Chapter 5: Radiant Coolers

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Overview

A radiant cooler is a passive thermal device used on spacecraft to cool components to cryogenic temperatures via radiative heat exchange to the space environment. The effective temperature of deep space is approximately 3 K, which makes it a very good radiative sink. Radiant coolers can be used on spacecraft instruments because those instruments operate in a high-vacuum environment that eliminates convective heat transfer. A radiant cooler is inherently a long-life device, because it requires no moving parts or stored refrigerants and consumes only the small amount of electrical power needed for maintaining stable temperatures. It can be turned off or warmed up by additional heaters or a cover over the emitting surface that can be closed.

Traditionally "radiant cooler" has referred to a radiator that operates in the temperature range of 60 to 200 K (Fig. 5.1). The lower limit results from the T^4 nature of radiative heat transfer. Below 60 K, most instruments cannot afford the volume or mass of the radiant cooler. In simplistic terms, environmental and other parasitic heat loads cannot be minimized enough to allow operating temperatures less than 60 K.

Figure 5.1: *(Fig. 1.1, reproduced here for convenience.)* Operating temperature and cooling capacity of cryogenic cooling systems.

Generally, radiant cooler designers are provided the temperature or temperature range at which a component must operate for a particular application. The most common application for a radiant cooler is to cool a detector in an instrument to a particular operating temperature. To sense radiation at a particular wavelength, λ, a quantum detector must be cooled to a temperature, T, at which the thermal (phonon) energy, kT, is much less than the energy of an incoming quantum, hc/λ. In these expressions, k refers to Boltzmann's constant, h refers to Planck's constant, and c is the speed of light. Computed temperatures that are required for a typical intrinsic HgCdTe quantum detector, at a variety of wavelengths, are shown in Table 5.1. For a comparison, consider that a wavelength of 0.56 μm corresponds to the human eye's maximum daylight sensitivity.

Table 5.1: Temperature Required for Useful Sensitivity of a HgCdTe Detector

Maximum Wavelength (μm)	Temperature for Useful Sensitivity (K)
7	215
10	150
12.5	120
15	100
20	75
30	50

A notional form of a radiant cooler is shown in Fig. 5.2. The component to be cooled is typically mounted directly to the radiating surface (also called a "patch") or thermally coupled to it via a flexible strap. The patch (innermost cold stage) is mounted to the surrounding cooler housing by means of low-thermal-conductance supports. External inputs, such as Earth's (or another planet's) heat loads and views to warm spacecraft or instrument structure, result in a thermal load on the cone and the warm stages of the cooler. A radiant cooler can be designed for a planet-oriented spacecraft in a low, geostationary, or highly elliptical orbit.

Figure 5.2: Simplified radiant cooler concept.

In most applications, radiant coolers require a shield with highly specular (mirrorlike) surfaces. The shield's outward-sloping walls are designed such that cold space is the only external body seen by the emitter surface, either directly or by reflection on the walls. (Diffusely reflecting shield surfaces would not work, because they would reflect some energy down onto the patch.) The cone acts as a projection mirror or directional antenna that limits the view of the patch exclusively to cold space. The shield wall may be attached to the ambient-temperature cooler or instrument housing. This arrangement implies that the shield or cone temperature may be as high as 300 K.

To reduce the radiative heat load from the shield to the emitter surface, appropriate thermal control coatings—white/black paint or OSR (optical solar reflector) tiles—can be applied to a bib at the end of the cone to cool the shield (Fig. 5.2).The cone end can thus be designed to reject some of the energy conducted in from the warm structure to which it is mounted back out to space, thereby lowering the cone temperature. The cone end's emitter surface, however, is not allowed to have a radiative view to the patch; that would increase patch temperature.

Radiant coolers operating in the 60–100 K temperature range often comprise multiple stages. The emitter surface may be surrounded by an intermediate radiator stage, and/or an additional cooled housing. The addition of multiple stages reduces the overall parasitic load on the patch stage.

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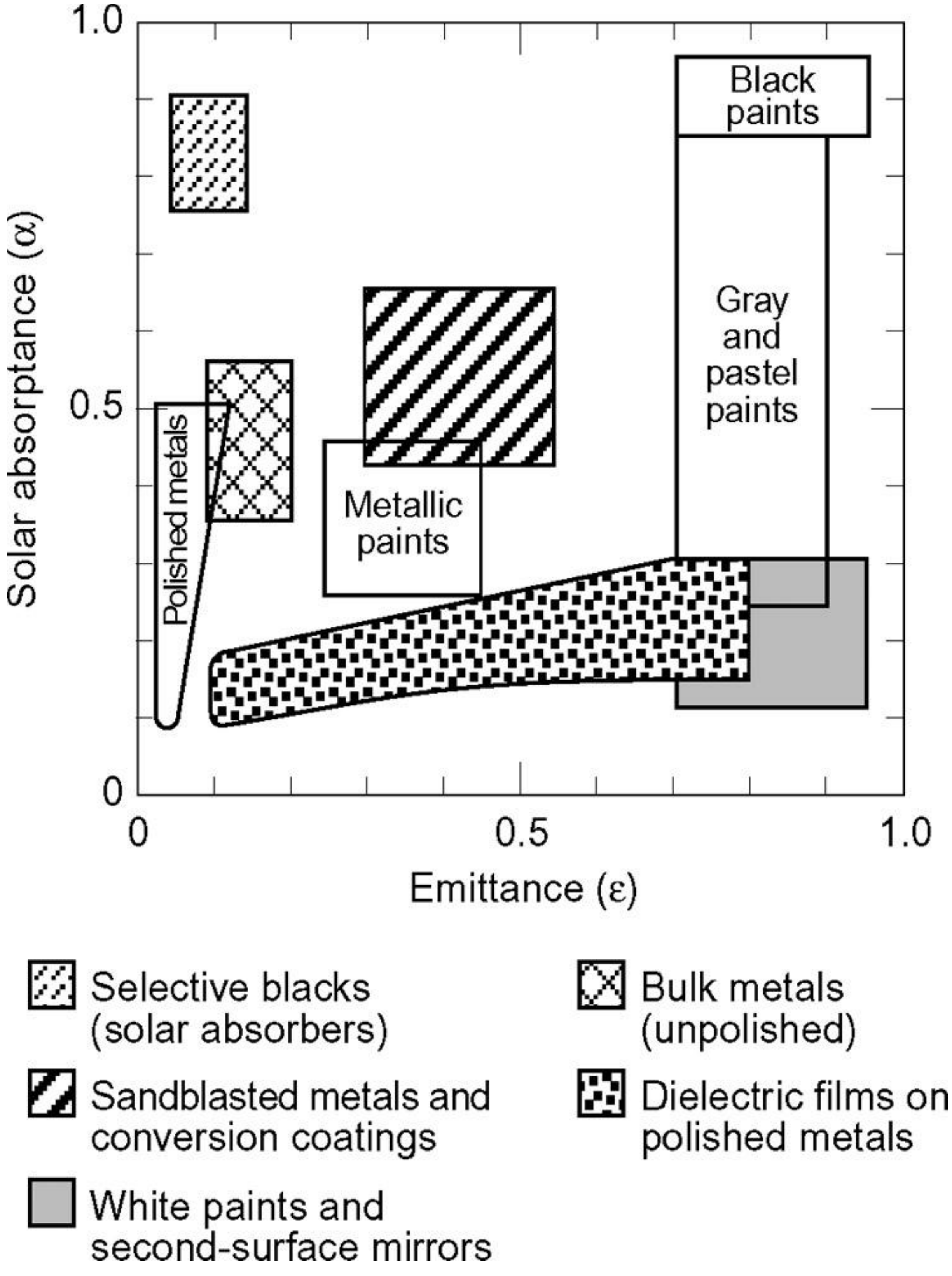


Common Thermal Surface Finishes

Almost all visible surfaces on the inside and outside of uncrewed spacecraft are thermal-control finishes; this reflects the fact that all physical objects absorb and emit thermal energy in the form of radiation. The flow of heat resulting from absorption and emission by these surfaces must be controlled in order to achieve a thermal balance at the desired temperatures. The principal external surface finishes seen on most spacecraft are the outer layer of insulation blankets, radiator coatings, and paints. Electronics boxes located inside the spacecraft, and the structural panels to which they are attached, are usually painted to achieve a high emittance. (While most paints have the required high emittance regardless of color, black paints have been the conventional choice for internal applications.) Internal temperature-sensitive components that do not dissipate much heat, such as propellant lines or tanks, often have a low-emittance finish of aluminum or gold. Common thermal finishes and their optical properties are shown in Table 4.1.

Table 4.1: Properties of Common Thermal Surface Finishes

Surface Finish	**α—Absorptance (beginning-of-life)**	**ε—Emittance**
Optical Solar Reflectors		
8-mil quartz mirrors	0.05 to 0.08	0.80
Quartz mirrors (diffuse)	0.11	0.80
2-mil silvered Teflon	0.05 to 0.09	0.66
5-mil silvered Teflon	0.05 to 0.09	0.78
2-mil aluminized Teflon	0.10 to 0.16	0.66
5-mil aluminized Teflon	0.10 to 0.16	0.78
White Paints		
S13G-LO	0.20 to 0.25	0.85
PCBZ	0.16 to 0.24	0.87
Z93	0.17 to 0.20	0.92
ZOT	0.18 to 0.20	0.91
Chemglaze A276	0.22 to 0.28	0.88
Black Paints		
Chemglaze Z306	0.92 to 0.98	0.89
3M Black Velvet	~0.97	0.84
Aluminized Kapton		
1/2 mil	0.34	0.55
1 mil	0.38	0.67
2 mil	0.41	0.75
5 mil	0.46	0.86
Metallic		
Vapor-deposited aluminum (VDA)	0.08 to 0.17	0.04
Bare aluminum	0.09 to 0.17	0.03 to 0.10
Vapor-deposited gold	0.19 to 0.30	0.03

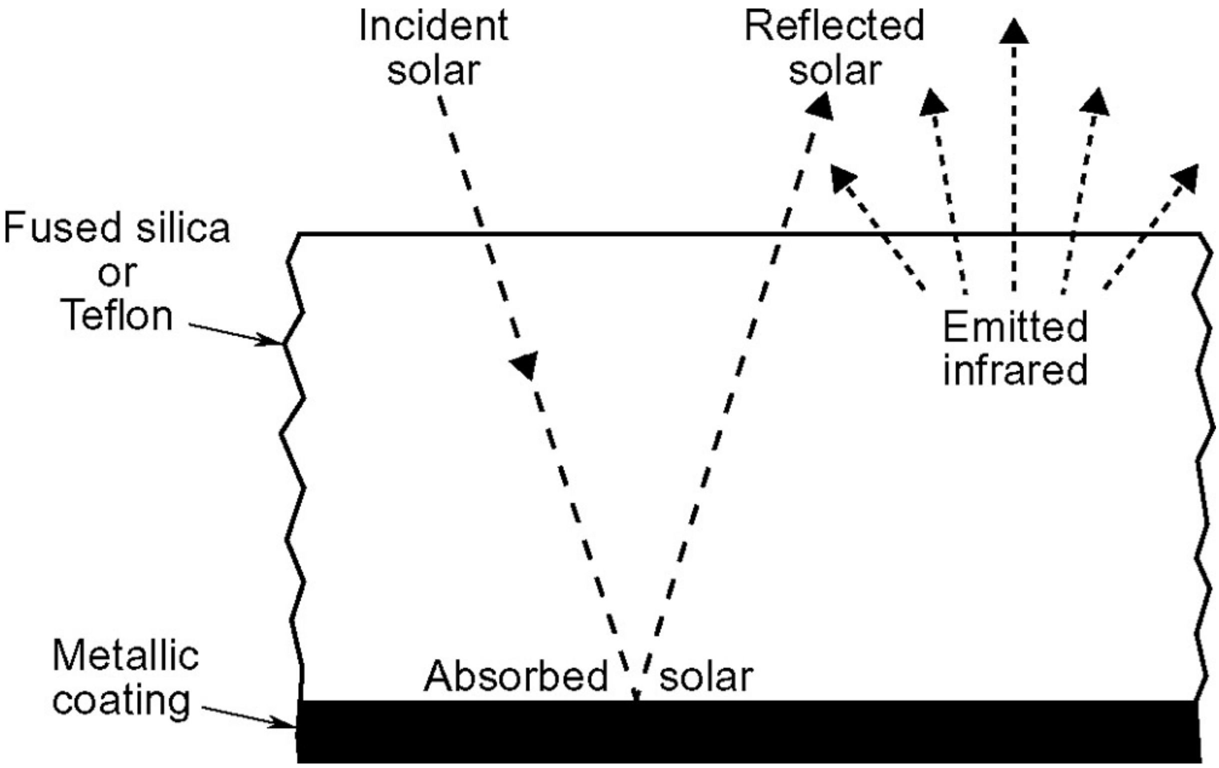
Table 4.1: Properties of Common Thermal Surface Finishes		
Surface Finish	**α—Absorptance (beginning-of-life)**	**ε—Emittance**
SiOx on VDA rape	0.14	0.12
FSS-99 (overcoated silver)	0.03	0.02
Mylar		
1/4-mil aluminized Mylar, Mylar side	(Material degrades in sunlight)	0.34
Beta cloth	0.32	0.86
Astro Quartz	~0.22	0.80
TiNOX	0.95	0.05
Maxorb	0.90	0.10

The outer-cover layer of insulation blankets is usually made of aluminized Kapton, black Kapton, or Beta cloth. Aluminized Kapton is a gold-colored material that has a moderate solar absorptance, a high IR emittance, and a typical thickness of 1 to 3 mils. Black Kapton has a high solar absorptance because it is loaded with carbon to improve electrical conductivity for blanket-grounding purposes. Beta cloth is a very tough Teflon-coated glass fabric that has a low solar absorptance and high emittance. As will be discussed in Chapter 5, the choice of which material to use as the outer-cover layer of the blanket is driven by design requirements such as thermal optical properties, glint prevention, electrical grounding, stress handling, and micrometeoroid protection.

Radiator coatings are typically second-surface mirrors or white paint. The principle behind the second-surface mirror (illustrated in Fig. 4.4) is the use of a visibly transparent material, such as quartz glass or Teflon, to achieve a high emittance, along with a reflective silver or aluminum coating on the back to minimize solar absorptance. Quartz second-surface mirrors, often referred to as optical solar reflectors (OSRs), typically come in small tiles with dimensions on the order of a few cm and a thickness of up to 0.25 mm (10 mils). These tiles are bonded to the radiator surface with acrylic or silicone adhesives. (When bonding to a metal substrate, acrylic adhesive should not be used below −45°C because the mirrors may crack or delaminate.) Teflon second-surface mirror material, sometimes referred to as flexible OSR, comes in a variety of thicknesses (and therefore emittances) and is usually supplied as a tape or sheet with an acrylic adhesive backing for ease of installation. Standard quartz and Teflon OSRs are highly specular, but they also come in a diffuse variety that has a somewhat higher absorptance.

Figure 4.4: Second-surface mirror thermal finish.

While space-qualified paints are available in a variety of colors, black and white are by far the most commonly used. Almost all paints have a high emittance, so the choice is really between solar absorptance (and its degradation in the space environment), ease of application, and electrical conductivity to meet grounding requirements. Most internal spacecraft surfaces are painted black for high emittance, while exterior surfaces, including radiators, are often painted white to minimize absorbed solar energy. In choosing a white paint, one must consider that some paints will experience a greater increase in absorptivity than others as a result of the effects of the space environment. Metallic paints, such as leafing aluminum paint, may have



an emittance as low as 0.2, but these are rarely used on spacecraft. In situations where radiative heat transfer must be minimized, low-emittance metallic finishes are often used. These include bare or polished surfaces of aluminum components, Kapton tape with a vapor-deposited aluminum or gold coating (metal side exposed), or bare stainless steel. Typical applications are aluminized (or aluminum) tape on propellant lines and tanks to limit heat loss and stainless-steel radiation shields to block the radiative view from hot thruster nozzles to sensitive spacecraft components. In general, these metallic finishes are not used on large exterior surfaces because their high absorptance-to-emittance ratio would make them run very hot in direct sunlight. Small exterior components that are conductively coupled to spacecraft structure, however, may sometimes have a metallic finish.

A number of specialty finishes find occasional use in spacecraft thermal control. These include very high-absorptance, very low-emittance finishes, like Maxorb and TiNOX, that are used to raise the temperature of a surface exposed to the sun; very low-absorptance, overcoated silver for sun shields on cryogenic radiators; moderately low solar-absorptance and -emittance finishes like aluminum paints or silicon-oxide-coated aluminum for mitigating temperature swings of exposed spacecraft structure; and controlled anodize and alodine processes for aluminum surfaces on which other thermal-control coatings are not allowed. The thermal engineer should be very careful about using absorptance and emittance values that are reported in the literature for anodized or alodined surfaces because the surface optical properties are highly dependent on the specific process used. Properties obtained from these processes are very repeatable, though, if the process is tightly controlled, such as by a military specification. Duckett and Gilliland[4.1] describe a NASA/Langley-developed controlled chromic-acid-anodizing process for aluminum that allows the user to select any combination of emittance (within the range of 0.10 and 0.72) and absorptance (within the range of 0.2 to 0.4) and obtain both values to within ±0.02.

Appendix A and Touloukian[4.2] contain a much more extensive list of space-qualified finishes that have been used on actual satellites along with corresponding optical properties that have been obtained from a variety of sources. Most of the values given here are for "normal" temperature ranges, and substantial changes may occur at cryogenic or very high temperatures.[4.2],[4.3] While the reported properties have been obtained from what are believed to be reliable sources, differences in reported values are not uncommon. Therefore, in designs that are sensitive to surface properties, measuring the absorptance and emittance of samples of the actual flight finish is recommended.

[4.1]R. J. Duckett and C. S. Gilliland, "Variable Anodic Thermal Control Coating on Aluminum," AIAA-83-1492, *AIAA 18th Thermophysics Conference* (1–3 June 1983).

[4.2]Y. S. Touloukian, *Thermophysical Properties of Matter* (IFI/Plenum, New York and Washington, 1972).

[4.3]M. Donabedian, "Emittance of Selected Thermal Control Surfaces at Cryogenic Temperatures," The Aerospace Corporation, ATM 90(9975)-10 (15 December 1989).