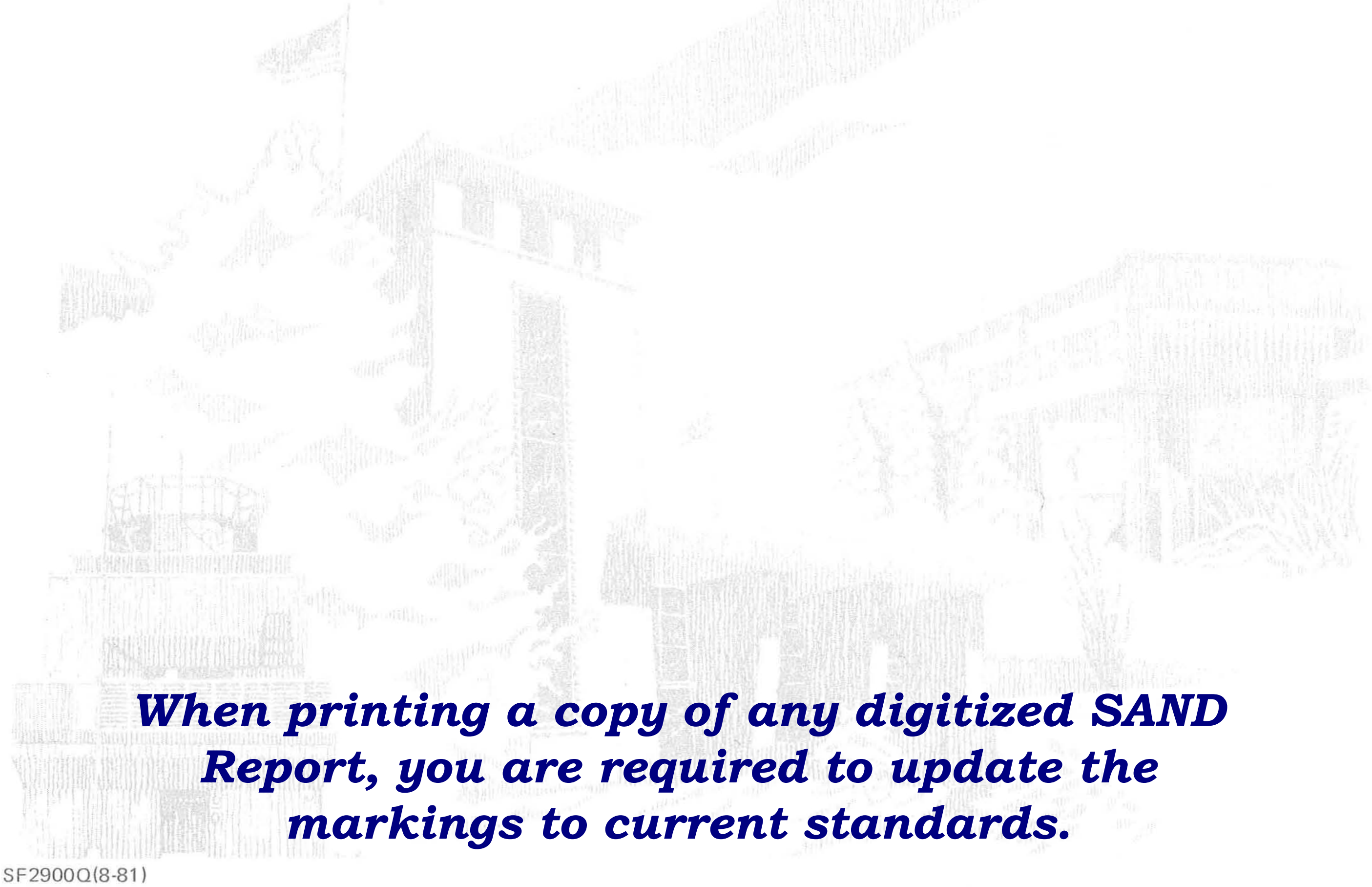
SANDIA REPORT SAND86—0675 • Unlimited Release • UC—62d
Printed June 1986

The Effect of Vitrification Temperature Upon the Solar Average Absorptance Properties of Pyromark® Series 2500 Black Paint

Carolynn Nelson, A. Roderick Mahoney

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550
for the United States Department of Energy
under Contract DE-AC04-76DP00789



SF2900Q(8-81)

Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

NTIS price codes
Printed copy: A02
Microfiche copy: A01

SAND86–0675
Unlimited Release
Printed June 1986

Distribution
Category UC–62d

The Effect of Vitrification Temperature Upon the Solar Average Absorptance Properties of Pyromark® Series 2500 Black Paint

Carolynn Nelson
Ceramics Development Division
A. Roderick Mahoney
Thermophysical Properties Division
Sandia National Laboratories
Albuquerque, NM 87185

Abstract

A significant drop in production efficiency has occurred over time at the Solar One facility at Barstow, California, primarily as a result of the degradation of the Pyromark Series 2500 black paint used as the absorptive coating on the receiver panels. As part of the investigation of the problem, the solar-averaged absorptance properties of the paint were determined as a function of vitrification temperature, since it is known that a significant amount of the panel surface area at Solar One was vitrified at temperatures below those recommended by the paint manufacturer (540°C, 1000°F). Painted samples initially vitrified at 230°C (450°F), 315°C (600°F), 371°C (700°F), and 480°C (900°F) exhibited significantly lower solar-averaged absorptance values (0.02 absorptance units) compared to samples vitrified at 540°C (1000°F). Thus, Solar One began its service life below optimal levels. After 140 h of thermal aging at 370°C (700°F) and 540°C (1000°F), all samples, regardless of their initial vitrification temperatures, attained the same solar-averaged absorptance value (α_s = 0.973). Therefore, both the long-term low-temperature vitrification and the short-term high-temperature vitrification can be used to obtain optimal or near-optimal absorptance of solar flux. Further thermal aging of vitrified samples did not result in paint degradation, clearly indicating that high solar flux is required to produce this phenomenon. The panels at Solar One never achieved optimal absorptance because their exposure to high solar flux negated the effect of long-term low-temperature vitrification during operation. On future central receiver projects, every effort should be made to properly vitrify the Pyromark coating before its exposure to high flux conditions.

Acknowledgment

We thank C. Tuthill, 7471-1, for his help in preparing the samples.

Contents

Figures

Tables

The Effect of Vitrification Temperature Upon the Solar Average Absorptance Properties of Pyromark® Series 2500 Black Paint

Introduction

Pyromark® Series 2500 black paint, manufactured by Tempil*, is a nonselective high-temperature absorptive coating that has been applied to the central receiver panels at Solar One in Barstow, California. The solar absorptance of the receiver has declined in the first few years of operation from an initial value of 0.93 in 1982 to 0.88 in 1984 (Baker, 1986). This decrease in the average solar absorptance of the central receiver appears to be caused by the degradation of the Pyromark paint over time and has led to several studies of the effects of paint application and processing variables on the absorptance of the coating. This report addresses the effect of vitrification temperature on the solar-averaged absorptance of the paint.

The manufacturer of Pyromark 2500 paint recommends that after application to an abraded surface, the paint be processed in the following way: The paint must be air-dried for 18 h before curing and vitrification. It must be cured at 250°C (480°F) for 2 h, then heated to 540°C (1000°F) for 15 min. This procedure was not strictly followed for panels on the Solar One facility, primarily because of their size. The panels at Barstow were sandblasted, painted, air-dried and mounted onto the tower. The field of heliostats were then used to heat the panels to temperatures >200°C (400°F).

Thermal data collected from the receiver during operation show that the temperature of panel surfaces varies as a function of panel position on the tower and location along individual panel length (Baker, 1986). Figure 1 shows the temperature profile of the boiler panels observed on Solar One. We can deduce from these observations that large portions of the receiver panels on Solar One were not vitrified at the 540°C (1000°F) temperature recommended by the manufacturer. The effect, if any, that this discrepancy in the paint processing has upon its performance is not known at this time. The purpose of this study is to determine how, and to what extent, variation in the vitrification temperature affects the absorptance and emittance properties of the coating.

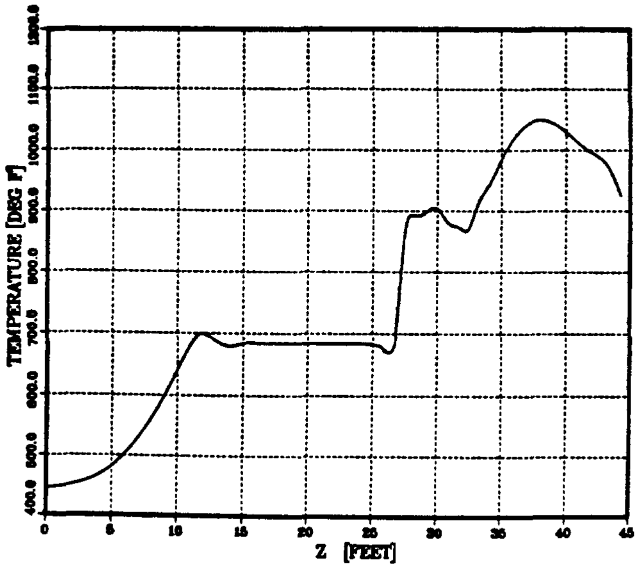


Figure 1. Temperature profile of receiver tube crown during operation at Solar One facility [Baker, 1986]

Experimental Procedures

One-inch squares of nonabraded Incolloy 800 sheet were painted with Pyromark Series 2500 black paint. After the paint had air-dried for 24 h, the samples were cured at 250°C (480°F) for 2 h. Subsequently, two samples were vitrified for 1 h at each of the following temperatures: 230°C (450°F), 315°C (600°F), 370°C (700°F), 480°C (900°F), and 540°C (1000°F). Upon cooling to room temperature, the total hemispherical reflectance properties of the samples

---

*Tempil Division, Big Three Industries, Inc., South Plainfield, NJ were measured from 256 to 2400 nm using a Beckman 5270 spectrophotometer with integrating sphere accessories. The solar-averaged reflectance values, ρ_s, were calculated by averaging the spectral reflectance data over an air mass (AM) 1.5 solar spectral distribution. Solar-averaged absorptance values are obtained by subtracting the reflectance values from one (i.e., $\alpha_s = 1 - \rho_s$). These measurements were referenced to NBS standards to an accuracy of ±0.005 absorptance units, where 100% absorptance is equivalent to 1.00 absorptance unit. Measurement of the normal emittance (100°C and 300°C black body spectrum) properties was done using a Gier Dunkle Model DB-100 portable infrared reflectometer. Measurement uncertainty is within ±0.02 emittance units (100% emittance = 1.00 emittance units). A detailed description of the instrument operation can be found in Pettit (1978). One of each pair of samples that had been vitrified at each of the test temperatures was aged at 370°C (700°F). The second set was aged at 540°C (1000°F). The aging temperatures were chosen to simulate the lower and upper temperatures measured at the panel surfaces on Solar One during operation as shown in Figure 1. After 140, 300, 630, 1200, and 2400 h of aging, additional room-temperature absorptivity measurements were made.

Results

The effect of the vitrification temperature on the paint absorptance is shown in Figure 2. The solar absorptance of the paint is progressively lower in samples that were processed at temperatures <540°C (1000°F) (Table 1). The emittance of the samples does not seem to be affected by the different vitrification temperatures. The decrease in absorptance with decreasing vitrification temperature occurs across the entire wavelength range measured (98% of total solar range). In addition, the shape of the absorptance curve changes as a result of a significant increase in the reflectance of ultraviolet radiation in the low-temperature samples. The solar-averaged absorptance of the samples vitrified at 540°C is 0.02 units higher than the initial average solar absorptance of Solar One (0.97 vs 0.95).

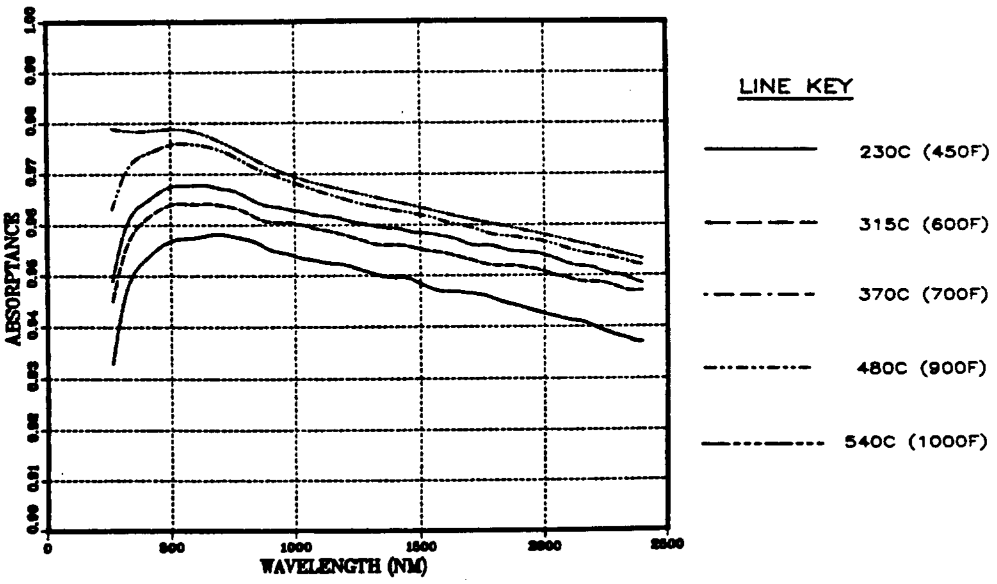


Figure 2. Absorptance spectra for Incolloy 800 samples coated with Pyromark paint after vitrification at various temperatures

Table 1. Solar-averaged absorptance and normal emittance (100°C and 300°C) of Pyromark Series 2500 black paint on Incolloy 800 substrates—aging temperature: 540°C (1000°F)

Vitrification Temperature	Optical Properties	Time at Temperature (h)					
		0	140	305	630	1200	2400
230°C (450°F)	α_s	0.954	0.972	0.973	0.973	0.973	0.974
	$\epsilon_{(100°C)}$	0.83	0.86	0.86	0.86	0.87	0.85
	$\epsilon_{(300°C)}$	0.74	0.81	0.81	0.81	0.81	0.82
315°C (600°F)	α_s	0.961	0.971	0.971	0.971	0.972	0.972
	$\epsilon_{(100°C)}$	0.82	0.88	0.87	0.88	0.89	0.87
	$\epsilon_{(300°C)}$	0.73	0.85	0.84	0.84	0.85	0.84
370°C (700°F)	α_s	0.964	0.972	0.973	0.973	0.973	0.973
	$\epsilon_{(100°C)}$	0.84	0.88	0.87	0.88	0.89	0.87
	$\epsilon_{(300°C)}$	0.77	0.85	0.84	0.84	0.85	0.84
480°C (900°F)	α_s	0.971	0.972	0.973	0.972	0.971	0.973
	$\epsilon_{(100°C)}$	0.85	0.88	0.88	0.88	0.89	0.87
	$\epsilon_{(300°C)}$	0.80	0.85	0.85	0.84	0.85	0.84
540°C (1000°F)	α_s	0.973	0.973	0.973	0.973	0.972	0.973
	$\epsilon_{(100°C)}$	0.87	0.87	0.87	0.87	0.88	0.86
	$\epsilon_{(300°C)}$	0.80	0.83	0.83	0.83	0.84	0.83

Figure 3 illustrates the effects of high-temperature aging of the samples after vitrification. After 140 h at 540°C, all samples had similar absorptance curves and the same α values, within the accuracy of the measurements (Table 1). The emittance values remained unchanged. The absorptance of the low-temperature samples increased dramatically, whereas that of the high-temperature samples remained unchanged. The absorptance values as a functon of wavelength for the samples vitrified at 540°C and 230°C and subsequently thermally aged at 540°C are shown in Figures 4 and 5 for comparison.

Figure 6 shows the effect of low-temperature (370°C) aging of the samples that were vitrified at various temperatures. The absorptance of samples vitrified at low temperatures increased considerably from the levels measured on these same test pieces immediately after vitrification (Table 2). The increase in absorptance, however, is not as much as that observed in the samples aged at 540°C. In addition, considerable ultraviolet reflectance still occurs in these samples. The emittance values of the samples were, again, unaffected by the thermal aging process. Figure 7 shows the results for the sample vitrified at 230°C and thermally aged at 370°C for comparison with the same sample aged at 540°C (Figure 5).

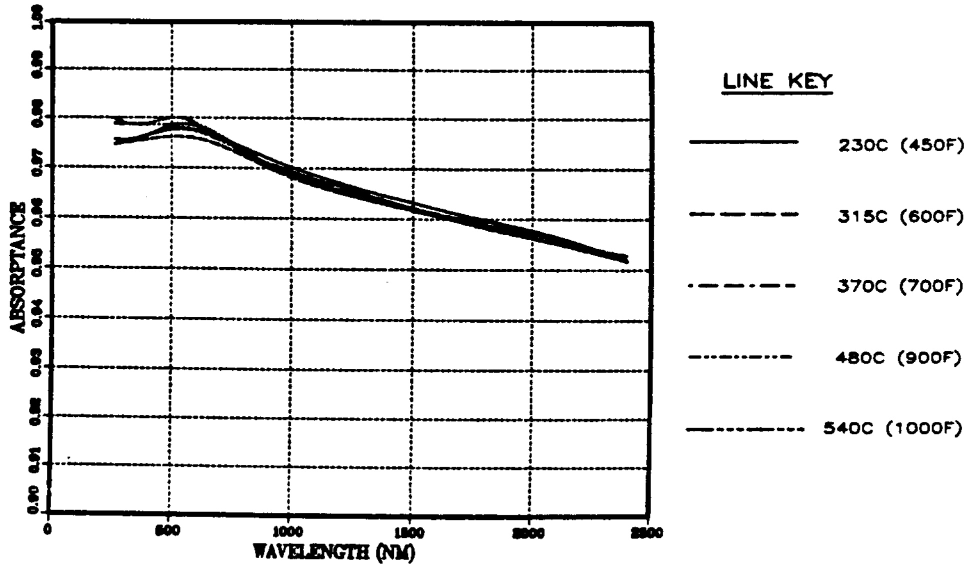


Figure 3. Absorptance spectra for Incolloy 800 samples coated with Pyromark 2500 paint, vitrified at various temperatures and subsequently aged at 540°C (1000°F) for 140 h

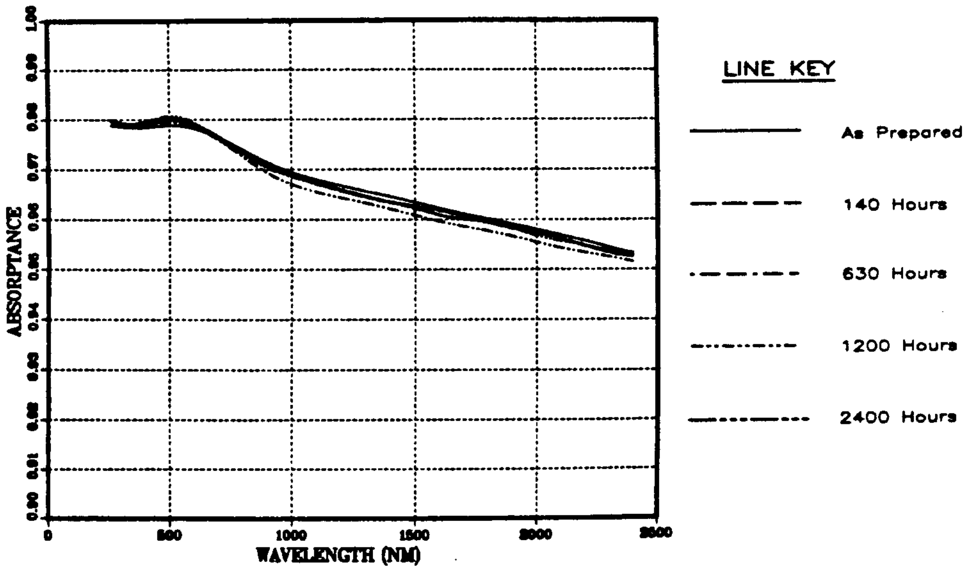


Figure 4. Absorptance spectra for an Incolloy 800 sample coated with Pyromark 2500 paint, vitrified at 540°C (1000°F) and aged at 540°C (1000°F) for up to 2400 h

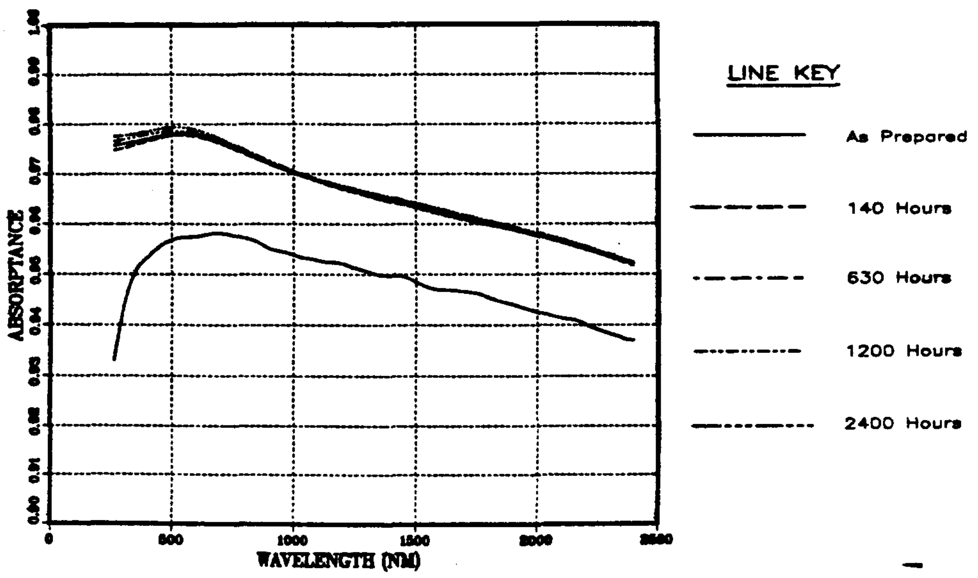


Figure 5. Absorptance spectra for an Incolloy 800 sample coated with Pyromark 2500 paint, vitrified at 230°C (450°F) and aged at 540°C (1000°F)

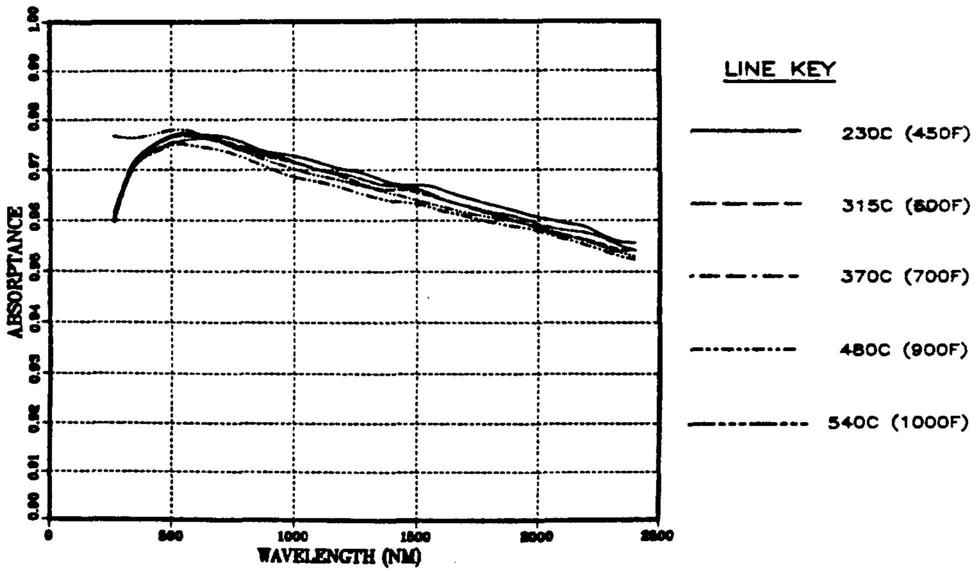


Figure 6. Absorptance spectra for Incolloy 800 samples coated with Pyromark 2500 paint, vitrified at various temperatures and subsequently aged at 370°C (700°F) for 140 h

Table 2. Solar-averaged absorptance and normal emittance (100°C and 300°C) of Pyromark Series 2500 black paint on Incolloy 800 substrates—aging temperature: 370°C (700°F)

Vitrification Temperature	Optical Properties	Time at Temperature (h) 0	140	305	630	1200	2400
230°C (450°F)	α_s	0.956	0.973	0.975	0.976	0.977	0.977
	$\epsilon_{(100°C)}$	0.83	0.86	0.86	0.86	0.87	0.86
	$\epsilon_{(300°C)}$	0.74	0.79	0.79	0.78	0.78	0.78
315°C (600°F)	α_s	0.961	0.972	0.974	0.974	0.975	0.976
	$\epsilon_{(100°C)}$	0.82	0.87	0.87	0.87	0.89	0.87
	$\epsilon_{(300°C)}$	0.73	0.83	0.82	0.81	0.82	0.81
370°C (700°F)	α_s	0.959	0.972	0.974	0.975	0.975	0.976
	$\epsilon_{(100°C)}$	0.84	0.86	0.86	0.86	0.87	0.86
	$\epsilon_{(300°C)}$	0.77	0.79	0.77	0.77	0.77	0.77
480°C (900°F)	α_s	0.968	0.971	0.972	0.972	0.972	0.973
	$\epsilon_{(100°C)}$	0.85	0.86	0.86	0.86	0.88	0.86
	$\epsilon_{(300°C)}$	0.80	0.78	0.78	0.78	0.79	0.78
540°C (1000°F)	α_s	0.972	0.973	0.973	0.972	0.972	0.973
	$\epsilon_{(100°C)}$	0.87	0.88	0.87	0.87	0.88	0.87
	$\epsilon_{(300°C)}$	0.80	0.81	0.80	0.82	0.82	0.80

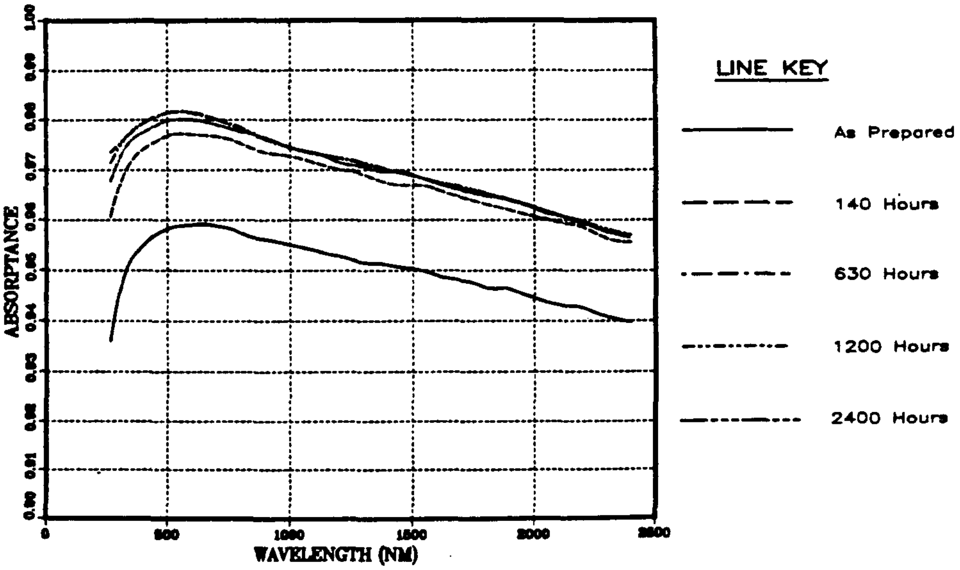


Figure 7. Absorptance spectra for an Incolloy 800 sample coated with Pyromark 2500 paint, vitrified at 230°C (400°F) and aged at 370°C (700°F) for up to 2400 h

In addition to the difference in optical properties, the samples that were vitrified at low temperatures and aged at 370°C also exhibited poor paint adhesion relative to the high-temperature samples. All samples were handled in the same manner and to the same degree. The samples vitrified and aged at low temperatures showed considerably more damage from handling during measurement of the absorptance properties.

Discussion

Figures 2 through 7 clearly show that the temperature of vitrification of Pyromark Series 2500 black paint affects the solar absorptance. If vitrification at 540°C cannot be achieved, then long-term heat treatment at lower temperatures can be used to obtain absorptances almost as high as those produced by vitrifying at the recommended temperatures. The increase in ultraviolet reflectance of surfaces that are vitrified at low temperatures should not have much effect upon the efficiency of energy production since the contribution to the solar flux at the earth's surface of wavelengths <400 nm is only 3.5% (Lind et al., 1980).

Since we know that only limited parts of the panels at Solar One experienced the recommended vitrification temperature, we can deduce that a significant portion of the panel surfaces began service life below optimal absorptivity. This situation would have corrected itself during tower operation over time if paint degradation were not also affecting the absorptance of the coated panel surfaces. Since loss of efficiency at the absorbing surface translates directly to loss of efficiency in energy production at Solar One, the relatively high reflectance of Pyromark Series 2500 black paint not cured at 540°C can have an impact of 2% on the overall efficiency of the facility.

The low-temperature vitrification of the painted panels on Solar One has probably also contributed to problems of poor paint adhesion. The fact that coated surfaces vitrified at temperatures <540°C were easily damaged during handling implies that physical abrasion of similarly vitrified areas of receiver panels would occur readily. Inspection of the panels on Solar One identified several small isolated areas where the paint could be easily rubbed off. Poor paint adhesion has been observed previously on prototype receiver panels at the CRTF at Albuquerque, NM (Pettit, 1986). The sources of this problem are not completely understood.

In future applications of Pyromark 2500, every attempt should be made at attain the recommended vitrification temperature of 540°C on as much of the painted surfaces as possible so that solar reflectance is minimized and paint adhesion is enhanced. This might be achieved for future receivers by using large annealing furnaces such as those common in the glass industry, where heat treatment of large pieces of plate glass is necessary. If the recommended temperature cannot be attained, then long-term heat treatment at lower temperatures can be used to lower the surface reflectance considerably.

Until the mechanisms of paint degradation are identified, Pyromark Series 2500 black paint on Incolloy 800 substrates will continue to decrease in absorptance as a function of time. However, the cost effectiveness of Solar One can be increased by optimizing the absorptance of the panels with high-temperature vitrification of freshly applied paint. In this way, the facility will start out at a high efficiency and will operate at higher levels for a longer period of time. Based upon the observations of Baker (1986) shown in Figure 8, and assuming that the rate of degradation remains constant, an initial absorptance 0.02 units higher than that observed at Solar One in 1982 extends the operation time required to reach the current level of absorptance by ~10 months.

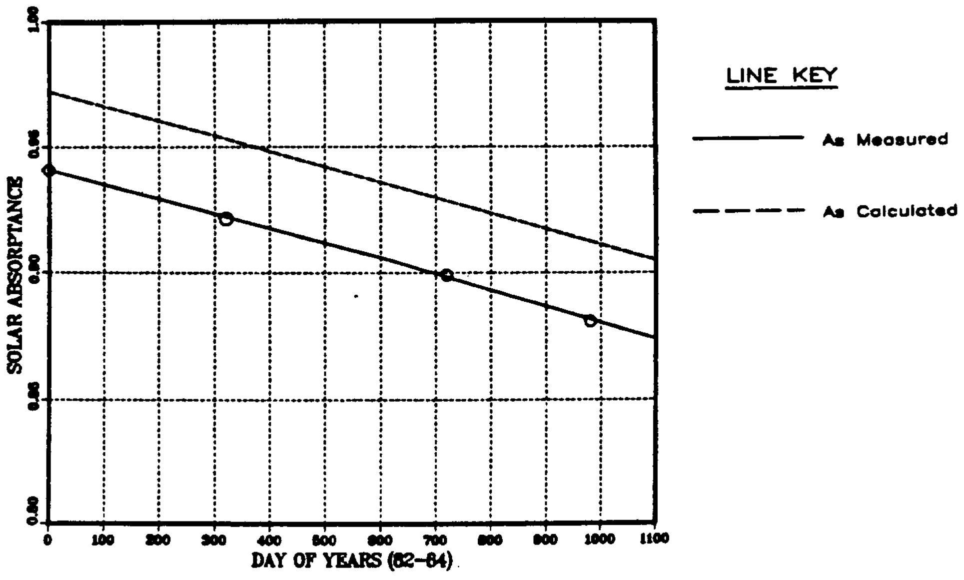


Figure 8. Weighted average solar absorptance for Solar One [Baker, 1986]. (The dashed line represents our estimate of the decline in α_s of the receiver, coated with properly vitrified Pyromark paint.)

Conclusions

The solar absorptance of Pyromark Series 2500 black paint is significantly affected by the vitrification temperature. Samples vitrified at the manufacturer's recommended temperature of 540°C exhibit higher solar-averaged absorptance values than those prepared at lower temperatures (0.97 vs 0.95). The absorptance properties of low-temperature vitrified painted surfaces can be improved by additional heat treatment at temperatures >370°C (700°F). Long-term heat treatment at 540°C (1000°F) will eventually increase the absorptance of the surface to that of a surface that was vitrified at 540°C. Low-temperature heat treatment will increase the absorptance of the surface, but not to the same degree. Thermal aging of samples prepared according to the manufacturer's recommendations does not cause paint degradation with time. Poor paint adhesion was also observed on samples vitrified <540°C and did not improve with additional low-temperature aging.

The initial solar absorptance and, thus, the efficiency of future central receiver panels coated with Pyromark Series 2500 black paint can be improved by vitrifying the painted surfaces at the manufacturer's recommended temperature. The effectiveness of repainting receivers already in operation that have panels coated with Pyromark 2500 paint may be increased by doing the same. However, since the effects of underlying old paint upon the adhesion, curing, and vitrification of layers of fresh Pyromark paint are not known, only the application of Pyromark Series 2500 black paint to clean Incolloy 800 substrates can be recommended at this time.

References

Baker, A.F. *10-MWe Solar Thermal Central Receiver: Pilot Plant Receiver Solar Absorptance Measurements and Results,* Monograph 3, SAND86-8210. Albuquerque, NM: Sandia National Laboratories, June 1986.

Lind, M. A., R. B. Pettit, and K. D. Masterson. "The Sensitivity of Solar Transmittance, Reflectance, and Absorptance to Selected Averaging Procedures and Solar Irradiance Distributions." *Journal of Solar Energy Engineering,* 102:34-40 (1980).

Pettit, R. B. Personal communication (1986).

Pettit, R. B. "Evaluation of Portable Optical Property Measurement Equipment for Solar Selective Surfaces." *Eng for Power* 100:409 (1978).

DISTRIBUTION:

1824	A. R. Mahoney (10)
1824	J. N. Sweet
1840	R. J. Eagan
1845	F. P. Gerstle, Jr.
1845	C. Nelson (10)
8471	A. F. Baker
8471	A. C. Skinrood
8471	M. C. Stoddard
8024	P. W. Dean
3141	S. A. Landenberger (5)
3151	W. L. Garner (3)
3154-1	C. H. Dalin (28) For DOE/OSTI (Unlimited Release)