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THIN FILM COATINGS FOR IMPROVED α/ϵ RATIOS

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New thin film coatings have been developed for fused silica, ceria doped glass, and Corning 0211 microsheet which provide increased emissivity and/or decreased solar absorption.

Emissivity is enhanced by suppression of the reststrahlen reflectance and solar absorption is reduced by externally reflecting the ultraviolet portion of the solar spectrum.

Optical properties of these coatings make them suitable for both solar cell cover and thermal control mirror applications. Measurements indicate equivalent environmental performance to conventional solar cell cover and thermal control mirror products.

INTRODUCTION

Increased system requirements on next generation spacecraft have stimulated interest in methods for obtaining more power from solar arrays. One potential method involves lowering the operating temperature of conventional solar arrays either by decreasing the unusable solar energy absorbed or by increasing the energy re-radiated into space. Estimates based on simple assumptions (Reference 1) indicate that 1% power gains can be achieved for each 0.02 decrease in array solar absorption. Power gains of 1% can also be achieved for each 0.04 increase in front side emissivity on a two-sided array and for each 0.02 increase in emissivity on a one-sided body mounted array.

Thin film coatings have been developed for solar cell coverglass materials which increase emissivity and decrease solar absorption of the solar cell assembly. Coverglass materials considered include fused silica, ceria doped glass (CMX), and microsheet. Additional gains may be possible by application of these coatings to the thermal control mirror (TCM) surfaces of spacecraft; further lowering operating temperature.

Figure 1 illustrates a conventional solar cell assembly. Coverglasses for conventional cells usually have thin film coatings applied to both their internal and external surfaces. External coatings have most often been single layer MgF_2 antireflection (AR) coatings. Internal coatings are normally ultraviolet reflecting coatings (UVR) which protect the adhesive from ultraviolet light exposure which causes darkening.

ENHANCED EMISSIVITY COATINGS

Coverglass emissivity, ε, is related to spectral reflectivity $R(\lambda)$ as follows from Reference 1,

$$\varepsilon = 1 - \frac{\int_{\lambda_1}^{\lambda_2} R(\lambda) BB_T(\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} BB_T(\lambda) d\lambda} \qquad (1)$$

where λ is the radiation wavelength, and $BB_T(\lambda)$ is the blackbody spectral distribution function for a blackbody at temperature T. For spacecraft applications, T is near 300 Kelvin and 96% of the distribution is contained between 5.0μm (λ_1) and 50.0μm (λ_2). Equation 1 indicates that surfaces with low reflectance between 5μm and 50μm will have high emissivities.

Figure 2 shows infrared spectral reflectance data for conventional AR coated fused silica. Overlaid on this data is the 300 Kelvin blackbody radiance distribution function. Notice that fused silica has a high reststrahlen reflectance near the peak of the blackbody distribution at 9.6μm. An external coating which reduces this reflectance will be effective in increasing the emissivity of the coverglass. Of course, this coating should neither significantly reduce transmittance of the coverglass in the silicon solar cell response band, nor degrade the environmental durability. As will be shown, the enhanced emissivity coatings developed have these desirable properties.

REDUCED SOLAR ABSORPTION COATINGS

Solar absorption, α, of a solar cell assembly is related to the spectral absorption, $A(\lambda)$, by

$$\alpha = \frac{\int_{\lambda_1}^{\lambda_2} A(\lambda) S(\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} S(\lambda) d\lambda} \qquad (2)$$

where $S(\lambda)$ is the solar irradiance spectral distribution function. Since only 0.2% of solar radiation is below 0.25μm and only 3.7% is above 2.5μm, these values were selected for λ_1 and λ_2 respectively for purposes of discussion.

Although lower α will reduce operating temperatures thereby improving conversion efficiencies, methods to decrease α are beneficial if they decrease $A(\lambda)$ only in the region outside the spectral response band of the solar cell. Figure 3 shows the spectral absorption from 0.25μm to 2.5μm for ceria doped glass. Overlaid on this data is an approximate solar spectral distribution function. It can be seen from the figure that the coverglass will contribute to $A(\lambda)$ of the assembly only in the ultraviolet region. This region is outside the response band of the solar cell. An external coating which reflects rather than absorbs the ultraviolet energy will be effective in beneficially reducing the α of the solar cell assembly. As with the enhanced emissivity coating, this coating must neither significantly reduce transmittance of the coverglass in the spectral response band, nor degrade the environmental durability. Coatings have been developed which meet these requirements.

APPLICATION TO FUSED SILICA

Enhanced emissivity coatings can be very beneficial to the performance of fused silica. Figure 4 shows infrared reflectance data for a conventional fused silica coverglass (MgF_2 coated) and for a coverglass coated with an enhanced emissivity coating. Note that the reststrahlen reflectance at 8.85μm near the peak of the blackbody distribution has been substantially reduced. Reflectance has been slightly increased at longer wavelengths, but this has minimal effect since the blackbody distribution has a low weighting factor in this region.

Table I gives performance data for this enhanced emissivity coating. The conventional fused silica coverglass is labeled AR/BR in that table where the AR is a single layer MgF_2 coating and the BR is an internal ultraviolet reflecting coating. BR stands for "blue" reflector to differentiate this conventional internal coating from the new external UVR coating. The emissivity listed in the table is normal emissivity, ϵ_N, which is the emissivity calculated from Equation (1) using specular reflectance data measured at near normal angle of incidence. Weighted average transmittance, $\bar{T}$, is the transmittance of the coverglass weighted by the cell spectral response and the solar spectral distribution function. Values of $\bar{T}$ given assume the internal side of the coverglass is adjacent to an adhesive with refractive index 1.43. Measurements were made on 0.3mm thick substrates. Environmental tests were performed in MIL SPEC test equipment except for radiation exposure. Radiation exposures were conducted by Boeing Radiation Effects Laboratory.

Since conventional fused silica coverglass is non-absorbing in the ultraviolet and has an internal ultraviolet reflecting coating, no technical advantage can be obtained with the use of an external UVR coating. However, an external UVR coating was deposited and tested on fused silica because it has potential for cost reduction. Manufacturing costs would be reduced since one external coating would replace both the internal and external coatings on conventional fused silica coverglass. The data in Table I shows that this approach yields equivalent technical performance to conventional coverglass.

APPLICATION TO CERIA DOPED GLASS

Although uncoated CMX has a higher emissivity than uncoated fused silica, emissivity coatings are still effective. The infrared reflectance of both MgF_2 coated and enhanced emissivity coated CMX is shown in Figure 5. As with fused silica, the reflectance near the peak of the 300 Kelvin blackbody curve has been reduced by the enhanced emissivity coating. Performance data for this coating is shown in Table II. Ceria doped glass does not require an internal ultraviolet reflecting coating because it absorbs sufficiently in that spectral region to protect the adhesive. This high absorption below 0.35μm increases the overall solar absorption of a CMX covered solar cell assembly. The absorption of MgF_2 coated CMX is compared to external UVR coated CMX in Figure 6. The comparison shows substantially reduced absorption between

0.27µm and 0.35µm. This spectral region contains 4% of the solar energy output. By proper design, the UVR coating can also serve as an AR coating. Table II lists the performance data for this coating. The data indicates equivalent or better performance in all categories to the MgF_2 coated CMX coverglass.

APPLICATIONS TO MICROSHEET

The physical properties of Corning 0211 microsheet are very similar to CMX glass except that ultraviolet absorption begins at 0.315µm instead of 0.35µm. This cutoff wavelength is too low to adequately protect the adhesive and therefore conventional microsheet coverglass has an internal ultraviolet reflecting coating (BR), as well as an external MgF_2 AR. In the infrared, the reflectance properties of microsheet are identical to CMX. Figure 7 shows the infrared reflectance of conventional microsheet coverglass as well as enhanced emissivity coated microsheet. Performance data is given in Table III.

The lower ultraviolet absorption cutoff wavelength of microsheet as compared to CMX means that conventional microsheet coverglass will have less solar absorption than CMX. However, there is still improvement possible with the use of an external UVR coating. The ultraviolet absorption of coventional (AR/BR) coated microsheet and external UVR coated microsheet is shown in Figure 8. Substantially reduced absorption occurs between 0.27µm and 0.32µm, a band which contains 1.8% of the sun's energy. Table III shows a reduction in α of 1.8% with the external UVR coating along with other relevant performance data.

One drawback to microsheet as a coverglass substrate is its slightly lower resistance to high energy electron radiation. The transmission loss indicated in Table III is substrate related, not coating related, as confirmed by identical coatings on different substrate materials and by Reference 2. Selection of microsheet as a coverglass material must therefore be limited to missions which will not receive high radiation dosage.

APPLICATION TO THERMAL CONTROL MIRRORS

A conventional thermal control mirror is a fused silica coverglass uncoated on the external surface and internally coated with a broadband metallic reflector. The metal strongly absorbs the ultraviolet so no additional adhesive protection is required.

Uncoated fused silica has essentially identical infrared reflectance to MgF_2 coated fused silica. Therefore, the data given for enhanced emissivity coatings on fused silica coverglass will apply directly to thermal control mirrors. (See Figure 4 and Table I).

The absorption of thermal control mirrors is low everywhere except in the ultraviolet where metals stop reflecting. An external UVR coating will be beneficial to TCM's by lowering absorption in this region. Figure 9 shows a comparison of the absorption from 0.28µm to 0.50µm of uncoated and UVR coated thermal control mirrors. Solar absorption is reduced by 2.3%. Environmental data is identical to that given in Table I for a UVR coating on fused silica.

CONCLUSION AND WORK IN PROGRESS

It has been shown that enhanced emissivity coatings and external ultraviolet reflecting coatings can improve the α/ε ratio for solar cell coverglass materials, as well as thermal control mirrors. Table IV is a comparison table giving,

1) Normal emissivity values achievable for each coverglass material,
2) Reduction in solar absorption possible with external UVR coatings, and
3) Estimated percentage power increases achievable from a fixed planar array if both enhanced emissivity and external UVR coatings are employed.

Although data presented in this paper applied to the independent application of either an enhanced emissivity coating or an external UVR coating, preliminary development results indicate that both can be simultaneously utilized. Effort is ongoing to optimize transmittance in the cell response band for the combined designs. Final $\bar{T}$ values greater than 96% are anticipated with no loss in environmental durability.

REFERENCES

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2. Crabb, R.L.; "Evaluation of Cerium Stablized Microsheet Coverslips for Higher Solar Cell Outputs"; Conference Records of the 9th IEEE Photovoltaic Specialists Conference, Silver Springs, Maryland 1972.

3. Rancourt, J. et al.; "Emissivity Enhancement of Fused Silica for Space Applications"; Proc. 4th European Symp. 'Photovoltaic Generators in Space', Cannes, France 1984.

TABLE I. Performance Data on Fused Silica Coverglass

Performance Parameter	Conventional AR/BR	Enhanced Emissivity	External UVR
Normal Emissivity ϵ_N	0.82	0.89	0.82
Coverglass Solar Absorption α	<.01	<.01	<.01
Weighted Average % Transmittance $\bar{T}$	97.1	97.0	97.7
Environmental Durability			
Humidity per MIL-C-675	Pass	Pass	Pass
Adhesion per MIL-M-13508	Pass	Pass	Pass
Abrasion per MIL-C-675	Pass	Pass	Pass
Salt Fog per MIL-STD-810B	Pass	Pass	Pass
Temperature Cycle (-320°F to 350°F)	Pass	Pass	Pass
Radiation Damage			
0.56 Mev protons to $5 \times 10^{13}/cm^2$	None	None	None
1.0 Mev electrons to $2 \times 10^{15}/cm^2$	None	None	None

TABLE II. Performance Data on Ceria Doped Glass

	Coating Type		
Performance Parameter	Conventional MgF_2	Enhanced Emissivity	External UVR
Normal Emissivity ϵ_N	0.86	0.90	0.86
Coverglass Solar Absorption α	.048	.048	.011
Weighted Average % Transmittance $\bar{T}$	97.0	96.3	96.8
Environmental Durability			
Humidity per MIL-C-675	Pass	Pass	Pass
Adhesion per MIL-M-13508	Pass	Pass	Pass
Abrasion per MIL-C-675	Pass	Pass	Pass
Salt Fog per MIL-STD-810B	Pass	Pass	Pass
Temperature Cycle (-320°F to 350°F)	Pass	Pass	Pass
Radiation Damage			
0.56 Mev protons to $5 \times 10^{13}/cm^2$	<1% $\bar{T}$ loss	<1% $\bar{T}$ loss	<1% $\bar{T}$ loss
1.0 Mev electrons to $2 \times 10^{15}/cm^2$	<1% $\bar{T}$ loss	<1% $\bar{T}$ loss	<1% $\bar{T}$ loss

TABLE III. Performance Data on Microsheet

Performance Parameter	Coating Type Conventional AR/BR	Enhanced Emissivity	External UVR
Normal Emissivity ϵ_N	0.86	0.90	0.86
Coverglass Solar Absorption α	.023	.023	.005
Weighted Average % Transmittance $\bar{T}$	97.3	96.8	97.8
Environmental Durability			
Humidity per MIL-C-675	Pass	Pass	Pass
Adhesion per MIL-M-13508	Pass	Pass	Pass
Abrasion per MIL-C-675	Pass	Pass	Pass
Salt Fog per MIL-STD-810B	Pass	Pass	Pass
Temperature Cycle (-320°F to 350°F)	Pass	Pass	Pass
Radiation Damage			
0.56 Mev protons to $5 \times 10^{13}/cm^2$	<1% $\bar{T}$ loss	<1% $\bar{T}$ loss	<1% $\bar{T}$ loss
1.0 Mev electrons to $2 \times 10^{15}/cm^2$	3% $\bar{T}$ loss	3% $\bar{T}$ loss	3% $\bar{T}$ loss

TABLE IV. Improvement Potential from Coverglass Coatings

	Coverglass Material		
Performance Parameter	Fused Silica	CMX	Microsheet
ϵ_N	0.89	0.90	0.90
α Decrease	None	0.037	0.018
Estimated % Power Increase	1.8	2.9	1.9

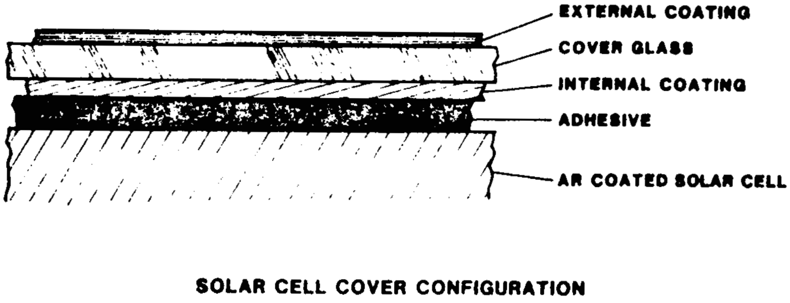

Figure 1: Coverglass components in a conventional solar cell assembly.

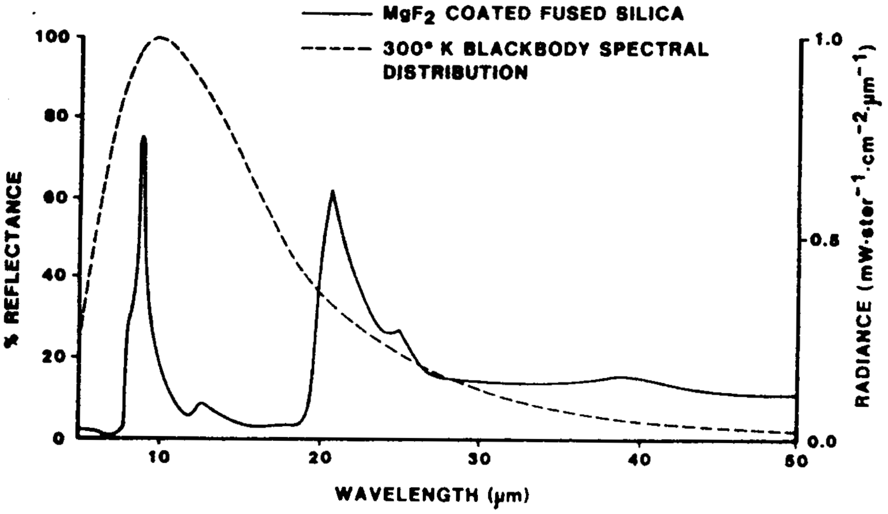

Figure 2: Infrared reflectance of fused silica coverglass showing high reflectance near the peak of a 300 Kelvin blackbody spectral distribution.

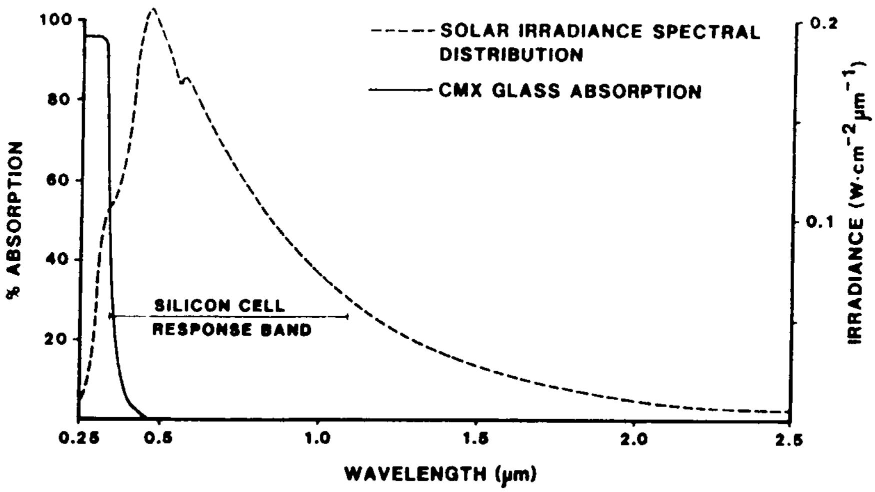

Figure 3: Absorption in ceria doped glass relative to the solar irradiance spectral distribution.

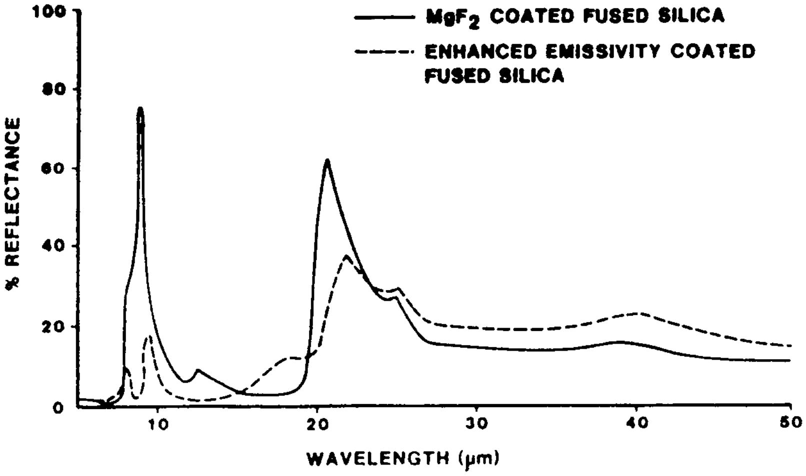

Figure 4: Infrared reflectance of MgF_2 coated and enhanced emissivity coated fused silica showing reflectance suppression near 10μm.

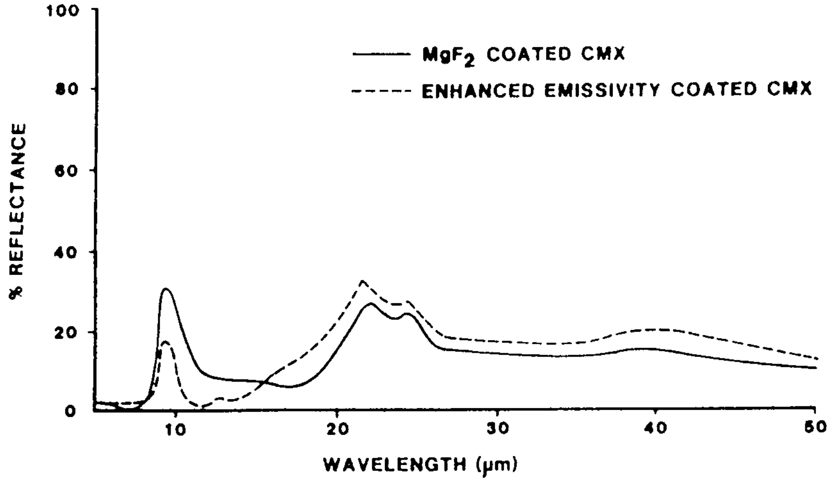

Figure 5: Infrared reflectance of CMX glass showing redistribution of reflectance produced by the enhanced emissivity coating.

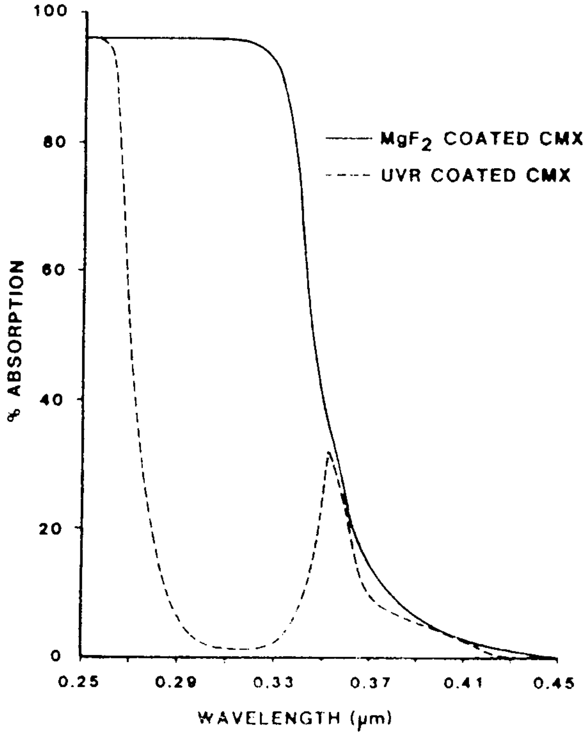

Figure 6: Ultraviolet absorption of MgF_2 and UVR coated CMX. UVR coating decreases UV absorption.

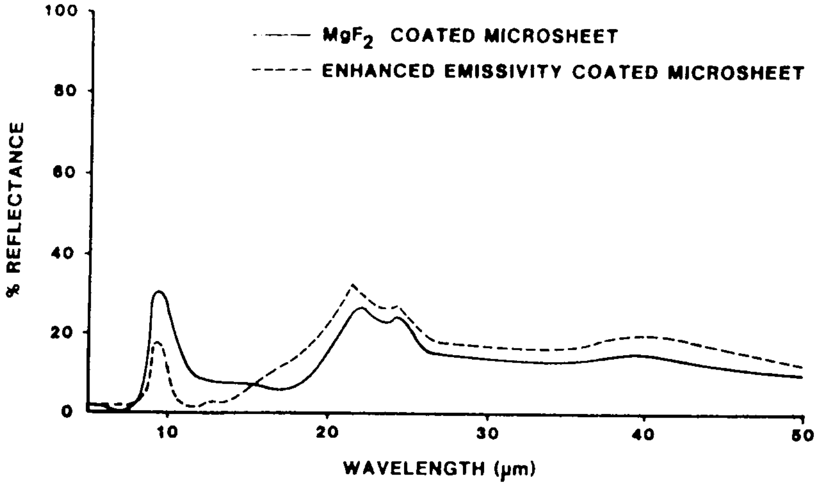

Figure 7: Infrared reflectance of microsheet with and without enhanced emissivity coating.

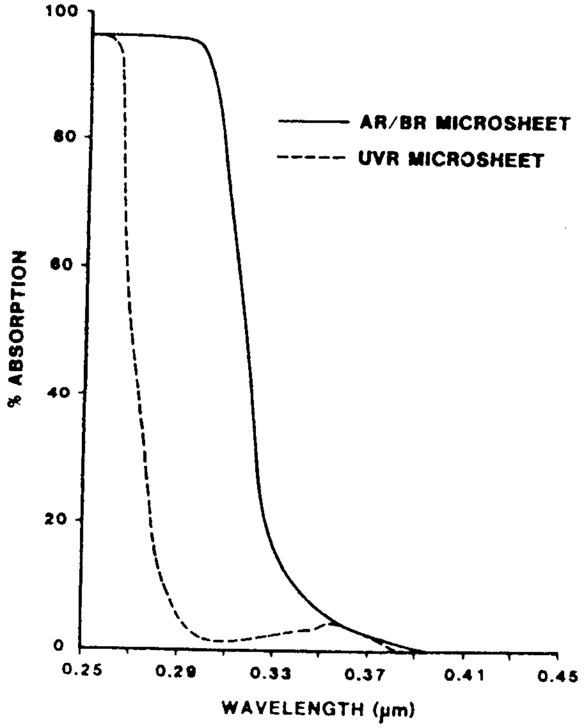

Figure 8: Ultraviolet absorption of conventional and UVR coated microsheet.

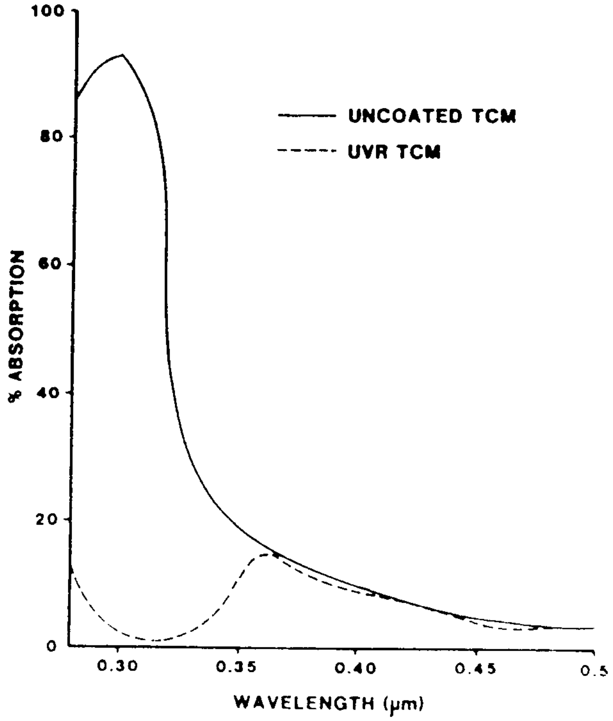

Figure 9: Ultraviolet absorption of thermal control mirror with and without UVR coating.