Simplistic Solar Shield Analysis

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This document provides a simplistic model for a solar shield. The geometry is shown in Figure 1, where solar irradiance hits the front side of the shield normal to its surface. This irradiance power, I_s is approximately equal to 1366 Watts/m^2 at one Astronomical Unit (AU, the average distance from the Sun to the Earth). The shield absorbs some fraction of this power given by the parameter, α_1, causing the front surface to heat. This causes power to be radiated corresponding to an averaged emissivity, ϵ_1 (emissivity is a function of wavelength for most materials, but here we assume an averaged emissivity, simplifying the analysis). Heat is also conducted away from the front surface to the back surface, corresponding to a thermal conductivity, k, of the solar shield.

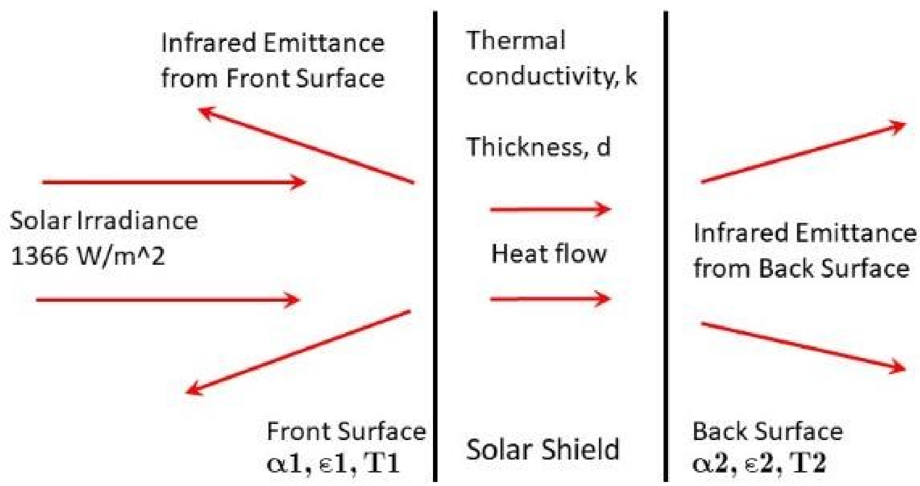

Figure 1: The solar irradiance illuminates the front side of the solar shield. Power is emitted from the front side and is conducted through the shield, resulting in emitted power from the back of the shield.

Assuming the shield has been in place long enough to reach a steady-state temperature, the absorbed power must equal the emitted power plus the conducted power. Mathematically

$$\alpha_1 I_s = \epsilon_1 \sigma T_1^4 + k(T_1 - T_2)/d \tag{1}$$

where σ is the Stefan Boltzmann constant (5.67×10^{-8} W/(m^{2}K^4)). T_1 and T_2 are the temperatures of the front and back surfaces of the solar shield, and d is the thickness of the solar shield.

The back surface of the solar shield is also assumed to be at steady-state, so the power conducted to the back surface must equal to power radiated from the back surface, i.e.

$$\epsilon_2 \sigma T_2^4 = k(T_1 - T_2)/d. \tag{2}$$

These two equations describe the power flow through the solar shield and can be solved for the front and back temperatures. Note that these yield a pair of fourth order polynomials, which when solved yield 16 sets of solutions, most of which are complex. The results shown below were obtained from one specific set that yields real values in the correct temperature range and correspond to the physical solution.

First consider the case where both the front and back surfaces of the solar shield are coated with a highly emissive surface that has relatively low solar absorbance, e.g. a clear plastic, white paint, or Y_2O_3. Figures 2 and 3 show the resulting temperatures for the front and back surfaces as a function of the front surface solar absorbance and for four different ratios of the thermal conductivity divided by the shield thickness. If multi-layer insulation (MLI) were used with a thermal conductivity of 10^{-4} /(m K) and if the shield were 0.01 meters thick (1 centimeter), then $k/d = 0.01$ Watts/(m^2 K) the smallest value shown. A thinner shield, or one composed of something with higher thermal conductivity would yield a higher ratio, so values of k/d ranging from 0.01 to 10 are given in the plots.

Figure 2 shows that the temperature of the shield front is dependent on the absorptivity of the shield, but is not strongly dependent on the conductive power flow through the shield. However, Figure 3 shows that the temperature of the back of the shield, for this case, is the reverse, strongly dependent on the power flow through the shield and not on the power absorbed by the front of the shield (i.e. α_1). So in this case, as the absorptivity of the front of the shield increases, the front temperature changes, resulting in greater infrared emission from the front and greater heat flow through the shield. However, if the shield has low thermal conductivity, little power gets through the shield and the back stays at a low temperature.

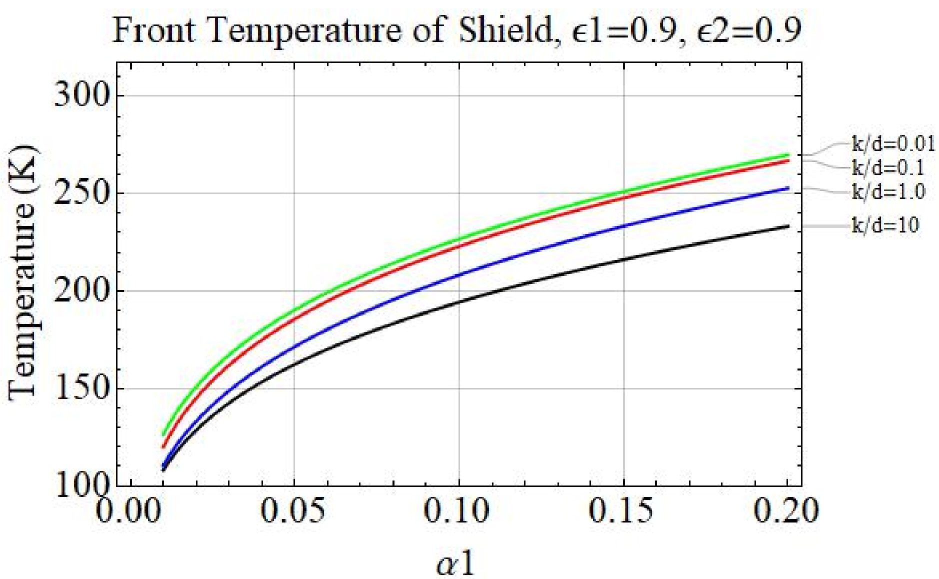

Figure 2: The temperature of the front of the solar shield when the front and back are highly emissive in the infrared, as a function of the front solar absorbance and for four different conductivity/thickness ratios.

In this first case, the back of the shield is a good infrared emitter, which might not be desirable and can result in significant heat being launched onto a shaded object (this might be an LH2 tank at 20 K). If the shield is made of MLI with $k/d = 0.01$, then the back of the shield is between 60 K and 80 K and can emit as much as 256 times more power than the LH2 tank. So it might be worth considering placing a silver layer on the back of the solar shield to lower its emittance, which is the next case considered. Let the emittance of the back of the shield be 0.02, a poor infrared emitter. Figures 4 and 5 show the temperatures of the front and back of the solar shield for this case.

Figures 4 and 5 show that if infrared emission is limited from the back of the shield, then for k/d ratios of 1.0 and 10, the front and back of the shield are at nearly the same number. For shields with a lower k/d ratio (thicker or lower thermal conductivity) the temperature of the back surface does drop to a lower temperature than the front. The discontinuity of the red plot is due to a transition between fourth order polynomial solutions and I have chosen not to fix this since the trends are still apparent. Also, the temperature of the back surface is now affected by the solar absorption of the front surface, indicating that a lower absorptivity

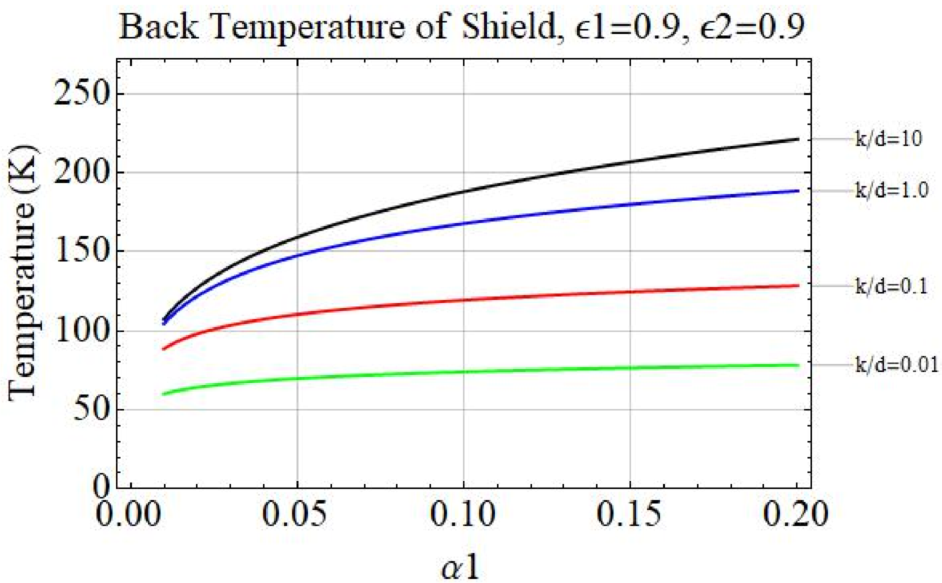

Figure 3: The temperature of the back of the solar shield when the front and back are highly emissive in the infrared, as a function of the front solar absorbance and for four different conductivity/thickness ratios.

is preferred.

Consider the case of a solar absorptivity of 0.1 and $k/d = 0.01$. If the back is a good infrared emitter it reaches a temperature of about 75 K (Figure 3). If the back is a poor emitter it reaches a temperature of about 160 K. The temperature is higher, but the infrared power emitted is about half of that emitted by the high emissivity back surface. So even though the shield is warmer in this second case, it emits less infrared power towards the shaded object. This difference is even more apparent if the front of the solar shield has an absorptivity of 0.01. The high emissivity back surface is at 60 K, while the low emissivity back surface is at 110 K. In this case, even though the back surface of the low emissivity case is warmer it emits only a 1/4 of the power (the same as a 41 K surface).

As a third and final case, assume that the front and back surfaces of the shield are silvered and have infrared emissivities of 0.02. This may appear promising due to the high reflectivity of silver, however, silver absorbs strongly in the UV and has an absorptivity of about 0.06. So the shield absorbs significant optical power and can not emit it due to the low infrared emissivity of silver. Consequently, the front of the shield can reach high temperatures, as can the back, especially when the k/d ratio is large allowing high power flow through the shield, as shown in Figures 6 and 7.

More optimization can be performed if actual emissivities are known. In addition, the emissivity of the shaded object (e.g. a LH2 tank) should be accounted for as well. A low emissivity coated LH2 would radiate minimal infrared power, but would also absorb only a fraction of the irradiant power hitting it from the back surface fo the shield. A high emissivity coating would allow the LH2 tank to emit IR power, but would result in the absorption of impinging infrared power. An ideal design may require different coatings on different LH2 tank surfaces depending on what that surface is facing.

1 Conclusion

If the goal is to launch minimal radiant power onto a shaded object, such as an LH2 tank, using a single solar shield (note that that Webb telescope utilizes a series of solar shields to achieve low radiant power), then the front of the shield should be a good infrared emitter and have a very low solar absorptivity. The back of the shield should be the opposite and have a very low emissivity. Taking these values to something close to their theoretical limits, let the back emissivity be 0.01 (silver at long wavelengths might achieve

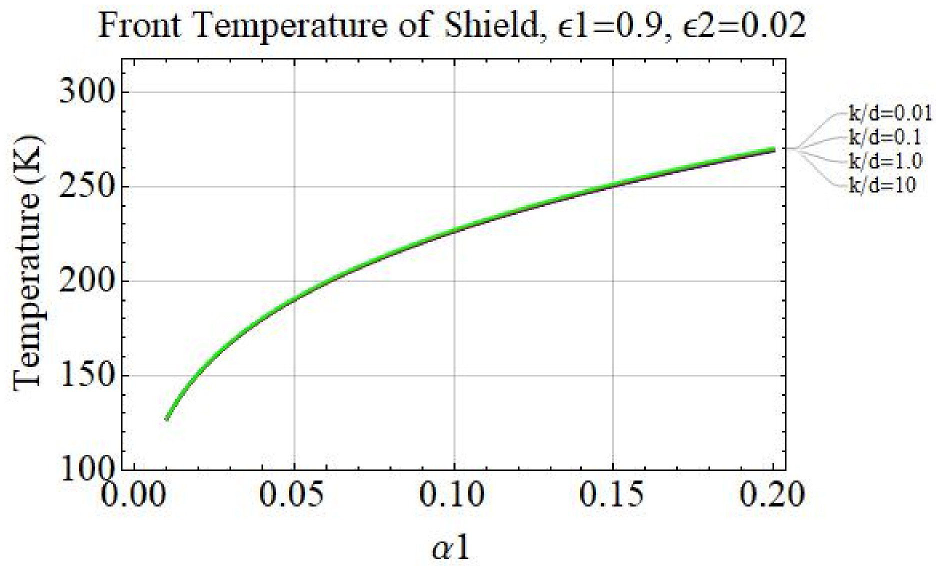

Figure 4: The temperature of the front of the solar shield when the front is highly emissive and the back is not highly emissive in the infrared, as a function of the front solar absorbance and for four different conductivity/thickness ratios.

even better than this) and let the front solar absorptivity range from 0.001 to 0.05. 0.001 is close to what may be possible with selected, dry, pressed powders. The result for the back surface of the shield is shown in Figure 8, predicting (disregard the discontinuities) that for very low solar absorptivity, that the thermal conductivity and thickness of the shield are not important since the curves approach each other. Also, at this approximate theoretical limit, the back surface is at about 70 K, but due to the low emissivity, emits the same net power as a 22 K object. Possibly low enough to negate any heating of the LH2 tank from the sun.

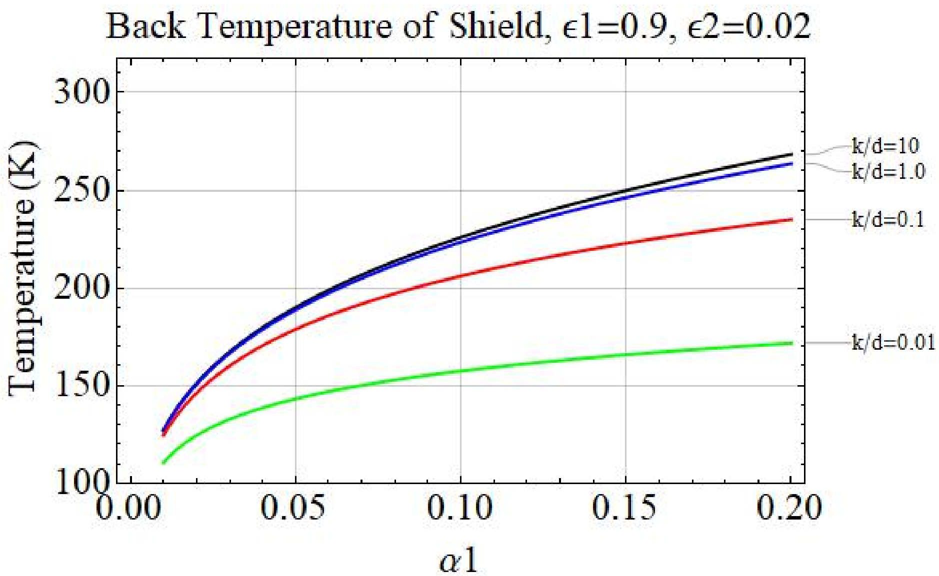

Figure 5: The temperature of the back of the solar shield when the front is highly emissive and the back is not highly emissive in the infrared, as a function of the front solar absorbance and for four different conductivity/thickness ratios.

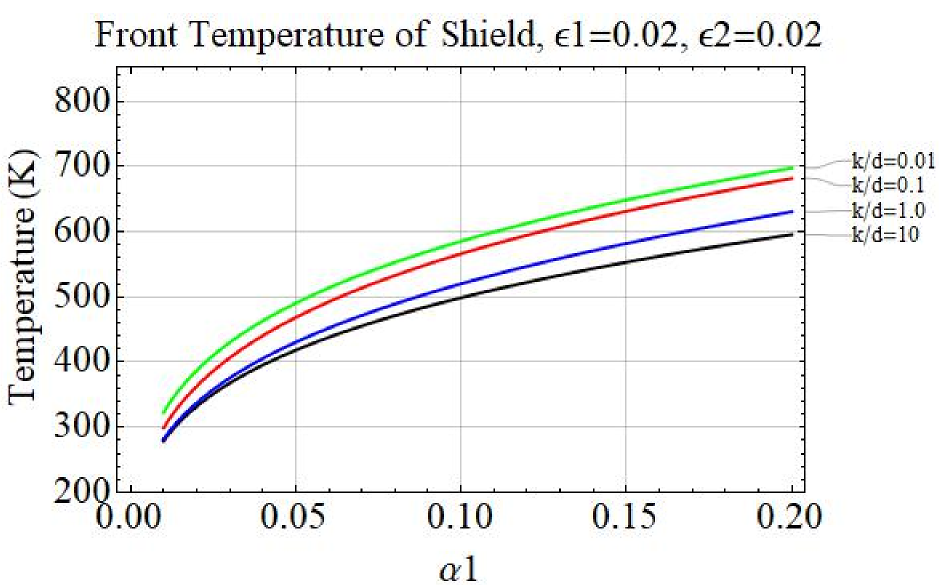

Figure 6: The temperature of the front of the solar shield when the front and back are not highly emissive in the infrared, as a function of the front solar absorbance and for four different conductivity/thickness ratios.

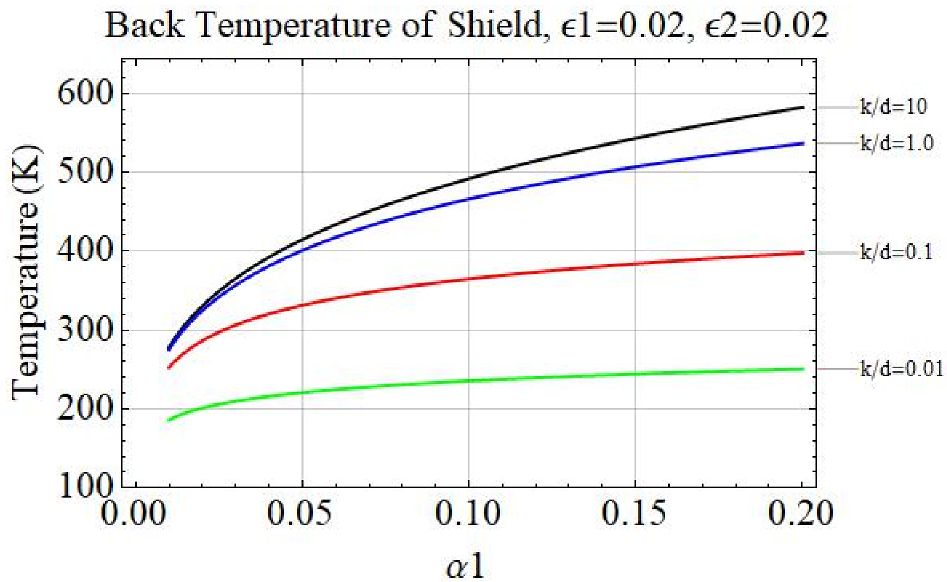

Figure 7: The temperature of the back of the solar shield when the front and back are not highly emissive in the infrared, as a function of the front solar absorbance and for four different conductivity/thickness ratios.

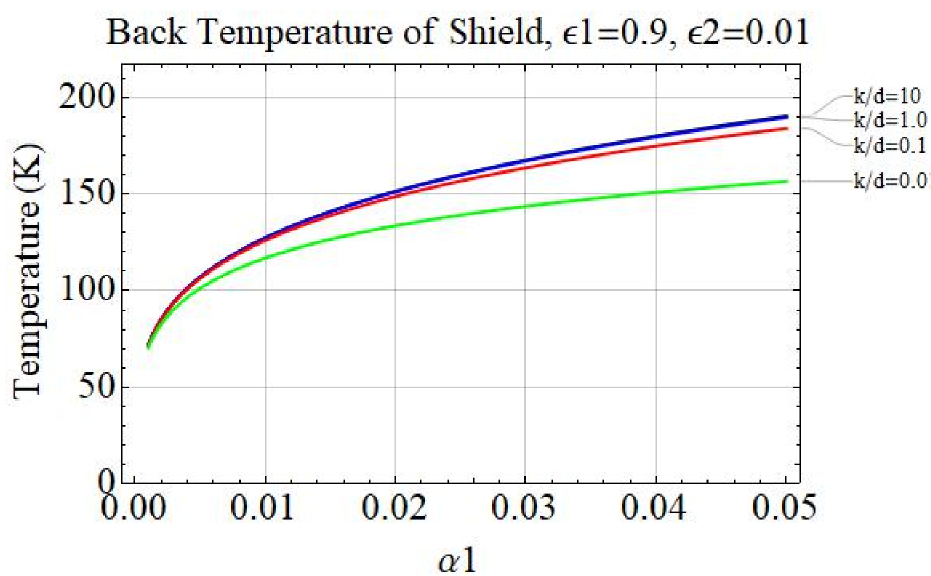

Figure 8: The temperature of the back of the solar shield when the front is highly emissive in the infrared and the back is a very poor emitter, as a function of the front solar absorbance and for four different conductivity/thickness ratios.