

# PASSIVE COOLING FOR MERCURY SURFACE LANDER ELECTRONICS

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## ABSTRACT

A significant barrier to operation of a mission on the surface of Mercury is the temperature. At Mercury's perihelion distance of 0.313 AU, the solar intensity is 10.6 times the solar flux at Earth orbit, and at the subsolar point, the maximum surface temperature reaches 427°C. For a mission landing on the surface of Mercury at latitude of 40°S, we analyzed using passive thermal control to reduce the temperature of the critical electronics to within the operation temperature limits of silicon devices. The thermal control requires reducing the thermal conductance and infrared flux from the high temperature surface and surrounding spacecraft, and moderating the solar heat input using a surface coating with high solar reflectivity, and maximizing thermal cooling with high infrared emissivity. Using this approach, we find that we can passively cool an electronics box to a temperature of 393K (120°C) using a radiator-white surface with solar absorptivity 0.11 and infrared emissivity 0.91. This temperature is well under 175C target we use for the limits of high-temperature silicon integrated circuits, including RAM and microcontrollers. We could further reduce this operating temperature to as low as 321K (48°C) with an advanced thermal coating, a temperature well within the operational limits of conventional electronics.

## INTRODUCTION

Mercury is the least explored planet in the inner solar system, and although significant scientific questions exist which could be addressed by a Mercury lander, to date only orbiters and flyby missions have explored the planet, and no missions are planned to land on the surface. A significant barrier to long-duration operation on the surface is the temperature. While thermal control has been demonstrated for orbital missions to Mercury, thermal control for surface missions is considerably more difficult, since the hot surface of the planet will radiate to a lander<sup>1,2</sup>.

Mercury has a 3:2 resonance between the orbital period and the rotational period, and at perihelion, the closest distance from the sun, alternate sides of the planet face the sun on each orbit. This results in each side of the planet having a "hot pole," the spot oriented to the sun at perihelion. At Mercury's perihelion distance of 0.313 AU, the solar intensity is 10.6 times the solar flux at Earth orbit. At the subsolar point, the maximum surface temperature<sup>3</sup> reaches 427°C, a temperature far too high to operate conventional silicon electronics. At latitudes away from the equator, the temperature decreases, and in the polar regions the temperature can be below the ice point; however, there is interest in operating a landed mission on the surface at near-equatorial and mid-latitude locations, at which high temperatures are experienced.

This study assumed a landed location of 40°S latitude, the location chosen for an earlier concept study of a Mercury lander done for the 2020 NASA planetary science decadal survey<sup>4</sup>. In this

earlier study, the mission baseline was to operate only during the Mercurian night, with the science operations concluding shortly after sunrise. The current study looks at the possibility of extending such a mission to operate during the Mercurian daytime for a Mercury mission targeted for a landing at latitude of 40°S.

## APPROACH

### Electronics

One approach to daytime operation is to use high-temperature electronics, such as the silicon carbide integrated circuits being developed for future Venus missions<sup>5,6</sup>, which are capable of operation at temperatures well in excess of 500°C. However, SiC electronics are not yet capable of all of the function required for a mission, and hence it is desirable to incorporate some silicon-based electronics (particularly for memory storage) as well.

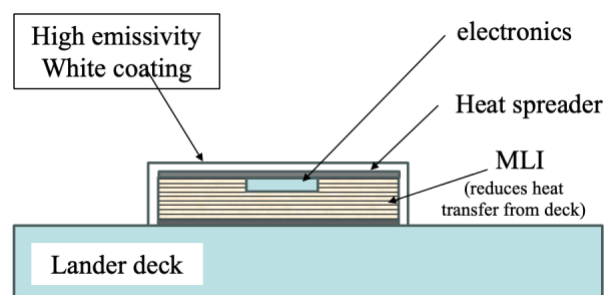
The maximum operating temperature of silicon integrated-circuit based electronics depends on the component and on the type. A survey of high-temperature Si microelectronics shows that silicon-on-insulator integrated circuits<sup>7,8</sup> are available with commercially available devices having maximum operating temperature up to 200°C, with some components available with operating temperature as high as 350°C (with some degradation in performance). To incorporate margin, we used a target temperature of 175°C as the maximum for the thermal enclosure holding the electronics.

For operation of silicon electronics, we analyze whether it is possible to use passive thermal control to reduce the temperature of the critical electronics to within the operation temperature limits of silicon devices.

### Thermal approach

The thermal control incorporates three components: minimize solar heat by low optical absorptivity, minimize IR heating from hot surface (and hot lander) by multi-layer insulation (MLI), minimizing heat conduction from the lander by minimizing heat conduction through the structural and wires, and maximize infrared emissivity (with zero view factor to surface or lander) using a surface coating with high solar reflectivity and high infrared emissivity. Figure 1 shows this approach in schematic.

Multi-layer insulation is a conventional technology used as thermal insulation in spacecraft, and high-temperature compatible MLI has been demonstrated on missions such as the Bepi-Columbo mission to Mercury<sup>2</sup>.



**Figure 1: schematic of thermal control.**

### Absorptivity and emissivity

For a flat surface exposed to sunlight at an intensity  $I$ , the equilibrium temperature can be calculated from Stefan-Boltzmann law as a function of the infrared emissivity  $\epsilon$  and the solar absorptivity  $\alpha$ :

$$T = (\alpha I / \epsilon \sigma A)^{1/4} \quad (1)$$

where  $\sigma$  is Stefan-Boltzmann constant  $\sigma=5.67E-8 \text{ W}/(\text{m}^2\text{K}^4)$ . For an equatorial landing site at the hot pole, the incident intensity is the perihelion solar constant,  $14.5 \text{ kW}/\text{m}^2$ ; for our proposed landing site at  $40^\circ\text{S}$  latitude (and assuming the surface is directed flat upward, to minimize view of the surface), this is multiplied by the cosine of the latitude, a factor of 0.77.

This will be the operating temperature in the ideal case, ignoring self-generated heat by the electronics, heat leak through the MLI, and heat leak from wires, standoffs, *etc.* This is a reasonable first approximation, since these factors are all small compared to solar absorption.

A number of thermal coatings used in space with low solar absorptivity and high infrared emissivity were analyzed. Two coatings that have been used operationally in space are Z93 white thermal paint, used as a coating for thermal radiators, with typical measured absorptivity and emissivity<sup>9,10,11</sup> of  $\alpha = 0.15$  and  $\varepsilon = 0.91$ ; and YB-71 white thermal paint used as an overlayer on Z93 paint<sup>7</sup>, with  $\alpha = 0.11$  and  $\varepsilon = 0.87$ . These values have been shown to be robust after exposure to the space environment on the LDEF (“Long Duration Exposure Facility”) experiment<sup>9</sup>. A slightly more advanced thermal coating, but with less spaceflight data, is AZW/LA-II thermal paint<sup>12</sup>. At 0.33 mm thickness, measured absorptivity and emissivity for this is  $\alpha = 0.09 \pm 0.02$ ,  $\varepsilon = 0.91 \pm 0.02$ . However, the 0.33 mm coating showed difficulties in adhesion. A slightly thinner layer, 0.22 mm, showed better adhesion<sup>13</sup>, with  $\alpha = 0.11$  and  $\varepsilon = 0.91$ .

Using these values, the calculated maximum equilibrium of the sun-facing radiator at the landing site of  $40^\circ\text{S}$  will be:

- Z23: 423 K (150°C)
- YB-71 on Z93: 397K (124°C)
- AZW/LA-II white: 393K (120°C)

Based on this calculation, all three of these thermal paints produce equilibrium temperature at the designated landing site well below the  $175^\circ\text{C}$  requirement.

For some silicon electronics other than SOI technology, lower temperatures would be required. An alternative approach would be to use an optical surface reflector (OSR), essentially a mirror, featuring a transparent glass front surface with high emissivity and a metallic second surface with high reflectivity in the solar spectrum. OSRs have been used in several missions, including the Mercury orbiters MESSENGER<sup>1</sup> and Bepi-Columbo<sup>2</sup>, to moderate the solar array temperature by reflecting away excess solar irradiance. For an advanced OSR with a UVS coating, we used parameters of  $\alpha = 0.06$  and  $\varepsilon = 0.83$ .

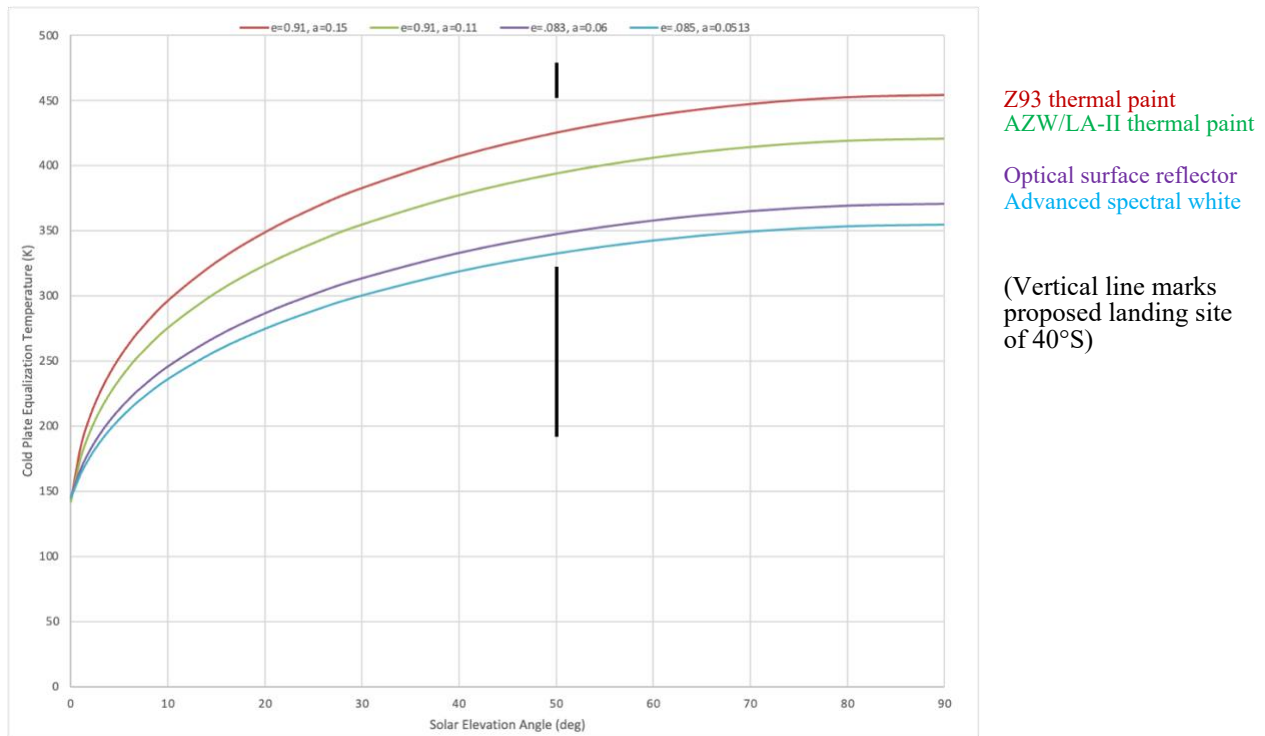
A somewhat more advanced thermal coating is the advanced spectral white thermal coating. This was developed in a NASA Innovative Advanced Concepts (NIAC) project to develop passive in-space cryogenic fluid storage<sup>14</sup>, and is based on a paint incorporating  $\text{Y}_2\text{O}_3$ -particulates to produce a high-emissivity white coating. If this approach can achieve the same low  $\alpha/\varepsilon$  ratio at high temperatures as have been demonstrated at cryogenic temperatures, even lower temperatures can be achieved. The material has been tested in space on the MISSE platform on the International Space Station<sup>15</sup>. Measured values are  $\alpha = 0.046 \pm 0.005$  and  $\varepsilon = 0.85$  for the spray-on version of the coating, and  $\alpha = 0.012$ ,  $\varepsilon = 0.85$  for the material in the form of a tile. Although the tile has a significantly lower absorptivity, it is not yet clear how the tile holds up to space exposure, and hence we assumed the spray-on coating, adding the error bar on the measured absorption. Using these values, the calculated maximum equilibrium of the sun-facing radiator at the landing site of  $40^\circ\text{S}$  will be:

- OSR: 345K (72°C)
- Advanced spectral white: 321K (48°C)

### Detailed calculation

We ran a more detailed thermal model, incorporating the heat generated by the electronics, the heat leak through the support struts and wires, and heat leaks through the MLI. In addition, a one-watt radioisotope heater unit (RHU) was added; this is to ensure that the electronics do not get too cold during the Mercury night. These heat sources were small compared to the solar absorption, and hence the detailed calculation results were not significantly different from the ideal case calculated above.

Figure 2 gives the detailed calculation of the equilibrium temperature for four sun-facing surface conditions at Mercury perihelion, shown as a function of the sun angle. For an upward-facing flat plate, the sun angle of 90° corresponds to noon at an equatorial landing site. The detailed calculated results confirm the ideal calculations above. Even at an equatorial landing site, all the thermal paints except the Z93 meet the 175°C requirement, while the OSR and advanced spectral white coatings achieve temperatures below 100°C.



**Figure 2: Calculated equilibrium temperature of electronics box at Mercury perihelion for sun angles from 0 to 90°**

### CONCLUSIONS

For a proposed mission to the surface of Mercury, we find that we can passively cool an electronics box using passive thermal control, holding the temperature in the electronics enclosure to 393K

(120°C) using a radiator-white surface with solar absorptivity 0.11 and infrared emissivity 0.91. This temperature is well under 175°C target for the limits of high-temperature silicon integrated circuits, including RAM and microcontrollers. With optical surface reflectors or advanced spectral-white thermal coating, this temperature could be reduced to as low as 321K (48°C), which is well within the operational limits of most conventional electronics.

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