Thermal Protection Design for Solar Eruption Close-Approach Probes (Postprint)

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Abstract

Yunnan Observatories, Chinese Academy of Sciences, has for the first time proposed a scientific project for close-up detection of solar eruption processes and their corresponding magnetic field structures. This project will conduct unprecedented close-range measurements of the solar atmosphere and the violent activities occurring within it. The detector developed for the project will operate in the near-Sun region for a duration exceeding that of both the Parker Solar Probe (PSP) and the Solar Orbiter spacecraft, and its thermal protection system will encounter difficulties far surpassing those of the latter two. This paper first analyzes the characteristics of the orbital environment for close-up detectors, proposes design concepts for thermal protection, and then presents specific plans for thermal protection system design, simulation, and ground testing. Preliminary research demonstrates that the thermal protection system design offers advantages including excellent radiative heat dissipation, high temperature resistance, and high stability and reliability.

Full Text

Study on Design Scheme of Thermal Protection for Solar Eruption In-Situ Probe

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Abstract

The Yunnan Observatories of the Chinese Academy of Sciences has proposed a scientific project for in-situ measurements of solar eruption processes and their corresponding magnetic field structures, which would conduct unprecedented close-range measurements of the solar atmosphere and intense activities occurring within it. The probe developed for this project will operate in near-solar regions for longer durations than both the Parker Solar Probe (PSP) and Solar Orbiter, presenting thermal protection challenges far exceeding those encountered by these missions. This paper first analyzes the orbital environment characteristics of the in-situ probe, proposes design concepts for thermal protection, and then presents specific designs, simulations, and ground experimental schemes for the thermal protection system. Preliminary research demonstrates that the proposed thermal protection system design offers advantages including excellent radiative heat dissipation, high temperature resistance, and high stability and reliability.

Keywords: In-situ solar eruption probe; Thermal protection; Radiative cooling; Coating

Nearly all activities of Earth’ s organisms depend on energy from the Sun, and any solar activity or variation affects human life and environmental safety in myriad ways. With the widespread application of modern high-tech systems such as wireless communications, satellite navigation, and the Internet, the impact of charged particles from solar eruptions—including solar flares and coronal mass ejections (CMEs)—on human life has become increasingly evident. Intense solar events like the “Carrington Event” and the “1989 Quebec Event” can severely affect modern human life and even survival quality. As the only star that humans can study through close-range 探测, the Sun requires increasingly rigorous monitoring and early warning systems to address the potential future impacts of intense solar activity.

On August 12, 2018, PSP launched from the Kennedy Space Center in Florida, destined to traverse the solar atmosphere and explore regions never before probed by near-solar spacecraft, conducting contact measurements of the solar corona and solar wind origins and dynamics. PSP utilizes multiple Venus gravity assists to approach the Sun, with its perihelion gradually decreasing across 24 elliptical orbits. However, it remains within regions less than 10 solar radii from the Sun’ s center for only about 20 hours per orbit—too brief to accurately detect nearly random solar eruption phenomena [?].

As Europe’ s Solar Orbiter project and Russia’ s “Interheliozond” mission proceed, human solar exploration is entering a new era. Chief Scientist LIN Jun from Yunnan Observatories, Chinese Academy of Sciences, first proposed the in-situ measurement project for solar eruption processes and their corresponding magnetic field structures, which would conduct unprecedented close-range measurements of a star’ s atmosphere and intense activities. The proposed Chinese Solar Eruption In-Situ Probe (hereinafter referred to as the “in-situ probe”) will operate long-term in orbits within 10 solar radii of the Sun’ s center. The thermal protection system shields the probe’ s instruments and equipment from intense solar radiation heating, solar wind and interstellar dust erosion, and cosmic cold black radiation cooling, making it critical to mission success. Unlike

PSP, the in-situ probe will maintain a heliocentric distance of less than 10 solar radii for several years, facing thermal protection challenges far exceeding PSP and representing a research gap in deep space exploration.

1. Orbital Environment of the Solar Eruption In-Situ Probe

Long-term, close-range solar activity detection requires the probe to remain in near-solar orbits continuously. The Chinese Solar Eruption In-Situ Probe currently plans to employ near-circular solar orbits at 5–10 solar radii from the Sun' s center, with orbital inclinations of 10–20° [?]. The orbital thermal environment primarily includes: ultra-intense solar electromagnetic radiation (solar radiation intensity at 5 solar radii reaches 1,848 times that near Earth, approximately 2.53 MW/m^2); continuous solar wind impact and erosion; and intermittent bombardment by various charged particles from intense solar activities such as CMEs and flares. Additionally, the probe faces the cosmic background with an equivalent radiation temperature of about 3 K, while also experiencing strong radiative cooling from the cosmic cold black environment.

2. Thermal Protection Challenges for the In-Situ Probe

The in-situ probe will spend far more time within 10 solar radii than PSP, continuously facing ultra-intense solar radiation without precedent. The sun-facing side directly confronts intense solar radiation while the back side faces cosmic background radiation at an equivalent temperature of 3 K, requiring both high-temperature reduction on the sunward side and low-temperature protection on the back side. Kinetic heating and impact damage from charged particles and interstellar dust affect the efficacy of functional coatings and electronic equipment on the probe' s surface. Both before and after orbital insertion, the probe requires power from solar panels, but the solar radiation intensity incident on the panels varies dramatically. The thermal protection system must enable the solar panels to generate sufficient power without burning out under different irradiation intensities. The in-situ probe carries instruments including electromagnetic field detectors, high-energy particle detectors, extreme ultraviolet coronal spectrometers, extreme ultraviolet imaging spectrometers, low-frequency radio spectrometers, and white-light coronagraphs [?]. Except for instrument sensor heads, all other components reside in the shadow of the heat shield and would be cooled to extremely low temperatures through radiative exchange with the cosmic cold black environment without protection. As the largest system on the in-situ probe, the thermal protection system must adopt lightweight, compact designs to reduce launch costs. Furthermore, post-launch maintenance and replacement are impossible, making stability and reliability paramount in thermal protection system design.

3. Thermal Protection Design Concepts for the In-Situ Probe

The in-situ probe first requires a heat shield facing solar radiation to block intense solar radiation, CMEs, and solar wind, creating a protected working area for instruments and support structures. The shield should feature high temperature resistance, ultra-high solar radiation reflectance, charged particle impact resistance, low density, and high strength, with 外形设计应避免出现热和应力奇点. The heat shield must also accommodate pointing errors—when the probe' s orientation to the Sun deviates, the shield must still protect scientific equipment. Additionally, all sun-facing surfaces must withstand charged particle impacts without functional degradation, while equipment in the shield' s shadow requires thermal protection against cosmic cold black radiation cooling. Finally, to enhance system reliability, passive thermal control technologies with proven reliability should be prioritized.

4. Thermal Protection System for the In-Situ Probe

The core components of the in-situ probe' s thermal protection system include the heat shield and sun-facing coating, radiators, truss structure, solar panels, and equipment bay. The sun-facing coating is the surface protective layer on the shield' s sunward side directly confronting solar radiation. [Figure 1: see original paper] illustrates the schematic of the thermal protection system based on a plate-type heat shield.

The heat shield, located at the probe' s forefront, blocks intense solar radiation and low-energy charged particle erosion, creating a long-term working environment for probe equipment. Its sun-facing coating serves as the first line of defense against ultra-intense solar radiation. The shield connects to radiators via a truss structure (only partially shown in [Figure 1: see original paper]). Radiators mounted on the truss surface feature high-emissivity coatings for radiative heat dissipation to space, while their inner surfaces have multilayer insulation (MLI) films with low emissivity and high reflectance. The probe uses solar panels for power, and scientific instrument surfaces are covered with MLI films to provide appropriate operating temperatures.

4.1 Sun-Facing Coating

As the first line of defense, the sun-facing coating on the heat shield must meet the following key requirements: (1) withstand long-term ultra-intense solar radiation, low-energy charged particle, and interstellar dust erosion; (2) if multi-layered, exhibit strong bonding between layers and the substrate to prevent peeling or flaking during pre-launch and orbital temperature variations; (3) avoid interlayer reactions or high-temperature decomposition while preventing substrate material diffusion; and (4) incorporate crack-arresting designs to prevent crack propagation.

PSP' s sun-facing coating employs white alumina ceramic with tungsten metal coating. This paper proposes two alternative designs: a special transparent alumina coating with iridium, and an ultra-high-temperature coating design.

4.1.1 Parker Solar Probe Sun-Facing Coating

PSP uses white smooth alumina ceramic with tungsten barrier coating as its sun-facing coating, over a carbon substrate of C/C composite and carbon foam. The white smooth alumina ceramic coating exhibits high reflectance in visible and near-infrared bands, with high total solar reflectance and low absorptance. Alumina ceramic demonstrates excellent radiation damage resistance, strong capability to withstand short-wave radiation and charged particle bombardment, and a melting point exceeding 2,000°C. PSP' s alumina ceramic coating contains magnesium oxide dopant as a grain growth inhibitor (GGI) to further increase solar reflectance and reduce thermal expansion coefficient at high temperatures, matching that of the underlying tungsten coating to improve bonding and withstand large thermal gradients without cracking or peeling. Since high-temperature alumina reacts with the carbon substrate, turning gray, the tungsten barrier coating prevents high-temperature interaction. Tungsten, with a melting point exceeding 3,000°C, is the metal with the highest melting point. PSP' s alumina ceramic coating features a porous structure that arrests cracks when they encounter micropores.

PSP' s heat shield dissipates heat through radiative exchange with cosmic cold black. At perihelion, the sun-facing coating' s equilibrium temperature approaches 1,700 K. The spectral radiance curve for a 1,700 K blackbody is shown in [Figure 2: see original paper], with maximum thermal radiation occurring at approximately 1.7 m wavelength, where about 39.25% of thermal radiation energy concentrates in the 1.3–2.4 m peak band.

A 1,700 K blackbody' s radiant exitance in the 1.3–2.4 m band is approximately 185,870 W/m^2. Solar radiation in this band accounts for about 12.7% of total solar radiation; at 10 solar radii, the solar flux density in this band is only 80,561 W/m^2. The difference between these values is 105,309 W/m^2, with a ratio of approximately 2.3072. If the 1,700 K coating has solar absorptance and thermal emissivity of 0.6 in this band, the difference reduces to 63,185.4 W/m^2 while maintaining the same ratio. If both values decrease to 0.2, the ratio remains 2.3072, but the difference further reduces to 21,061.8 W/m^2. At thermal equilibrium, an opaque object' s thermal radiation capability increases with its absorptance. Therefore, higher spectral emissivity near the wavelength of maximum thermal radiation enhances the difference between self-radiation and absorbed solar radiation, improving radiative cooling.

PSP' s sun-facing coating lacks specialized emissivity design, resulting in weak radiative cooling capability and relatively low solar reflectance. Metco105SFP alumina ceramic powder doped with magnesium oxide forms white alumina ceramic combined with a 76.2 m TAN barrier coating. At room temperature, this coating achieves 61.62% solar reflectance and 60.56% thermal emissivity. After vacuum heat treatment at 1,180°C, solar reflectance increases to 73.64% with 49.76% emissivity; at 1,400°C, reflectance reaches 74.04% with 45.96% emissivity [?].

These reflectance and emissivity values are lower than common glass-type secondary surface mirrors in aerospace applications, yielding weaker radiative cooling. Additionally, alumina ceramic' s intrinsic thermal conductivity is too high, transmitting unreflected radiation heat to the tungsten barrier and carbon foam layers. Its high hardness and modulus result in low high-temperature fracture toughness and damage tolerance, making it prone to cracking and requiring toughening through doping. Its low thermal expansion coefficient creates significant thermal mismatch with metals. Thus, finding superior ceramic coating materials is crucial.

4.1.2 Sun-Facing Coating Based on Special Transparent Alumina Ceramic To overcome PSP coating limitations, this paper proposes a novel design comprising transparent alumina ceramic/rare-earth tantalate transition layer/iridium metal film, as shown in [Figure 3: see original paper].

The coating includes a high-temperature-resistant, high-solar-reflectance iridium metal film on the heat shield' s carbon substrate, a rare-earth tantalate transition layer, and a special transparent alumina ceramic coating, forming a high-temperature, high-thermal-resistance secondary surface mirror-like coating. Nanometer-thick transparent alumina ceramic exhibits high solar radiation transmittance, while platinum-group metal iridium provides high reflectance and blocks high-temperature interaction between alumina ceramic and the carbon substrate. As a strong oxygen ion insulator, the rare-earth tantalate transition layer further prevents high-temperature interaction. Alumina ceramic powder grain sizes range from tens of nanometers to tens of micrometers; alumina ceramic exhibits maximum absorptance and emittance for wavelengths similar to its grain' s equivalent circular diameter. If the coating' s average temperature at closest solar approach is T, and is the wavelength corresponding to maximum thermal radiation for a blackbody at temperature T, then matching the alumina ceramic grain size to at temperature T can significantly increase spectral emissivity near this wavelength, improving radiative cooling [**?**]. Additives like magnesium oxide and yttrium oxide can also adjust the band emissivity of transparent alumina ceramic.

Rare-earth tantalates, developed by Professor Feng Jing' s team at Kunming University of Science and Technology, represent the most promising thermal barrier coating materials, featuring higher operating temperatures (200–300°C above conventional coatings), excellent high-temperature toughness, low thermal conductivity, high thermal expansion coefficient, and strong oxygen ion insulation. They can block heat transmitted through alumina, reduce thermal mismatch with metal barrier layers, improve overall high-temperature fracture toughness, and prevent thermal cracking and peeling [**?**, **?**]. This proposed coating design increases emissivity near the wavelength of maximum thermal radiation at closest approach, enhancing radiative cooling capability while overcoming PSP coating limitations in toughness and thermal mismatch, thereby improving thermal protection and extending probe lifetime.

4.1.3 Rare-Earth Tantalate/Ultra-High-Temperature Carbide Composite Coating The above coatings face a major challenge: maintaining high surface reflectance and emissivity under variable temperature, long-term high-temperature, intense solar irradiation, and charged particle bombardment. Once surface optical properties degrade, equilibrium temperature rises sharply, while alumina ceramic' s melting point is only 2,054°C. Tantalum carbide and hafnium carbide offer ultra-high melting points (exceeding 3,750°C), high hardness, excellent impact resistance, and chemical stability, potentially serving as ultra-high-temperature ceramic coatings on C/C composite substrates with transition layers.

Ceramic coatings and C/C composites typically have mismatched thermal expansion coefficients, creating large thermal stresses and cracking during temperature changes. Although literature [?, ?] reports that ceramic coatings with hafnium carbide nanowires can improve toughness through pull-out, bridging, and crack deflection mechanisms, nanowire structures are unstable at high temperatures with poor sintering resistance, leading to reduced toughness and cracking. Intrinsically high-fracture-toughness coating materials are needed. Literature [?, ?] indicates that rare-earth tantalates exhibit ferroelastic toughening—ferroelastic domain rotation at high temperatures absorbs stress, causing strain delay and significantly improving high-temperature toughness. Additionally, white rare-earth tantalates strongly reflect solar radiation. Using rare-earth tantalates as a capping layer on ultra-high-temperature carbide coatings presents a potential solution for the in-situ probe' s sun-facing coating. Figure 4: see original paper-(c) shows the microstructure of ferroelastic domains in rare-earth tantalates, while (d) illustrates the ferroelastic toughening mechanism [?].

Professor Wang Weimin at Wuhan University of Technology' s School of Materials Science and Engineering (see references [?, ?]) has developed hafnium carbide powder with average particle size of 300 nm for coating applications. Tantalum carbide, hafnium carbide, and rare-earth tantalate ceramics are all ultra-high-temperature materials that can allow heat shield operating temperatures exceeding 2,000°C. The radiant exitance of a 2,000 K blackbody is comparable to solar irradiance at 6.45 solar radii. Even if all incident solar radiation is absorbed by the ultra-high-temperature coating, at distances greater than this threshold···

4.2 Heat Shield Design and Thermal Simulation PSP' s heat shield consists of two C/C composite layers with carbon foam between them, sun-facing coating on the outer C/C layer, and low-thermal-conductivity carbon foam. [Figure 5: see original paper] shows the cross-sectional structure. This design ensures shield strength while significantly reducing mass.

China has numerous experienced, technically strong development teams for ultra-high-temperature C/C composites and SiC materials, including teams led by Dean Li Hejun at Northwestern Polytechnical University, Academician Huang Boyun at Central South University, Academician Du Shanyi at Harbin Institute of Technology, Academician Sun Jinliang at Shanghai University, Hu Zijun at the Aerospace Materials and Technology Research Institute (703 Institute of Aerospace First Academy), and the Xi' an Aerospace Composites Research Institute (Aerospace 43rd Institute). The in-situ probe' s heat shield also adopts the dual C/C composite layer with carbon foam design, considering three shapes: plate, hemispherical, and conical. For equivalent shading area, these shapes offer different radiative heat exchange areas and solar irradiance. Hemispherical and conical designs provide better heat dissipation than plate designs but have larger volume and mass, requiring greater launch vehicle capability. The simple, compact plate design was selected for thermal simulation.

At 5 solar radii, the Sun' s viewing angle is approximately 22.62°, so the heat shield must ensure only the sun-facing coating surface receives direct solar illumination. The plate-type heat shield is designed as a thin frustum with a 2.5 m diameter sun-facing surface, 2.38 m bottom diameter, and 30 cm thickness. This frustum design ensures side and bottom surfaces are not directly illuminated. The annular main radiator is coaxial with the heat shield and equipment bay, with an outer diameter of 2 m near the shield' s bottom. The entire design ensures the main radiator and equipment bay remain in the shield' s shadow while accommodating pointing errors.

The plate heat shield features three C/C composite layers covering three carbon foam surfaces, each 0.25 cm thick for a total of 0.5 cm. The carbon foam layer is 29.5 cm thick with 97% porosity, thermal conductivity of approximately 0.05 W/m·K, and density of about 0.016 g/cm³. The carbon foam mass is 23.077 kg, the three C/C composite layers total 54.62 kg, and the sub-millimeter-thick sun-facing coating mass is negligible, yielding a total heat shield mass under 78 kg. The C/C composites undergo high-temperature graphitization, where the turbostratic graphite structure undergoes three-dimensional rearrangement, reducing interlayer spacing and increasing crystallite size, transforming the material toward a graphite crystal structure. After graphitization at 2,500°C, C/C composite strength and high-temperature capability are further enhanced.

After orbital insertion, the heat shield reaches thermal stability. The simplified thermal equilibrium equation for an isothermal body is:

$$\alpha A_1 S + A_1 \varepsilon_1 \sigma T_{CMB}^4 + \varepsilon_2 \sigma T_{CMB}^4 (A_2 + A_3) + A_4 \varepsilon_2 \sigma T_a^4 = A_1 \varepsilon_1 \sigma T_s^4 + \varepsilon_2 \sigma T_s^4 (A_2 + A_3 + A_4) + C \quad (1)$$

Parameter definitions are provided in .

The heat shield' s back side features a truss structure with radiators mounted on it. The truss uses low-thermal-conductivity titanium alloy. Since the heat shield' s back side temperature is relatively low, conductive heat transfer C between the shield and truss can be neglected compared to radiative dissipation.

[Figure 6: see original paper] shows a thermal protection system without gap between radiator and heat shield. In this configuration, the inner circular area' s radiative environment consists of the radiator' s inner surface and equipment bay top, both covered with MLI films featuring low emissivity and high reflectance.

After multiple reflections, most heat shield radiation is absorbed by the back surface, effectively eliminating radiative exchange in the inner circle. Equation (1) simplifies to:

$$\alpha A_1 S + A_1 \varepsilon_1 \sigma T_{CMB}^4 + \varepsilon_2 \sigma T_{CMB}^4 (A_2 + A_3) = A_1 \varepsilon_1 \sigma T_s^4 + \varepsilon_2 \sigma T_s^4 (A_2 + A_3) \quad (2)$$

Calculating Equation (2) yields equilibrium temperatures for various coating emissivity and absorptance values, shown in [Figure 7: see original paper] and [Figure 8: see original paper].

At 5 solar radii, the heat shield' s equilibrium temperature is far higher than at 10 solar radii. Lower absorptance and higher emissivity reduce equilibrium temperature. When < 0.2, the shield temperature remains below 1,100°C at 10 solar radii regardless of emissivity, and below 1,600°C at 5 solar radii. These calculations neglect back-side heat exchange, representing upper temperature limits. Smooth coatings have high solar reflectance and low absorptance. Assuming $= 0.2$ and $= 0.2$, absorbed solar power is 126,199.18 W/m² at 10 solar radii and 504,796.73 W/m² at 5 solar radii. [Figure 9: see original paper] and [Figure 10: see original paper] show thermal simulation results for $= =$ [value] at 10 and 5 solar radii.

At 10 solar radii, the heat shield averages 966.05°C, with the sun-facing surface reaching 1,545.4°C, back center at 747°C, and edges as low as -15.479°C. At 5 solar radii, average temperature is 1,479.34°C, sun-facing surface peaks at 2,381.5°C, back center at 1,112°C, and edges at 0.16295°C. The gapless design prevents back-side radiative cooling, causing excessive temperatures.

With a 30 cm gap (as in [Figure 1: see original paper]), [Figure 11: see original paper] and [Figure 12: see original paper] show thermal simulations at 10 and 5 solar radii with $= =$ [value]. The gap dramatically reduces back-side temperatures to tens of degrees Celsius, substantially improving the high-temperature situation by enabling radiative exchange with cosmic cold black.

Smooth, highly reflective surfaces are non-Lambertian; their average emissivity, reflectance, and sum vary slightly with temperature but generally range 0.95–1.0. PSP' s white alumina ceramic smooth coating is a typical non-Lambertian surface with high solar reflectance but without specialized emissivity design near the peak wavelength. If exceeds 0.8, falls below 0.2, with higher corresponding to lower . A smooth coating with $= 0.8$ and $= 0.2$ would reach 2,400°C on the sun-facing surface at 5 solar radii; with $= 0.9$ and $= 0.1$, the temperature exceeds alumina ceramic' s melting point, making white alumina ceramic unsuitable for 5 solar radii orbits.

To meet requirements for closer orbits and longer near-solar durations, besides the proposed high-temperature, improved radiative cooling coatings, ultra-high-temperature heat pipe arrays can reduce heat shield temperatures. Heat pipe evaporators are embedded in the shield with condensers at the radiator, transferring heat to significantly lower shield temperatures. The heat pipe array runs parallel to the gap truss. Current ultra-high-temperature heat pipes operate at 1,500–2,000°C, typically using lithium working fluid with large latent heat of vaporization and moderate saturation pressure at high temperatures, offering high heat transfer capacity, isothermal performance, and variable heat flux characteristics. Researcher Qu Wei and his team at the Institute of Engineering Thermophysics are domestic authorities on heat pipes and phase-change heat transfer, having developed lithium ultra-high-temperature heat pipes operating above 1,500°C for hypersonic vehicle leading-edge cooling [**?**].

4.3 Radiators Since they don' t face direct solar radiation, the in-situ probe' s radiator requirements are similar to PSP' s. PSP' s radiator consists of multiple panels with high-emissivity coatings. The in-situ probe' s radiator is mounted on the truss between the equipment bay and heat shield, divided into sections A and B. Section A cools the heat shield via heat pipes; section B cools solar panels via heat pipes or water cooling. Section B features a radiation shield ring with adjustable coverage area. The ratio of shielded area to total section B area is defined as shielding factor M. Adjusting M changes the solar panels' equilibrium temperature.

[Figure 13: see original paper] shows the radiator schematic. The shield ring' s inner and outer surfaces are covered with MLI films that block radiative heat exchange with space. The ring is fixed to section B' s bottom, roughly flush, and can extend/retract via electric control along the central axis with a gap between its inner surface and the main radiator. The shield ring uses flexible folding layers or equivalent devices that can fully cover section B when extended.

4.4 Solar Panels and Thermal Control Scheme Conventional solar panel structure includes cells, tempered glass protective layer, adhesive layers, backsheet, and frame ([Figure 14: see original paper]). The tempered glass requires high transmittance to maximize solar absorption.

PSP employs solar panels with UV degradation mitigation. At perihelion, each watt of electricity generates about 13 watts of waste heat. PSP' s maximum power consumption is approximately 462 watts, requiring cooling of up to 6,000 watts of heat. PSP uses a complex circulating water cooling system based on a Hamilton Sundstrand centrifugal pump and 320 cubic foot volume compensation device, with total mass of 55 kg and power consumption under 43 watts. At 5 solar radii, if using PSP' s approach, the in-situ probe' s panels would generate hundreds of watts of electricity while producing tens of thousands of watts of waste heat, requiring an extremely large, complex water cooling system and massive radiator area—an insurmountable challenge. More complex systems are more vulnerable and prone to failure; such active water cooling reduces thermal control reliability.

To overcome water cooling limitations for solar panels at higher solar irradiance, this paper proposes a thermal control protective film that ensures adequate power generation while effectively reducing panel heating. The film features high solar reflectance, low transmittance, and low solar absorptance, comprising a high-transmittance glass substrate, metal film layer, and transparent alumina ceramic film layer. Metal options include iridium, platinum, or silver.

The transparent alumina ceramic layer provides high solar transmittance, while iridium, platinum, and silver offer high solar reflectance and high melting points. Adjusting metal film thickness controls transmittance, allowing appropriate solar radiation to reach cells for power generation. The high-transmittance glass substrate provides structural strength, with thickness determined by specific strength and weight requirements [?]. [Figure 15: see original paper] shows the spectral absorptance curve for a protective film comprising 100 nm silver film, 100 nm alumina film, and 2 mm high-transmittance glass substrate.

The 1-3,000 nm spectral absorptance curve is split into two parts: Figure 15: see original paper for 1-150 nm and (b) for 151-3,000 nm. [Figure 16: see original paper] and [Figure 17: see original paper] show the corresponding spectral transmittance and reflectance curves, respectively.

Solar radiation can be approximated as 5,770 K blackbody radiation. According to Planck’ s law, the spectral radiant exitance Mk( ) for a 5,770 K blackbody is:

$$M_k(\lambda) = \frac{c_1}{\lambda^5}\frac{1}{\exp(c_2/\lambda \cdot 5770) - 1}$$

where c is the first radiation constant and c is the second radiation constant. Solar spectral radiant exitance is shown for the 1-3,000 nm band, where radiation energy is primarily concentrated.

Based on the protective film’ s transmittance, absorptance, reflectance, and solar spectral radiant exitance, calculations show the film’ s solar transmittance is 0.07%, reflectance 97.61%, and absorptance 2.32%. At 5 solar radii, solar irradiance is about 1,848 times that near Earth. With this protective film, solar irradiance reaching the cells is only about 1.3 times Earth’ s solar irradiance, reflecting 97.61% of solar radiation and dramatically reducing thermal control requirements.

Besides water cooling, the in-situ probe can use heat pipe arrays to transfer panel heat to radiators. Panel backs connect to high-temperature heat pipe evaporators via high-temperature thermal silicone, with condensers at radiator section B. After orbital insertion, panel tilt angle and shielding factor M are adjusted based on measured temperatures to maintain operating range. The tilt angle is defined as the angle between the panel surface normal and heat shield central axis. With highly reflective protective film, waste heat during power generation is substantially reduced, potentially eliminating the need for radiator section B and enabling temperature control through tilt angle adjustment alone.

Additionally, the protective film’ s surface emissivity far exceeds that of bare metal, providing good radiative cooling.

4.5 Equipment Bay Thermal Control Instruments in the heat shield’ s shadow would be cooled to low temperatures through cosmic cold black radiation exchange. Additionally, pointing failures could expose instrument surfaces to direct solar radiation. Except for sensor heads, other components require protection against both low temperatures and intense solar radiation. The in-situ probe uses white MLI film wrapping instrument surfaces (excluding sensor heads), synthesized from polyimide and aluminum foil. Aluminum provides high reflectance for 200–1,200 nm radiation, suitable for reflecting solar radiation during pointing failures, while gold, silver, and copper have lower reflectance in the 200–600 nm band. MLI film’ s low emissivity reduces radiative exchange with cosmic cold black, effectively protecting internal equipment from intense radiative cooling.

5. Ground Test Design for Thermal Protection System

The orbital thermal environment includes cosmic cold black, vacuum, ultra-intense solar radiation, and charged particle bombardment. When UV, X, and photons and charged particles strike heat shield and panel coatings, they cause not only kinetic heating but also material physical, structural, and property changes—radiation damage. Compared to PSP, the in-situ probe operates much closer to the Sun with higher charged particle densities and thousands of times longer exposure within 10 solar radii, resulting in far greater radiation damage. When incident particles collide with coating lattice atoms, transferring kinetic energy exceeding the displacement threshold, atoms leave lattice positions, causing displacement damage. Surface displacement leads to sputtering and morphology changes, while internal displacement can create voids, surface cracks, reduced toughness, embrittlement, and creep. Incident particle energy can also excite or ionize coating electrons, breaking molecular bonds and causing radiolysis and strength loss. Therefore, ground simulation experiments for high-energy particle damage are essential. Orbital charged particle bombardment is simulated using cathode rays, proton beams, and -rays at equivalent doses; short-wave radiation is simulated using laboratory UV, X, and rays at equivalent doses.

Vacuum, cosmic cold black, and solar radiation can be tested in thermal vacuum chambers. Liquid nitrogen-cooled chamber walls simulate cosmic cold black, while intense solar irradiation is provided by solar simulators. For example, the KM6 thermal vacuum simulator’ s solar simulator comprises a lamp house (including support, condensing system, water-cooled baffle), planar mirror assembly, optical integrator, vacuum-sealed window, and collimating mirror —an off-axis collimated optical system. The condensing system uses 19 short-arc xenon lamps, each with an ellipsoidal condensing mirror and adjustment mechanism. Xenon light converges on the optical integrator, passes through the vacuum-sealed window to the collimating mirror, which reflects parallel beams to provide a 5.4 m diameter irradiation zone with 39,158 W total energy. The collimating mirror resides inside the vacuum chamber, with other components outside. KM6' s irradiance is relatively weak; Fresnel lenses or solar concentrators can focus radiation to orbital-equivalent intensities. [Figure 18: see original paper] shows a Fresnel lens focusing a 1 m diameter solar beam to a ~2 cm spot.

During ground testing, numerous temperature sensors monitor temperature changes in real time. The control system adjusts tilt angle , shielding factor M, or protective films while measuring panel temperatures and power generation under different states. Aging of heat shield, panels, and protective layers under intense solar radiation and cosmic cold black is measured. Changing defocus distance simulates thermal environments at different solar distances. Based on the probe' s operational cycle, one year of orbital thermal environment variation can be simulated weekly.

6. Conclusion

This paper presents an overall thermal protection system scheme for the in-situ probe with detailed designs for core components. The probe' s operational orbit differs fundamentally from PSP and Solar Orbiter, presenting far greater thermal protection challenges. The sun-facing coating is the system' s key element. To meet special requirements, this paper proposes two novel coating designs, establishing a foundation for future development. Compared to PSP' s thermal protection system, the proposed designs based on ultra-high-temperature heat pipes and panel protective films offer superior thermal control capability to withstand higher solar irradiance. Furthermore, the water-free passive thermal control technology provides higher stability and reliability.

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