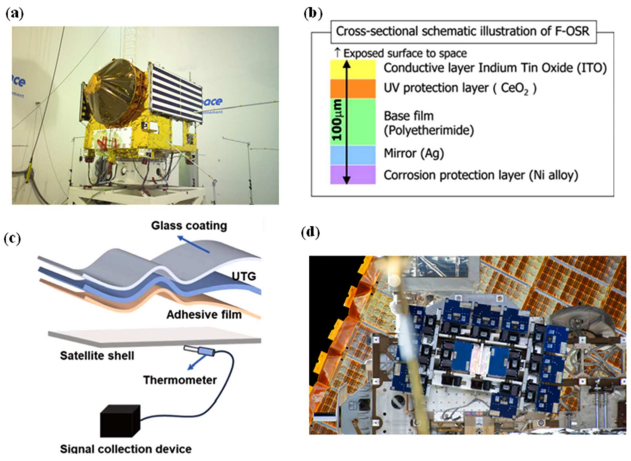


Fig. 1. (a) Venus Express ready for shipment to the Baikonur launch site. Credit: ESA-S. Corvaja.[6] (b) Flexible optical solar reflector (F-OSR), showing its multilayer structure and installation position on the space-exposure carrier. Courtesy of JAXA.[7] (c) A schematic diagram illustrating how the temperature is measured on the outer shell surface of the satellite.[8] (d) The MISSE Flight Facility on the exterior of the International Space Station. Image credit: NASA.[9] Reproduced from the publicly available source in Refs. [6,7,9]. Reproduced with permission from Ref. [8].

Subsequent theoretical studies by researchers at the Kennedy Space Center on "solar white" coatings showed that further suppressing solar absorption while maintaining efficient infrared emission could substantially lower the equilibrium temperature under ideal deep-space conditions. In particular, equilibrium temperatures below 50 K were theoretically predicted at 1 AU, suggesting potential applications in cryogenic storage and superconducting systems beyond conventional spacecraft temperature regulation.[10] Interestingly, this spectral requirement is highly consistent with the material characteristics demonstrated by terrestrial PDRC since 2014.[1,11] Recent PDRC research has rapidly advanced spectral engineering, photonic structures, porous materials, and lightweight radiative surfaces that combine very high solar reflectance with strong infrared emission. Therefore, terrestrial PDRC does not introduce radiative cooling into space; rather, its recent material and photonic advances provide new opportunities for improving and extending established spacecraft radiative thermal-control technologies. Terrestrial PDRC and established spacecraft radiative thermal-control technologies share a common physical basis: both seek to suppress absorbed solar radiation while enhancing outward thermal radiation. However, the environmental boundary conditions and engineering objectives of the two systems differ substantially. The cooling performance of terrestrial PDRC is influenced by complex factors such as the atmospheric window, air convection, background thermal radiation, and field of view conditions.[12] Thus, its design mainly focuses on increasing the emittance in the thermal window band and the solar reflectance to offset the heat gain from solar and background radiation. In space scenarios, there is no atmosphere or air; PDRC-inspired radiative cooling surfaces are not limited by the atmospheric window nor affected by convective heat transfer. Under idealized deep-space boundary conditions, broadband infrared emission can provide high theoretical heat-rejection potential. However, this does not mean that terrestrial PDRC materials can be directly transferred to space. The orbit and attitude changes of spacecraft cause the solar irradiance incident on such radiative-cooling surfaces to fluctuate.[13] Additionally, PDRC-inspired technologies for spacecraft thermal management must meet special requirements such as low mass, compactness, high stability, and resistance to cosmic particle radiation. Therefore, PDRC-inspired material concepts must be re-evaluated within the established framework of spacecraft thermal control, including AM0 irradiation, broadband infrared heat rejection, orbital geometry, view-factor constraints, planetary radiation, spacecraft self-radiation, environmental degradation, and mission-level reliability.[14]

This perspective discusses how recent advances in terrestrial PDRC may contribute to the further development of spacecraft radiative thermal control. We first compare the common physical basis and distinct boundary conditions of terrestrial PDRC and spacecraft radiative thermal-control technologies. We then discuss how material strategies developed in terrestrial PDRC — including high-reflectance coatings, photonic structures, porous materials, and adaptive radiative systems — may be re-evaluated for space environments. Particular attention is given to AM0 irradiation, broadband infrared emission, orbital geometry, view-factor constraints, environmental degradation, ground-simulation methods, and mission-level integration. The discussions help to assess how PDRC-inspired material and photonic strategies may complement and extend established spacecraft thermal-control technologies.

2. Common principles and distinct boundary conditions

Terrestrial PDRC and spacecraft radiative thermal-control technologies share the fundamental objective of minimizing

absorbed solar radiation while enhancing infrared heat rejection, although their operating environments and design constraints differ substantially.

2.1. Common principles

Terrestrial PDRC and spacecraft radiative thermal-control technologies share the same fundamental heat-transfer principle, namely reducing external radiative heat gain while enhancing outward thermal radiation. From the perspective of energy balance, this principle is primarily manifested in two aspects: first, enhancing the infrared radiative cooling capacity of PDRC by continuously transferring heat outward through infrared radiation channels tailored to the working environment, thereby maximizing steady-state radiative cooling efficiency and preventing the carrier temperature from rising excessively due to residual heat accumulation;[15] second, reducing the absorption efficiency of solar radiation across the entire spectrum by optimizing surface structures and selecting high-performance constituent materials, effectively shielding against solar irradiation and minimizing external heat intake from the outset.[16]

2.2. Key differences

The following compares representative energy-balance equations for terrestrial PDRC and a PDRC-inspired radiative-cooling surface operating in a spacecraft environment at temperature T.[10]

Terrestrial PDRC energy balance equation:

$$P_{\mathrm{net}}(T) = P_{\mathrm{rad}}(T) - P_{\mathrm{solar}}^{\mathrm{AM1.5}} - P_{\mathrm{atm}} - (P_{\mathrm{cond}} + P_{\mathrm{conv}}).$$

$P_{\mathrm{net}}(T)$ is the net cooling power of the terrestrial PDRC material at a temperature of T; $P_{\mathrm{rad}}(T)$ is the outward thermal radiation power; $P_{\mathrm{solar}}^{\mathrm{AM1.5}}$ is the absorbed terrestrial solar power by the material; P_{atm} is the absorbed atmospheric thermal-radiation power; P_{cond} is the conductive heat-transfer power between the material and the contacting solid (support); P_{conv} is the convective heat-transfer power between the material and the ambient air.

For a PDRC-inspired radiative-cooling surface in space:

$$\text{Sunlit}: P_{\mathrm{net}}(T) = P_{\mathrm{rad}}(T) - P_{\mathrm{solar}}^{\mathrm{AM0}} - P_{\mathrm{env}} - P_{\mathrm{cond}} - P_{\mathrm{sc}},$$
$$\text{Eclipse}: P_{\mathrm{net}}(T) = P_{\mathrm{rad}}(T) - P_{\mathrm{env}} - P_{\mathrm{cond}} - P_{\mathrm{sc}}.$$

$P_{\mathrm{net}}(T)$ is the net cooling power of the radiative-cooling surface under spacecraft boundary conditions at a temperature of T; $P_{\mathrm{rad}}(T)$ is the outward thermal radiation power; $P_{\mathrm{solar}}^{\mathrm{AM0}}$ is the absorbed AM0 solar power; P_{env} is the absorbed planetary albedo and infrared-radiation power, both depending on view factors; P_{cond} is the conductive heat-transfer power; and P_{sc} is the absorbed radiative power from surrounding spacecraft components, influenced by view factor.

The above formulae reveal substantial differences in the thermal boundary conditions of the two systems. The comparison shows that applying PDRC-inspired spectral strategies in space requires a fundamentally different set of thermal boundary conditions. Although both systems rely on low solar absorptance and high infrared emittance, the dominant heat-transfer channels, radiative sinks, degradation mechanisms, and evaluation criteria differ substantially. These differences are summarized in Table 1.

Table 1. Comparison of terrestrial PDRC and PDRC-inspired space radiative cooling in terms of boundary conditions and design implications.

Conditions	Terrestrial PDRC	Space radiative-cooling environment	Design implication for PDRC-inspired space radiative cooling
Solar irradiation	AM1.5 solar spectrum	AM0 solar spectrum with higher solar irradiance than terrestrial AM1.5	Minimize broadband solar absorptance
Atmospheric window	Rely on atmospheric transparency windows	Not constrained by atmospheric transparency windows	Utilize broadband infrared emission beyond the atmospheric window
Non-radiative heat transfer	Convective heat transfer and conductive heat transfer	Conductive heat transfer through spacecraft structures and interfaces	Minimize conductive heat leakage through structural and interface design
Background thermal emission	Long-wave radiation under the atmosphere and land environmental radiation	Planetary albedo and infrared radiation as well as radiative heat from other spacecraft components	Reduce absorbed planetary and spacecraft radiative heat loads
Environmental degradation	Environmental factors such as dust, rain, and oxidation	Atomic oxygen erosion and intense ultraviolet radiation	Use AO-resistant, UV-stable, radiation-tolerant, and low-outgassing materials
Surrounding temperature variation	Moderate diurnal and seasonal fluctuations	Sunlit–eclipse thermal cycling and extreme diurnal and seasonal fluctuations	Both static and adaptive/switchable thermal control are needed
Performance evaluation	Sub-ambient cooling	Equilibrium temperature, orbital thermal balance, long-term durability	Evaluated under realistic orbital boundary conditions, not only by material optical properties
Application scenarios	Buildings, photovoltaics, textiles, vehicles, food and agriculture, and outdoor equipment	Satellites, spacecraft surfaces, deep-space exploration, and space stations	Facile integration into thermal-management modules

Terrestrial PDRC is constrained by the 'atmospheric window' and can only transfer a portion of heat to deep space through radiation; at the same time, the presence of air convective heat transfer further diminishes its cooling efficiency. Thus, the spectral design of terrestrial PDRC is mainly governed by two requirements: minimizing solar absorption and maximizing radiative heat dissipation through the atmospheric transparency window. Terrestrial PDRC materials are usually designed to suppress absorption in the 0.3–2.5 μm solar band while maintaining high emissivity in the 8–13 μm atmospheric window. In contrast, a radiative-cooling surface operating in space is exposed to the AM0 solar spectrum and is not restricted by the atmospheric window. Broadband infrared emission can be utilized when the surface has a sufficient view factor to deep space. At the same time, planetary albedo, planetary infrared radiation, spacecraft self-radiation, solar incidence angle, and orbital attitude must be considered in the spectral and thermal design. Therefore, the design logic changes from atmospheric-window-centered spectral optimization on Earth to a coupled spectrum–view-factor–attitude design for mission-specific space thermal control. Moreover, since spacecraft thermal management involves multi-system coupling, it is necessary to evaluate the thermal interference from other spacecraft components on the radiative-cooling surface. In practice, terrestrial PDRC and spacecraft radiative-cooling surfaces differ substantially in their geometric relationships with the surrounding radiative environments, and varying geometric configurations lead to different view factors, which in turn cause differences in their performance. Therefore, PDRC-inspired technologies for space thermal management should not be regarded as a direct transfer of terrestrial cooling materials. Instead, terrestrial PDRC strategies must be re-evaluated within a mission-oriented framework that couples spectral selectivity, view-factor engineering, environmental durability, and system-level thermal integration.

3. Material strategies from terrestrial designs to space-oriented adaptation

Terrestrial PDRC research has developed a diverse range of material strategies. These terrestrial PDRC strategies provide a valuable material and design toolbox for advanced spacecraft radiative thermal control, although not all of them retain their effectiveness or relevance under extraterrestrial conditions. Adapting PDRC-derived material and photonic strategies for space applications therefore requires material strategies to be re-evaluated in light of space-specific constraints, such as vacuum operation, thermal cycling, harsh radiation, atomic oxygen exposure, and the need for lightweight, integrable, and highly reliable thermal control devices.

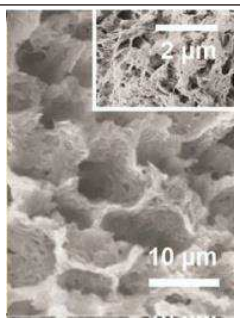
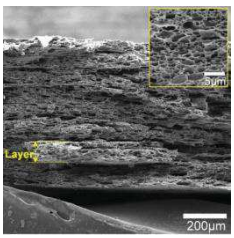
3.1. Terrestrial PDRC research

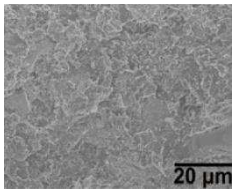
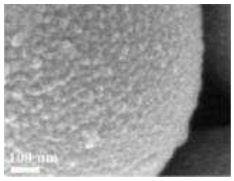
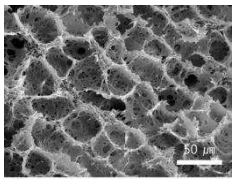
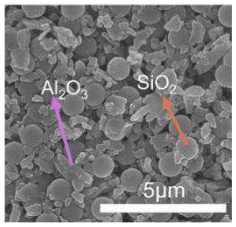
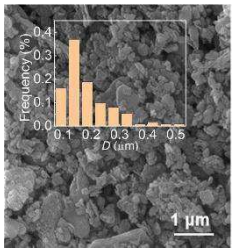
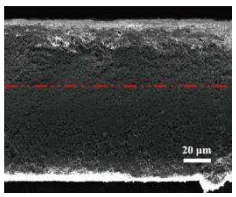
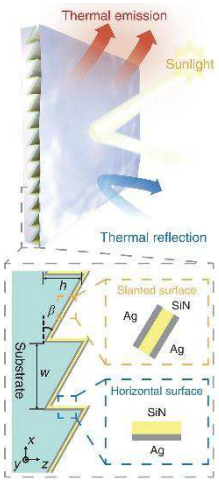
Researchers have conducted extensive explorations of terrestrial PDRC, and here we provide several examples, including static and dynamically tunable PDRC materials.

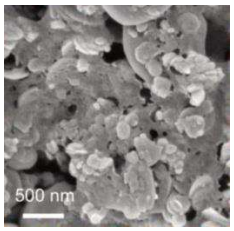
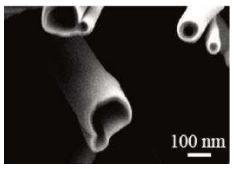
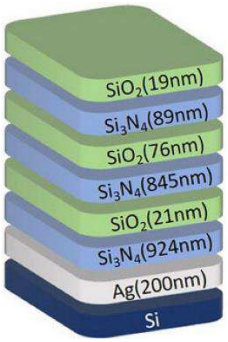
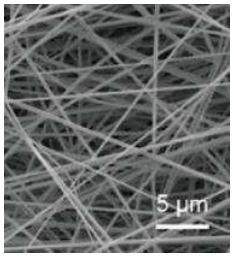
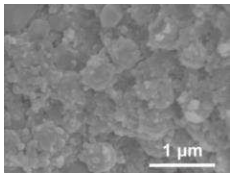
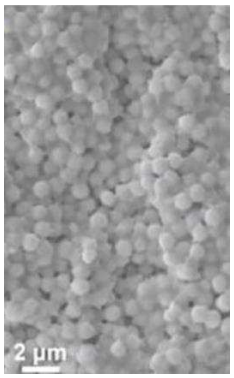
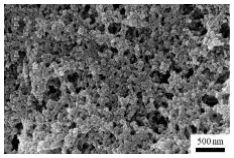
3.1.1. Static terrestrial PDRC

Static terrestrial PDRC includes various systems such as films, coatings, microstructures, and organic polymers.[17,18] Static terrestrial PDRC can reflect sunlight and emit infrared energy in the broadband infrared range, thereby reducing the device temperature. The development in recent years is shown in Table 2.

Table 2. Current status of static terrestrial PDRC materials.

Year	Material composition	Representative image/schematic	Reflectance	Emissivity	Sub-ambient temperature reduction
2018	Porous P(VdF-HFP)[a)]		96.0%	97.0%	6.0 °C
2021	FHPCM[b)]		97.2%	93.5%	N.A.

2022	CA/$CaSiO_3$[c)]		97.3%	97.2%	7.3 °C
2022	MTMS[d)]		93.8%	94.3%	10.5 °C
2022	Porous TPU[e)]		93.0%	90.0%	5.6 °C
2023	SiO_2 particles /Al_2O_3 particles /PU[f)]		95.8%	93.7%	9.1 °C
2023	h-BN/PFOTS/IPA[g)]		96.3%	92.7%	2.3 °C
2024	SiO_2 particles /Al_2O_3 particles /PVDF/PDMS[h)]		98.0%	95.0%	7.1 °C
2024	Si_3N_4/ Ag[i)]		97.8% (full-angle incidence at 0°–75°)	Around 75% (sky hemisphere) and around 10% (Earth hemisphere)	2.5±0.7 °C

2025	Porous hBN@P(VdF-HFP)/graphene [j)]		94.4%	90.4%	N.A.
2025	SiO_2 particles/P(VdF-HFP) [k)]		98.9%	98.2%	14.0 °C
2025	SiO_2/Si_3N_4 [l)]		97.4%	Around 80% (8–13 μm) and around 90% (16–25 μm)	12.6 °C
2025	es-HBPI [m)]		99.6%	93.0%	N.A.
2025	ZrO_2/K_2SiO_3 [n)]		96.0%	91.0%	N.A.
2026	$La/ZrO_2/K_2SiO_3$ [o)]		93.9%	94.1%	N.A.
2026	Porous MgO / Porous SiO_2 [p)]		95.0%	96.7%	7.2°C

[a)]Ref. [19], [b)]Ref. [20], [c)]Ref. [21], [d)]Ref. [22], [e)]Ref. [23], [f)]Ref. [24], [g)]Ref. [25], [h)]Ref. [26], [i)]Ref. [27], [j)]Ref. [28], [k)]Ref. [29], [l)]Ref. [30], [m)]Ref. [31], [n)]Ref. [32], [o)]Ref. [33], [p)]Ref. [34]. Reproduced with permission from Refs. [19–34].

Table 2 indicates that the optical performance of static terrestrial PDRC materials has entered a high-specification regime, with most representative systems showing solar reflectance above 95% and infrared emissivity above 90%. It should be noted that the reported sub-ambient temperature reductions are not directly comparable because they depend on local weather conditions, testing configurations, sample mounting, and non-radiative heat exchange. Therefore, the central challenge is shifting from optimizing optical properties to improving scalable fabrication, contamination resistance, angular selectivity, mechanical durability, and long-term outdoor reliability. Wang *et al*. fabricated a bilayer ultrahigh solar reflectance coating consisting of an upper PVDF layer containing Al_2O_3 and SiO_2 particles and a lower PDMS layer. This coating achieved a solar reflectance of 98% and an atmospheric window emissivity of 95%, with a maximum outdoor cooling of 7.1 °C at noon.[26] Compared with single-layer coatings of the same thickness, its performance was significantly enhanced, providing a new approach for the design of bilayer PDRC coatings. Wang *et al*. used high-temperature electrospinning combined with a spraying process to prepare hollow P(VdF-HFP) nanofiber composites incorporating SiO_2 particles. These films achieved a solar reflectance of 98.9% and a mid-infrared emissivity of 98.2%. Outdoor tests demonstrated that they could reduce the temperature of wooden house models by 14 °C, while maintaining stable cooling performance even after contamination.[29] At present, the solar reflectance and infrared emissivity of static terrestrial PDRC materials have nearly reached the theoretical performance limits and have entered the stage of high-performance manufacturability, with a focus on standardized testing, direction/angle control, and long-term reliability.

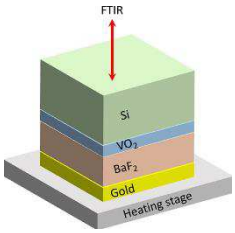
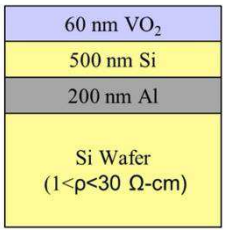
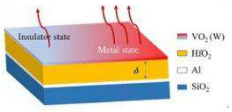
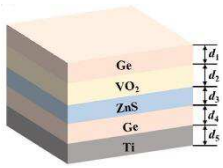
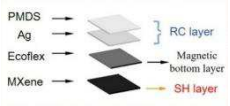
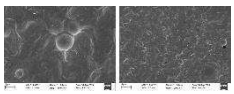
Extending these strategies to space applications requires consideration of both spectral functionality and environmental durability. Among the systems summarized in Table 2, the inorganic Si_3N_4/Ag and SiO_2/Si_3N_4 architectures are promising candidates for further evaluation because they combine angular or spectral control with reduced reliance on organic functional components susceptible to ultraviolet degradation. The angularly asymmetric emission of the Si_3N_4/Ag structure provides a basis for tailoring directional radiative exchange according to spacecraft geometry and attitude, whereas the multiband emission of the SiO_2/Si_3N_4 structure offers flexibility in selecting emission bands according to component operating temperatures and external radiative conditions.[27,30] For space adaptation, however, solar absorptance must be recalculated using the AM0 spectrum, and infrared performance must be assessed considering radiative exchange with deep space, Earth, and surrounding spacecraft components. Consequently, high atmospheric-window emissivity or substantial subambient cooling under terrestrial conditions does not necessarily translate into superior thermal-control performance in space. Experimental studies of all-inorganic coatings provide complementary evidence for environmental durability. Gong *et al.* developed a ZrO_2 submicrosphere/K_2SiO_3 metacoating that retained solar absorptance below 0.083 and infrared emissivity above 91.0% after proton and electron irradiation under the reported test conditions.[32] A subsequent La-doped ZrO_2 metacoating combined electronic-structure modification and improved lattice stability to suppress ultraviolet absorption and irradiation-induced defect formation, with its environmental resistance evaluated through proton, electron, ultraviolet, atomic oxygen, and thermal cycling tests.[33] These results support inorganic particle–binder combinations and defect control as promising approaches to maintaining optical performance under space-relevant exposure. They also provide a basis for further evaluating suitably designed all-inorganic coatings for space applications. Nevertheless, their demonstrated resistance cannot be directly extrapolated to the multilayer architectures discussed above, whose interfaces, adhesion, and complete-device durability require separate validation.

Polymer-based strategies also merit consideration when molecular and structural design are accompanied by environmental testing. Song *et al*. combined semi-alicyclic polyimide molecular design with electrospun nanofiber optimization to achieve a solar reflectance of 99.6% and a mid-infrared emissivity of 93.0%, and evaluated the resulting films through vacuum cooling and ultraviolet, atomic oxygen, and thermal cycling experiments.[31] This work demonstrates a route to combining low intrinsic solar absorption with strong optical scattering. However, the reflectance changes following ultraviolet exposure and the observed atomic oxygen erosion also highlight the need to assess durability alongside initial optical performance. For the polymer and porous-fiber systems in Table 2, material selection should therefore account for molecular resistance to degradation and the relationship between scattering efficiency and environmental exposure of the microstructure, with particular emphasis on spectral and structural retention after testing.

3.1.2. Dynamically tunable terrestrial PDRC

Dynamically tunable terrestrial PDRC includes various systems such as thermally responsive, electrically responsive, mechanically switchable, magnetically actuated, and other actively or passively reconfigurable systems.[17] Some dynamically tunable systems require external energy input, whereas passive thermally responsive or mechanically self-adaptive approaches can operate without active control. The development in recent years is shown in Table 3.

Table 3. Current status of dynamically tunable terrestrial PDRC materials.

Year	Material composition	Schematic diagram	Mechanism	Regulatory capability
2019	$Si/VO_2/BaF_2/Au$[a]		Metal-insulator transition of VO_2	Emissivity difference of 35.0% and around 7 times radiative power variation (27–100 °C)
2020	$Al/Si/VO_2$[b]		Metal-insulator transition of VO_2 /Fabry-Perot cavity resonance	The total emissivity increased from 14.0% (room temperature) to 60.0% (100 °C)
2022	W/VO_2[c]		Room temperature phase change (15–40 °C)	Daytime high temperature cooling on; nighttime low temperature cooling off
2024	nano-PE/PEO/AgNWs[d]		Mid-infrared double-sided asymmetric optical properties	95.4% reflectance, 93.2% emissivity (top) and 21.5% low emissivity (bottom)
2024	$Ge/VO_2/ZnS/Ge/Ti$/Spectral selective filter[e]		Metal-Insulator Transition of VO_2 at the Bottom	8.0% solar absorptance, 93.6% thermal emissivity (cooling mode) and 47.7% solar absorptance, 20.1% thermal emissivity (heating mode)
2025	P(VdF-HFP)/P(VdF-HFP)@TiN/Ag[f]		Flip to switch between cold and hot modes	Under outdoor conditions, compared with exposed skin, the temperature increases by 8.3 °C (heating mode) and decreases by 11.5 °C (cooling mode)
2025	MXene/PDMS/Ag[g]		Non-contact magnetic field-driven reversal of double-sided functional coatings	Switching between solar heating and radiative cooling modes
2025	Thermochromic powder/SiO_2 particles[h]		Thermochromic powder undergoes an optical state transition with temperature	The solar reflectance increased from 62% to 76%, and the mid-infrared emissivity increased from 89% to 94%

[a] Ref. [35], [b] Ref. [36], [c] Ref. [37], [d] Ref. [38], [e] Ref. [39], [f] Ref. [40], [g] Ref. [41], [h] Ref. [42]. Reproduced with permission from Refs. [36,37,39,40,42]. Reproduced from Refs. [35,38,41], published as an Open Access article.

Table 3 shows that dynamically tunable terrestrial PDRC regulates cooling, heating, or thermal insulation by tuning its optical properties through mechanisms such as phase transitions, double-sided asymmetry, and mechanical or magnetic flipping. Wang *et al*. proposed a temperature-adaptive selective emission structure based on doped VO_2. By utilizing the phase transition characteristics of VO_2, it enables all-weather radiative thermal management with daytime radiative cooling and nighttime radiative heating. During the day, the structure exhibits high reflection in the solar spectrum and high emission in the atmospheric transparency window, achieving a cooling power of 53.58 $W{\cdot}m^{-2}$. At night, it shows high absorption in the atmospheric radiation band and low emission in the transparency window, with a thermal loss of only 10.04 $W{\cdot}m^{-2}$.[39] Song *et al*. proposed a thermally adaptive radiative cooling coating with a critical temperature of 25 °C. It is prepared by combining thermochromic powder with SiO_2/TPX and can autonomously switch between cooling and heating modes according to temperature, with solar reflectance increasing from 62% to 76% and mid-infrared emissivity rising from 89% to 94%.[42] Currently, research on thermal regulation of dynamically tunable terrestrial PDRC mainly focuses on the adjustable range of mid-infrared emissivity, precision, switching ratio, and triggering methods. For space applications, passive or self-adaptive switching is particularly attractive because external power consumption, control complexity, and reliability risks should be minimized. For space use, however, the transition mechanism itself must be evaluated under vacuum, radiation, and thermal cycling conditions.

Temperature-responsive VO_2 structures illustrate how such self-adaptive regulation could accommodate changing thermal loads in space. During alternating sunlit and eclipsed periods, a radiator with appropriately designed switching behavior can enhance heat rejection as its temperature rises and reduce radiative heat loss as it cools. Thermal-vacuum experiments on an Al/Si/VO_2 structure provide evidence for temperature-dependent emissivity modulation, while work on tuning the VO_2 transition temperature demonstrates a route to matching the response to a target operating range.[36,37] These features make phase-transition strategies particularly relevant to applications requiring autonomous adjustment between heat rejection and heat retention. Their switching is nevertheless governed by the device temperature rather than orbital illumination alone. The transition temperature and hysteresis range must therefore be matched to component temperature limits, internal heat loads, and the thermal response over the orbital cycle.

Structural protection offers a complementary approach to improving the environmental compatibility of these devices. In the Si/VO_2/BaF_2/Au architecture, the outward-facing Si substrate transmits radiation within relevant infrared wavelengths while providing a barrier against direct atomic oxygen exposure of the internal functional layers.[35] This design illustrates how optical functionality and environmental protection can be integrated, although the proposed shielding effect should not be equated with experimentally established long-term durability. Further space-adaptation studies should assess whether the transition temperature, hysteresis characteristics, and emissivity modulation remain stable after environmental exposure, together with the integrity of the protective structure and interfaces. These criteria provide a practical basis for identifying which adaptive systems in Table 3 can retain useful thermal-control functionality under mission-specific conditions.

3.2. Space-oriented adaptation of PDRC material strategies

The material and spectral design strategies developed for terrestrial PDRC provide an important foundation for exploring next-generation spacecraft radiative thermal-control surfaces. However, the inherent differences between the space environment and the terrestrial environment mean that the design strategy for terrestrial PDRC cannot be directly applied to spacecraft thermal-control environments. The direct transfer of terrestrial PDRC materials to space applications still faces numerous challenges. The space environment features unique constraints such as vacuum, extreme temperature fluctuations, intense cosmic radiation, and atomic oxygen, all of which can significantly affect the performance of PDRC materials. The vacuum environment eliminates convective heat transfer, leaving radiative exchange and solid-state conduction through structural interfaces as the principal heat-transfer pathways. Repeated thermal cycling between high- and low-temperature conditions generates cyclic thermal stresses, which may degrade structural integrity and shorten service life. Energetic electrons, protons, and other particle radiation may induce structural and compositional changes, leading to degradation of the optical properties. Oxidative erosion by atomic oxygen can modify the surface composition and morphology, causing irreversible changes in the optical response of PDRC-inspired materials for space applications. At the same time, the large-scale preparation process directly determines whether the PDRC-inspired technologies can move from the laboratory to engineering application, and spacecraft components impose more stringent requirements on manufacturing scalability, batch consistency, dimensional accuracy, and cost control.

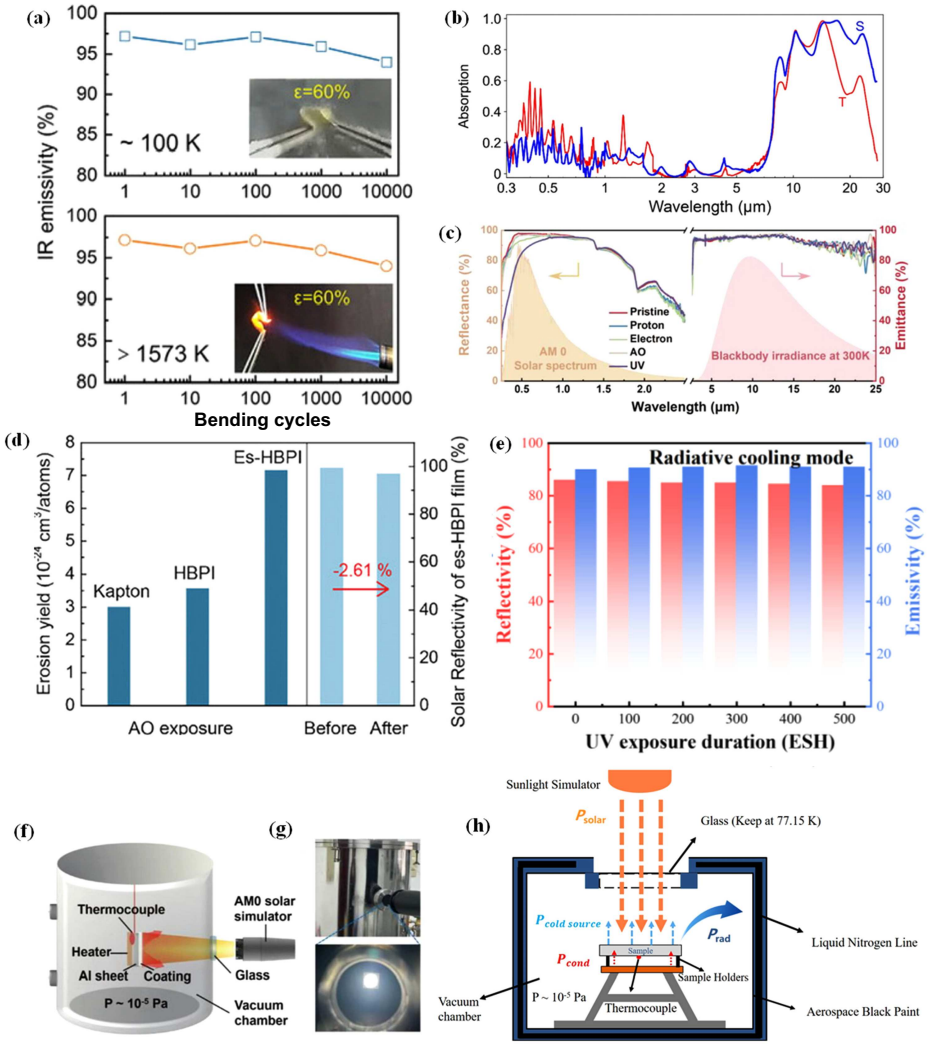


Fig. 2. (a) IR emissivity after bending cycles under low temperature and high temperature settings.[43] (b) Experimental absorption spectra of type T and type S.[44] (c) Spectral reflectance and emittance of the LZS metacoating before and after proton, electron, AO, and UV irradiations.[33] (d) Comparison of the AO erosion yield of Kapton film, HBPI film, and the es-HBPI film, and the solar reflectivity of the es-HBPI film before and after AO exposure.[31] (e) Changes in optical properties of TAMSJ under different UV irradiation times in radiative cooling mode.[45] (f) Schematic of the vacuum experimental setup simulating the space environment.[33] (g) Photographs of the experimental apparatus.[33] (h) Schematic illustration of a ground-based simulated experimental facility.[46] Reproduced with permission from Refs. [31,33,43,45]. Reproduced from Refs. [44,46], published as an Open Access article.

Figure 2 summarizes representative PDRC-inspired strategies for space thermal management from three perspectives: spectral optimization for efficient radiative cooling, environmental stability under space stressors, and ground-based simulation for evaluating extraterrestrial cooling performance. Guo *et al.* used a one-dimensional induced molding strategy to prepare CrO_3 high-entropy chromate nanofibers combined with SiO_2 nanofibers into a composite hyperstructured fabric, achieving a broadband infrared emissivity of 97.1% in the 0.7–15 μm range.[43] Figure 2(a) shows that the infrared emissivity of the metafabric remains stable after repeated bending under extremely low and high temperature conditions. Xiao *et al.* proposed a multi-material flexible thin-film optical solar reflector based on Ta_2O_5, which achieved a calculated net cooling power of 150.1 $W \cdot m^{-2}$ under conditions of one sun total solar irradiance in space.[44] Figure 2(b) shows the two types of OSR optimized for two different application scenarios, respectively. Gong *et al.* developed a lanthanum-doped zirconia submicrosphere-based fully inorganic supercoating through synergistic optimization of material composition and photonic structure. The coating achieved a solar absorptance of 6.1% and a thermal emissivity of 94%, while exhibiting only limited changes in optical properties after proton, electron, atomic oxygen, ultraviolet irradiation and 50 extreme thermal cycles.[33] Figure 2(c) shows the spectral reflectance and emissivity of this supercoating before and after exposure to protons, electrons, atomic oxygen, and ultraviolet radiation. Song *et al.* developed an electrospun polyimide nanofiber radiative-cooling film for spacecraft thermal management, which reduced UV-visible light absorption by alicyclic modified HBPI molecules, and achieved 99.6% solar reflectivity and 93% mid-infrared emissivity for nanofibers with an average diameter of approximately 290 nm.[31] Figure 2(d) shows the change in reflectivity of the film under

AO erosion. Hou *et al*. proposed a dynamic asymmetric-structured adaptive dual-mode thermal management device, which achieves autonomous switching between thermal insulation mode (infrared emissivity 4%) and radiative cooling mode (infrared emissivity 90%) through the tilting/collapsing deformation of a shape-memory Janus array.[45] Figure 2(e) shows the changes in the optical performance of the device under ultraviolet light exposure when it is in cooling mode. To achieve coordinated operation with other spacecraft subsystems, PDRC-inspired space radiative cooling materials should be compatible with the structural, thermal, and energy systems of the spacecraft, and reliable space-simulation experiments are therefore essential. In particular, the evaluation of extraterrestrial cooling performance has attracted increasing attention. Figures 2(f) and 2(g) show a representative vacuum experimental setup operated with room-temperature surroundings. In contrast to such conventional configurations, Zhang *et al*. theoretically analyzed the effects of cold-source temperature and effective conductive heat-transfer coefficient on the cooling performance of PDRC-inspired space radiative cooling materials, as illustrated in Fig. 2(h). They proposed an optimized ground-simulation scheme in which a liquid-nitrogen cold source of approximately -196 °C and an effective conductive heat-transfer coefficient of about 0.01 $\mathrm{W{\cdot}m^{-2}{\cdot}K^{-1}}$ can be used to better predict the maximum cooling capability of PDRC-inspired space radiative cooling materials.[46]

These examples show that PDRC-inspired approaches to spacecraft thermal management are defined not solely by high solar reflectance and high infrared emittance, but by the coupled requirements of spectral selectivity, environmental robustness, mechanical reliability, and ground-to-orbit performance validation. Based on these space-environment constraints, recent research has mainly advanced along two directions: improving spectral selectivity and long-term reliability. These efforts have led to multiple technical routes, including fiber fabrics, thin-film OSR, all-inorganic coatings, polymer nanofiber membranes, and variable emissivity devices. Although these systems differ in thermal-control logic, they are connected by the common goal of regulating solar absorption and infrared radiative exchange under space boundary conditions.

4. Limits and challenges

The performance limits of PDRC-inspired technologies should therefore be considered at three levels: ideal theoretical limits, ground-simulated limits, and mission-realistic on-orbit performance. At the first level, theoretical analysis forms the foundation for estimating the intrinsic cooling potential. The theoretical cooling limit under space radiative-cooling conditions differs from the ambient-temperature-based cooling limit commonly used for terrestrial PDRC. Under ideal deep-space boundary conditions, the limit is determined by the radiative energy balance between absorbed solar radiation and infrared heat rejection to deep space. Our previous ultra-broadband spectral calculations, which combined Monte Carlo simulations, Mie scattering, effective medium theory, and the transfer matrix method, also confirmed that the limiting performance of PDRC-inspired technologies depends on the prescribed radiative boundary conditions, including solar absorptance, infrared emissivity, radiative area, and view factor to deep space,[47] as shown in the schematic diagram of the simulation method. Solving the radiative transfer equation allows the calculation of the spectral reflectance and absorptance of coatings, and in conjunction with the Stefan–Boltzmann law, the minimum achievable temperature and maximum cooling power of PDRC-inspired space radiative cooling materials can be determined.

Under realistic orbital conditions, however, planetary albedo, planetary infrared radiation, spacecraft self-radiation, and conductive heat leakage further modify the practical cooling limit. For simplified thermal analysis of near-Earth-orbit spacecraft, an Earth-facing exterior surface can be represented as a unit-area flat plate with a single thermal-capacitance node. The absorbed Earth infrared radiation and albedo can then be incorporated into the single-node energy balance to calculate the surface-temperature response. Then, using the simplest single-node thermal model, the calculated Earth infrared radiation/albedo flux can be converted into surface temperature changes.[48] Figure 3(b) shows a schematic diagram of the surface temperature calculation of a single-node spacecraft. Mission-realistic cooling performance is generally lower than the ideal deep-space limit, and these empirical data are vital for refining and improving theoretical models.[49]

In practical applications, PDRC-inspired materials intended for spacecraft thermal management must withstand the harsh space environment. Compared to terrestrial conditions, the extreme conditions and complex disturbances unique to space can more significantly diminish the cooling efficiency of PDRC-inspired technologies. Figure 3(c) illustrates the severe space environment.[50] High-energy particle radiation can alter the microstructure of materials, affecting their optical properties; the strong oxidation/erosion caused by atomic oxygen can change the surface composition of materials, impacting both optical performance and service life. UV radiation can induce chain scission, crosslinking, oxidation, and embrittlement in polymer-based PDRC membranes, thereby reducing polymer toughness and weakening the adhesion between the polymer matrix, inorganic fillers, and adjacent functional layers.[51] Thermal cycling repeatedly imposes expansion–contraction stress because of the mismatched thermal expansion coefficients of these components.[52] When UV radiation and thermal cycling act simultaneously, UV-induced embrit-

tlement makes the material more susceptible to cyclic thermal stress, while thermal cycling continuously stretches and compresses these weakened regions. As a result, microcracks can form and propagate more rapidly than under UV radiation or thermal cycling alone, especially at surfaces, pores, and filler–matrix interfaces. In low-Earth-orbit environments, AO can oxidize and etch the organic matrix, producing volatile products.[53] This process can cause material loss, surface roughening, pits, voids, and even exposure of underlying layers. In the solar spectrum, moderate roughness may enhance diffuse reflection through multiple scattering, whereas severe erosion, contamination, or exposure of absorbing layers may increase solar absorption and impair cooling performance. In the mid-infrared band, microcracks and rough interfaces can alter the effective refractive index, optical path length, and local electromagnetic-field distribution, and may thereby attenuate, broaden, or shift infrared emissive features. Space dust and micrometeoroid impacts may compromise the integrity of material surfaces, leading to reduced spectral selectivity. Additionally, fluctuations in solar incidence angles due to orbital attitude changes can further deviate materials from their theoretical cooling performance. In fact, the challenges for PDRC-inspired technologies begin from the moment the spacecraft is launched. During liftoff and launch, materials are subjected to high levels of vibration, acoustic shock, and thermal flux. Once in orbit, exposure to high vacuum can cause water desorption and outgassing of organic materials or residues. Water desorption can alter the electrical and thermo-optical properties of materials, while outgassed species may condense on spacecraft surfaces and impair instrument performance. Figure 3(d) illustrates the safety threats encountered by the spacecraft from Earth to space.[54] However, theoretical analysis and practical applications often differ. To study the actual on-orbit cooling performance of PDRC-inspired radiative-cooling materials, on-orbit experiments are required in order to bridge the gap between theory and reality. Facilities such as CubeSat on-orbit exposure platforms enable researchers to directly measure the actual cooling temperature of PDRC in orbit, as well as its spectral degradation characteristics.[55]

In particular, for VO_2-based variable-emissivity radiators, high-energy particle irradiation may introduce defects, oxygen vacancies, local stoichiometric changes, stress accumulation, and interfacial degradation. These effects may shift the phase-transition temperature, broaden the hysteresis loop, reduce the infrared emissivity modulation amplitude, and degrade the switching ratio over multi-year missions. Electrochromic devices have been tested in orbit, demonstrating the feasibility of adaptive control for spacecraft thermal management.[56] In addition, a VO_2-based solid–solid phase-change material has recently been demonstrated on the DENDEN-01 CubeSat for battery temperature stabilization.[57] The DENDEN-01 device relies on latent heat storage and release rather than emissivity modulation. However, these demonstrations do not fully resolve the long-term stability of phase-transition-based thin-film variable-emissivity radiators. Recent institutional reports also stated that a VO_2-based smart thermal-control material has been applied to the Tianwen-2 probe,[58] but detailed in-orbit stability data have not yet been publicly reported. Therefore, the possible degradation of phase-transition temperature and emissivity switching ratio under combined particle radiation, UV exposure, vacuum, and thermal cycling remains an important issue for future adaptive radiative thermal-control devices.

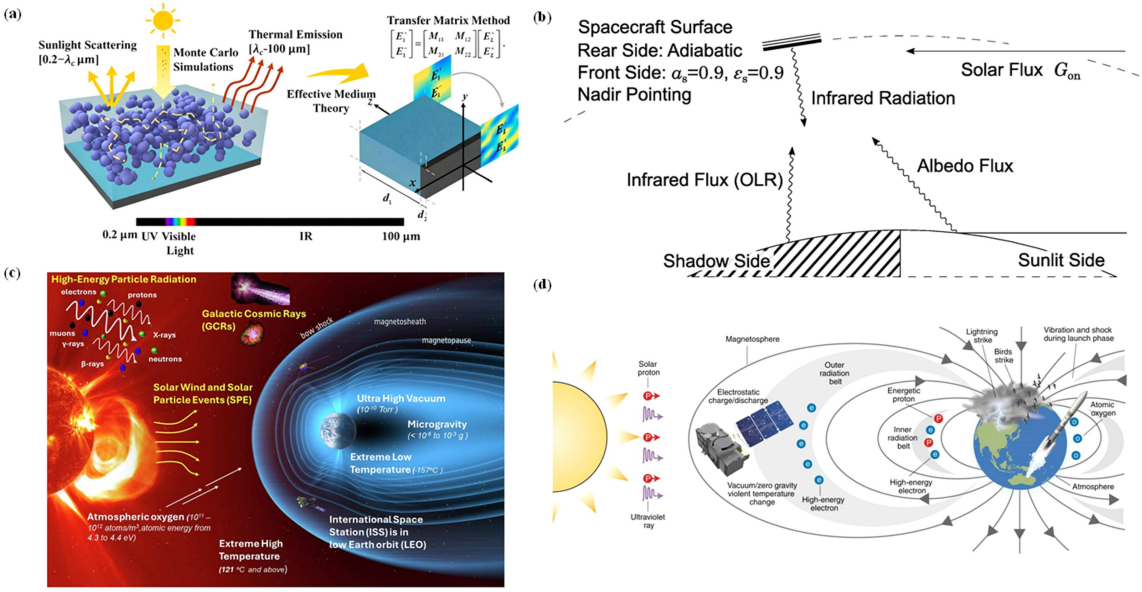


Fig. 3. (a) Schematic of the simulation methodology for extraterrestrial PDRC materials.[47] (b) Schematic of the single-node spacecraft surface-temperature model.[48] (c) Schematic diagram illustrating the characteristics of the harsh space environment.[50] (d) Challenges for spacecraft materials.[54] Reproduced with permission from Refs. [50,54]. Reproduced from Refs. [47,48], published as an Open Access article.

These limits and challenges suggest several possible design guidelines for future PDRC-inspired technologies. First, the cooling performance should be evaluated using mission-specific thermal-boundary models rather than ideal deep-space assumptions alone. In addition to direct AM0 solar irradiation, planetary albedo, planetary infrared emission, spacecraft self-radiation, conductive heat leakage, and view-factor effects should be included to estimate the mission-realistic cooling capability. Second, ground-simulation experiments should be improved by using cryogenic cold sources, suppressed surrounding thermal radiation, and low-conductance sample supports to reduce the discrepancy between laboratory measurements and actual orbital conditions. Third, long-term spectral stability requires space-resistant material systems, such as atomic-oxygen-resistant inorganic coatings, UV-stable polymers, radiation-resistant ceramics, protective barrier layers, and multifunctional hybrid structures. Fourth, adaptive or variable-emissivity devices may provide a promising route to cope with sunlit–eclipse thermal cycling and large temperature fluctuations. Finally, practical deployment also requires scalable fabrication, lightweight and flexible structures, reliable integration with spacecraft surfaces, on-orbit exposure tests, and post-exposure spectral characterization. Therefore, future PDRC-inspired technologies for space thermal management should be considered not simply as high-reflectance/high-emittance materials, but as mission-adapted radiative thermal-control strategies.

Therefore, PDRC-inspired materials for space thermal management must simultaneously meet three key criteria: high spectral selectivity (high solar reflectance/high infrared emissivity), environmental robustness, and long-term durability. The material should maximize solar radiation reflection to reduce heat absorption, while efficiently radiating heat in the infrared range to effectively dissipate internal spacecraft heat into deep space. The material must maintain the stability of its micro/nano structures and optical parameters under conditions of intense UV irradiation, particle flux, and extreme temperature cycles, avoiding degradation in reflectance/emissivity caused by aging, deformation, or component failure. The material should possess resistance to erosion, contamination, and impact to withstand external disturbances such as space dust, micrometeoroids, and debris, while mitigating the risk of thermal control failure resulting from long-term in-orbit degradation. Beyond intrinsic material properties, the practical application of these PDRC-inspired technologies also depends on system integration, scalable manufacturing, and mission-level validation. Such technologies must be compatible with spacecraft device structures and attitude control systems, avoiding interface or operational mismatches that could reduce overall reliability. From a manufacturing perspective, the process must be scalable and batch-consistent to ensure material thermal control performance and dimensional accuracy. At the same time, establishing verification procedures and quality standards for different orbital and attitude conditions is required to translate laboratory performance into reproducible in-orbit stability, providing support for subsequent engineering deployment.

5. Prospects and outlook

The future development of PDRC-inspired technologies for space thermal management should not merely pursue extreme cooling capacity, but rather focus on their integration with mission-specific spacecraft thermal-control systems. The diversity of space missions determines the differentiated needs for thermal management. By taking into account key parameters such as the thermal environment characteristics of specific space missions, equipment temperature thresholds, and energy constraints, tailored PDRC-inspired thermal-control solutions can be developed. In addition, promoting deep integration of PDRC-inspired technologies with established spacecraft thermal management systems will upgrade them from a single cooling device to a multifunctional thermal management module, achieving an integrated design that combines heat dissipation, insulation, and radiation resistance, enabling dynamic response to the thermal management requirements throughout the entire mission cycle. In this context, the role of PDRC-inspired technologies extends beyond simply lowering temperature; their value lies in providing lightweight, spectrally engineered, and potentially adaptive components within broader spacecraft thermal-management architectures.

Satellite thermal control is one of the most mature application scenarios of radiative cooling technology in space and provides an important engineering context for evaluating modern PDRC-inspired technologies. When satellites operate in low Earth orbit, they alternately experience sunlit and shadowed regions. PDRC-inspired radiative cooling materials must endure extreme temperature cycles without structural failure, while maintaining low solar absorptance and broad-spectrum infrared emissivity. Low solar absorptance and high infrared emittance favor heat rejection during sunlit operation, but the same high-emittance state may cause excessive radiative heat loss during eclipse. This trade-off highlights the potential value of adaptive or variable-emissivity strategies for orbital thermal management. Additionally, satellites have stringent requirements on the weight and volume of such thermal-control materials, necessitating lightweight and compact designs. Unlike satellites in low Earth orbit, deep space exploration scenarios further amplify the extremities of the space environment, imposing higher demands on the adaptability of PDRC-inspired radiative cooling materials. Although radiative-cooling surfaces in space can in principle utilize broadband infrared emission beyond the terrestrial atmo-

spheric window, they face challenges such as ultra-low temperatures, intense cosmic radiation, and interstellar dust impacts. In deep space regions far from the Sun, it is necessary both to dissipate internal heat from instruments through radiative cooling and to avoid excessive heat loss that could lead to internal equipment failure. Therefore, radiative cooling devices for deep space probes must provide precise thermal regulation, as well as high durability against interstellar dust impacts and intense cosmic radiation. For lunar facilities, PDRC-inspired radiative cooling materials must address unique challenges such as extremely low temperatures and lunar dust contamination. The lunar surface lacks atmospheric protection, with day–night temperature variations exceeding 300 °C, and temperatures in permanently shadowed regions at the lunar poles dropping as low as −253 °C.[59,60] Moreover, the lunar surface contains abundant dust, which, once accumulated, can severely affect the optical performance of radiative cooling device surfaces. Additionally, the vacuum environment and strong ultraviolet radiation on the Moon accelerate material aging. Therefore, radiative cooling devices for lunar facilities must not only adapt to extreme temperatures but also possess resistance to lunar dust contamination and vacuum UV-induced aging.

Spacecraft thermal-control systems are essential for maintaining the operational reliability and service life of onboard equipment. PDRC-inspired materials may complement established passive and active spacecraft thermal-control technologies by providing lightweight, spectrally engineered, scalable, and potentially adaptive thermal-control surfaces. Developers have continuously created high-performance materials; these material innovations may enhance radiative heat-rejection performance while providing the environmental adaptability required for space applications. With ongoing advancements in material innovation, device adaptation, and system-level validation technologies, PDRC-inspired materials and photonic strategies may become important components of next-generation spacecraft thermal-control systems, driving the evolution of space thermal control technology towards greater efficiency, reliability, and energy savings.

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