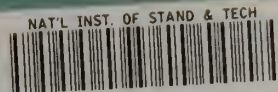


Reference

NBS
Publi-
cations

NAT'L INST. OF STAND & TECH

A11106 408010

NBSIR 82-2583

Outdoor Exposure Tests of Solar Absorptive Coatings

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
National Engineering Laboratory
Center for Building Technology
Building Materials Division
Washington, DC 20234

October 1982

Prepared for
U.S. Department of Energy
Office of Solar Heat Technologies
Active Solar Heating and Cooling Division
Washington, DC 20585

QC
100
.U56
82-2583
1982

NBSIR 82-2583

OCT 28 1982

not acc-ny
Q1100

US6

82-2583

1982

OUTDOOR EXPOSURE TESTS OF SOLAR ABSORPTIVE COATINGS

Larry W. Masters
James F. Seiler
Willard E. Roberts

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
National Engineering Laboratory
Center for Building Technology
Building Materials Division
Washington, DC 20234

October 1982

Prepared for
U.S. Department of Energy
Office of Solar Heat Technologies
Active Solar Heating and Cooling Division
Washington, DC 20585



U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, *Secretary*
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

ABSTRACT

This report is a follow up to an earlier report (NBSIR 81-2232, January 1981) in which data on the performance of selected absorptive coatings in both accelerated laboratory exposures and outdoor exposures at three sites were presented. The research presented in this report focuses upon the results obtained by continuing the outdoor exposures of absorptive coatings using ASTM E781-81, Standard Practice for Evaluating Absorptive Solar Receiver Materials When Exposed to Conditions Simulating Stagnation in Solar Collectors with Cover Plates.

Comparison of the results of the outdoor exposures with those obtained in accelerated laboratory exposures indicated that 1) the accelerated exposures, as described in ASTM E744-80, Standard Practice for Evaluating Solar Absorptive Materials for Thermal Applications, provide more severe exposure conditions than outdoor exposures, and 2) the degradation processes induced by outdoor exposure are adequately addressed by the accelerated laboratory exposures.

Key Words: absorptive coatings; accelerated laboratory exposures; degradation; outdoor exposures; simulated stagnation exposure; solar energy.

ACKNOWLEDGMENT

The authors gratefully acknowledge 1) the many suggestions provided by members of ASTM E44.04 on Materials Performance in planning and carrying out this study, 2) the interest demonstrated by the Office of Solar Heat Technologies of the Department of Energy in supporting the research, and 3) the cooperation of manufacturers who provided absorptive coating test specimens for inclusion in the study and commercial exposure test sites who performed outdoor exposures.

TABLE OF CONTENTS

	<u>Page</u>
ABSTRACT	iii
ACKNOWLEDGMENT	iv
LIST OF TABLES	vi
LIST OF FIGURES	vi
1. INTRODUCTION	1
1.1 BACKGROUND	1
1.2 OBJECTIVE	1
1.3 SCOPE	1
2. MATERIALS AND TEST PROCEDURES	3
2.1 MATERIALS	3
2.2 TEST PROCEDURES	3
2.2.1 Property Measurement Tests	3
2.2.2 Outdoor Exposure Tests	3
3. RESULTS AND DISCUSSION	5
3.1 EXPOSURES AT GAITHERSBURG, MARYLAND	5
3.2 EXPOSURES AT PHOENIX, ARIZONA	6
3.3 EXPOSURES AT MIAMI, FLORIDA	6
3.4 COMPARISON OF OUTDOOR EXPOSURE RESULTS WITH ACCELERATED LABORATORY RESULTS	7
3.4.1 Nickel Coated Foil	7
3.4.2 Anodized 6061 Aluminum	7
3.4.3 Anodized 1100 Aluminum	7
3.4.4 Copper Oxide	7
3.4.5 Black Chrome	8
3.4.6 Polyvinylidene Fluoride	8
3.4.7 Urethane	8
3.4.8 Alkyd	8
3.4.9 Epoxide	9
3.4.10 Silicone	9
3.4.11 Modified Polyester	9
3.4.12 Porcelain	9
4. CONCLUSIONS	10
5. BIBLIOGRAPHY	11

LIST OF TABLES

	<u>Page</u>
1. Absorptive Coatings and Substrates Used in the Study	12
2. Results of Outdoor Exposure at Gaithersburg, Maryland	13
3. Results of Outdoor Exposure at Phoenix, Arizona	14
4. Results of Outdoor Exposure at Miami, Florida	15

LIST OF FIGURES

1. Test Box Used for Outdoor Exposures	16
--	----

1. INTRODUCTION

1.1 BACKGROUND

The purposes of absorptive coatings used in solar energy collectors for heating and cooling applications are to absorb the sun's energy and convert it to thermal energy. The optical properties of absorptive coatings, i.e., solar absorptance (α) and infrared emittance (ϵ), are important attributes and are useful in assessing the performance and durability of coatings.

A 1977 report by Skoda and Masters [1]^{1/} identified a number of materials related solar collector problems in operational systems. The report pointed out the need for test methods to assess the effect of exposure conditions on the performance of solar collector materials, such as absorptive coatings. Subsequently, research was initiated to aid in developing the technical bases for new test methods for absorptive coatings. Results of accelerated laboratory exposures and outdoor exposures under simulated stagnation conditions (up to 12 months) were reported in 1981 [2]. These results were used in the development of ASTM E744-80, Standard Practice for Evaluating Solar Absorptive Materials for Thermal Applications [3]. The outdoor exposure tests initiated in the above study [2] were continued to obtain additional data on the ability of the coatings to withstand the simulated stagnation conditions and on the comparison of simulated stagnation exposure results with those obtained from accelerated laboratory exposures as included in ASTM E744-80 [3]. The additional data, for three outdoor exposure sites, are presented in this report. The outdoor exposure data previously reported [2] are included along with the new data for the convenience of the reader.

1.2 OBJECTIVE

The objective of the studies presented in this report was to obtain data on the performance of both selective and non-selective absorptive coatings when exposed outdoors to simulated stagnation conditions at three sites. Data on exposed coatings are needed to help assess the newly developed standard, ASTM E781-81, Standard Practice for Evaluating Absorptive Solar Receiver Materials when Exposed to Conditions Simulating Stagnation in Solar Collectors with Cover Plates [4], which is one testing option provided in ASTM E744-80 [3]. Data are also needed to aid in comparing results obtained by the two testing methods in E744-80: 1) accelerated laboratory exposure; and 2) simulated stagnation exposure (E781-81).

1.3 SCOPE

Test specimens of four selective and eight non-selective absorptive coatings on various substrates were exposed outdoors at three sites in accordance with ASTM E781-81 [4]. The solar absorptance and infrared emittance were measured before exposure and at approximately four month exposure intervals. The three exposure sites were: 1) Gaithersburg, Maryland, 2) Phoenix, Arizona, and 3) Miami,

^{1/} Numbers in brackets refer to references in the Bibliography.

Florida. The exposure times were cumulative; that is, the specimens were retrieved at each measurement interval and reinstalled in the outdoor exposure boxes after measurement of optical properties and visual inspection.

The test data contained in this report are not recommended for design purposes. The properties of absorptive coatings are likely to vary from manufacturer to manufacturer and from one production run to another. Data to aid design of collectors must, therefore, be obtained for the specific material to be used. The coatings used in this study were selected to cover a range of generic coatings so that test methods developed based upon the data would be broadly applicable. But the data on specific generic coatings do not necessarily represent the performance of all coatings within each generic grouping. In addition, the infrared emittance data reported are total normal emittance rather than total hemispherical emittance.

2. MATERIALS AND TEST PROCEDURES

2.1 MATERIALS

Absorber materials included in the test program were nickel coated foil, anodized aluminum, copper oxide, black chrome, polyvinylidene fluoride (two), urethane, alkyd, silicone, modified polyester, epoxide, and porcelain enamel. These were selected to provide a cross-section of generic types of absorber materials which have been or could be used in solar collectors. Substrates included steel, copper, and aluminum although not all absorbers were tested on all substrates. Table 1 includes a list of the materials and the substrates on which they were applied.

2.2 TEST PROCEDURES

2.2.1 Property Measurement Tests

Absorptance was calculated from reflectance as measured using ASTM E424-71, Method A [5], which utilizes an integrating sphere spectrophotometer, and total normal infrared emittance was measured using ASTM E408-71 [6]. Absorptance is reported as an integrated value from 0.35 to 2.1 μm for an Air Mass 2 solar spectrum. In addition to optical measurements, the specimens were visually inspected before and after aging.

2.2.2 Outdoor Exposure Tests

Triplicate specimens of each coating/substrate combination were exposed outdoors in accordance with ASTM E781-81 [4]. The exposure boxes, which simulate a solar collector, are shown in figure 1. The boxes included a single cover plate conforming to Type 1 (tempered low iron glass) of E781-81, fiber glass insulation, and a coated metallic specimen mounting plate. For exposure of selective coatings, the boxes contained a black chrome coated mounting plate while the boxes for exposure of non-selective coatings contained a flat black coated mounting plate. The Test Plan Option A of E781-81, in which specimens are returned to the boxes for continued exposure after each nondestructive measurement of properties (each time increment), was used in the study. The orientation (tilt angle) of the exposure boxes was adjusted four times each year to provide increased solar flux as follows:

Exposure Schedule at Each Tilt Angle

Tilt Angle	Gaithersburg ^{1/}	Phoenix ^{2/}	Miami ^{3/}
5°	May-August	April-August	April-August
local latitude	September	September	September
45°	October-March	October-February	October-February
local latitude	April	March	March

1/ 39° latitude

2/ 33° latitude

3/ 26° latitude

Exposures were performed at three sites having distinctly different climates: Gaithersburg, Maryland; Phoenix, Arizona; and Miami, Florida. The Maryland exposures were started in June 1978. Specimens were first retrieved for evaluation in October 1978. Subsequent exposure periods were: 1) from November 1978 to March 1979, 2) from April 1979 to August 1979, 3) from April 1980 to August 1980, 4) from November 1980 to March 1981, and 5) from May 1981 to September 1981.

The Arizona exposures were initiated in November 1978. The exposure periods were: 1) from November 1978 to March 1979, 2) from April 1979 to August 1979, 3) from May 1980 to September 1980, 4) from November 1980 to March 1981, and 5) from May 1981 to September 1981.

The Florida exposure periods were: 1) from June 1978 to October 1978, 2) from November 1978 to May 1979 (including a two month non-exposure period due to storm damage at the test site), 3) from July 1979 to November 1979, 4) from May 1980 to September 1980), 5) from December 1980 to April 1981, and 6) from May 1981 to September 1981.

The intent, at the initiation of the study, was to have the same exposure increments at all three sites throughout the test program. Weather and instrumentation problems caused some deviation from this intent as indicated in the actual dates of specimen exposure.

The mounting plate temperature of the boxes exposed at the Maryland site was monitored periodically near solar noon. A thermocouple embedded in the back side of the mounting plate was used for temperature measurements. Cumulative readings of total direct irradiation were recorded at each site as a possible basis for site comparison.

3. RESULTS AND DISCUSSION

Tables 2, 3, and 4 contain absorptance and infrared emittance data obtained for the three exposure sites. The initial absorptance and infrared emittance values (at time zero) are an average of ten specimens of each sample. With the exception of the emittance values for absorber C5 (copper oxide), the optical properties of each sample were reproducible within 0.01 unit from specimen to specimen. The values reported in tables 2, 3, and 4 for time increments other than 0 (zero) are the average of triplicate specimens.

During the study, a set of test specimens was stored as controls in the laboratory at $20 \pm 3^\circ\text{C}$ and 50 ± 5 percent r.h. Measurement of the absorptance and emittance after completion of all exposure tests demonstrated that no changes in the optical properties were induced in the control specimens.

The reader is referred to the previous report on this study [2] for photographs of the coatings before and after many of the exposure tests; these photographs illustrate the primary visual changes noted in the following discussion.

3.1 EXPOSURES AT GAITHERSBURG, MARYLAND

Table 2 contains the absorptance and infrared emittance data obtained for specimens exposed for various time increments at Gaithersburg, Md. The estimated total direct solar irradiation received during the 24 months of actual exposure was $10.88 \times 10^9 \text{ J/m}^2$.^{1/} The maximum mounting plate temperature observed with the selective coatings exposure box was 182°C ; that for the nonselective boxes was 148°C .

The data in table 2 show that little change was observed in the absorptance and emittance of most absorber materials during the exposures. The indicated change in absorptance and emittance of copper oxide must be interpreted with caution because of the large variability noted in emittance for unexposed (time zero) specimens. Black chrome on copper (D4) was observed to change in absorptance from 0.96 to 0.91 over the exposure period, although the emittance remained relatively unchanged. The emittance of the modified polyester specimens (M1, M4 and M8) was observed to increase by 0.05 to 0.10 units depending upon the substrate.

Visual inspection of the specimens at each exposure increment led to the following observations:

1. The adhesive used to bond the nickel coated foil to the aluminum substrate delaminated in several areas of the test specimens early in the course of exposures. The delaminations appeared to increase in number and area with increasing time of exposure. But the foil did not completely delaminate from the substrate during the exposure test. Delamination of the foil was also reported during laboratory oven aging tests [2].

^{1/} This value of solar irradiation is estimated because of instrument failures during approximately 10 percent of the exposure days.

2. The G9 (polyvinylidene fluoride on hot dipped galvanized steel) delaminated slightly during the 24 month exposure time. Previous laboratory exposures at 92°C and 97 percent r.h. were found to cause extensive delamination of this coating [2].
3. The modified polyester (M) coatings were gradually removed from the substrates with increasing time of exposure. The nature of the "removal" is more aptly described as vaporization as opposed to delamination. For the M8 specimens (modified polyester on aluminum), the loss of coating was nearly complete at the end of the exposure; for the M1 (steel) and M4 (copper) specimens, the loss of coating was less extensive than for the M8 specimens.

3.2 EXPOSURES AT PHOENIX, ARIZONA

Table 3 contains the results of the outdoor exposures at Phoenix, Arizona. The total direct solar irradiation received during the 20 months of actual exposure was 12.66×10^9 J/m². With the exception of C5 (copper oxide), the absorptance of specimens did not change more than 0.02 units during the 20 months of exposure. As noted in section 3.1, the copper oxide changes must be interpreted with caution. The emittance of the modified polyester specimens increased during the exposure, but not to the extent observed for the Maryland exposures. The emittance of other samples did not change by more than 0.02 units.

Visual observations were as follows:

1. The adhesive used to bond the nickel coated foil to the aluminum substrate delaminated in the same manner as noted in section 3.1.
2. The G9 (polyvinylidene fluoride on hot dipped galvanized steel) delaminated during the fourth exposure interval. When the specimens were retrieved after 16 months exposure, the coating on all three specimens was completely delaminated from the substrate.

3.3 EXPOSURES AT MIAMI, FLORIDA

Table 4 contains the results of the outdoor exposures at Miami, Florida. The total direct solar irradiation received during the 24 months of actual exposure was 13.62×10^9 J/m².

The data in table 4 are similar to the data in table 2 (Maryland) regarding 1) a loss of absorptance of black chrome on copper (D4), and 2) an increase in the infrared emittance of the modified polyester specimens (M1, M4 and M8). For most absorbers, the exposure resulted in little or no change in the optical properties.

Visual inspection of the test specimens provided the following observations:

1. The adhesive used to bond the nickel coated foil to the aluminum substrate delaminated as noted for the exposures in sections 3.1 and 3.2.

2. The G9 (polyvinylidene fluoride on hot dipped galvanized steel) delaminated slightly during the 24 month exposure. The extent of the delamination was comparable to that observed at the Gaithersburg, Maryland site.
3. The "removal" of modified polyester (M) reported for the Gaithersburg, Maryland exposures (section 3.1) was also observed at the Miami site. The extent of loss of coating was nearly complete for the M8 specimens (aluminum substrate) and less extensive for the M1 (steel substrate) and M4 (copper substrate) specimens.

3.4 COMPARISON OF OUTDOOR EXPOSURE RESULTS WITH ACCELERATED LABORATORY RESULTS

As noted in the Introduction to this report, results of accelerated laboratory exposures were previously reported [2] for the same coatings evaluated in this study. Since ASTM E744-80 [3] provides the option of testing using either accelerated laboratory exposure (Method A) or simulated stagnation exposure (Method B), it is important to compare the results obtained by outdoor exposure (simulated stagnation) to those obtained by accelerated laboratory exposure. The following discussion will highlight some of the major similarities and differences in the results from the two types of exposure.

3.4.1 Nickel Coated Foil

The optical properties of the nickel coated foil remained virtually unchanged during both the accelerated laboratory exposures and the outdoor exposures. The adhesive used to bond the foil to the substrate partially delaminated in outdoor exposures at all three sites and in the accelerated laboratory exposures involving oven aging.

3.4.2 Anodized 6061 Aluminum

The optical properties of B6 anodized aluminum specimens exhibited little if any change during the outdoor exposures and in all the accelerated laboratory exposures except the exposure to moisture using a condensation cycle. In the latter laboratory exposure, the infrared emittance increased from 0.81 to 0.90 over a period of 12 weeks exposure time.

3.4.3 Anodized 1100 Aluminum

The optical properties of B7 anodized aluminum specimens exhibited little if any change during the outdoor exposures and in all the accelerated laboratory exposures except moisture exposure. Exposure at 92°C and 97 percent r.h. led to an increase of absorptance (from 0.90 to 0.93) while exposure using the condensation cycle led to an increase in infrared emittance (from 0.82 to 0.91).

3.4.4 Copper Oxide

The outdoor exposures led to loss in absorptance of copper oxide specimens at all three exposure sites; the absorptance after the final exposure increment had changed from 0.95 to 0.90 (Maryland), to 0.87 (Arizona) and to 0.86 (Florida).

Loss of absorptance was also observed in the laboratory tests involving 1) oven aging, and 2) thermal cycling. The infrared emittance changes are of questionable significance because of the emittance variability noted previously for the copper oxide specimens.

3.4.5 Black Chrome

Black chrome on steel specimens (D2) exhibited little, if any, change in optical properties during the outdoor exposures and during the accelerated laboratory exposures.

Black chrome on copper specimens (D4) changed somewhat in absorptance during the outdoor exposures; the Maryland exposures led to a change from 0.96 to 0.91, Arizona from 0.96 to 0.94 and Florida from 0.96 to 0.91. The absorptance of D4 specimens decreased by 0.03 units or more in the following laboratory exposures: oven aging, thermal cycling and moisture condensation cycle.

3.4.6 Polyvinylidene Fluoride

As mentioned in sections 3.1, 3.2 and 3.3, the G9 specimens (polyvinylidene fluoride on hot dipped galvanized steel) exhibited coating delamination at all three exposure sites, although the delamination was more extensive at the Arizona site than at the other sites. The laboratory exposures consisting of 1) oven aging at 250°C and 2) aging at 92°C and 97 percent r.h. caused delaminations similar to those observed in the outdoor exposures.

The specimens of polyvinylidene fluoride on steel (H1) exhibited slight changes in emittance during the outdoor exposures but little, if any, change in absorptance. Oven aging at 200 and 250°C led to changes in emittance; at 250°C, the emittance decreased from 0.85 to 0.54 after 12 weeks exposure. Thermal cycling in the laboratory also led to a slight decrease in emittance.

The H8 (polyvinylidene fluoride on aluminum) exhibited little, if any, change in optical properties during outdoor exposure or during accelerated laboratory exposure, except for 1) a decrease in emittance (from 0.88 to 0.52) in oven aging exposures at 250°C, and 2) a decrease in emittance (from 0.88 to 0.85) in oven aging at 200°C and thermal cycling.

3.4.7 Urethane

Little or no changes in optical properties were obtained in the urethane specimens during outdoor exposure and in laboratory oven aging at 150 and 200°C. Oven aging at 250°C led to a removal of the urethane coating from both copper and aluminum substrates but it is unlikely that urethane coatings would be exposed to temperatures over 200°C in stagnating collectors. Thermal cycling led to removal of the urethane on steel.

3.4.8 Alkyd

The outdoor exposures induced only slight changes in optical properties for the alkyd specimens. Laboratory oven aging at 150 and 200°C also induced only

slight changes in optical properties. In oven aging exposures at 250°C and in thermal cycling, the alkyd coating was removed from some substrates during exposure. The 250°C oven aging exposure is probably unrealistic since it is unlikely that alkyd absorptive coatings would be exposed to temperatures greater than 200°C in stagnating collectors. Laboratory moisture exposure at 92°C and 97 percent r.h. led to a loss of absorptance (from 0.97 to 0.90) for alkyd on steel (J1) specimens. As previously mentioned [2], laboratory moisture tests led to corrosion of the surfaces of alkyd on aluminum specimens which did not significantly affect the optical properties. Corrosion of specimens was not observed following outdoor exposure but outdoor exposure in a well sealed box may not be indicative of corrosion in collectors with poorly sealed seams.

3.4.9 Epoxide

Only slight changes in optical properties of the epoxide specimens were obtained during the outdoor exposures. Laboratory oven aging at 200 and 250°C led to delamination of the coating from most substrates. Thermal cycling also led to delamination of the coating on steel and copper. Moisture exposures at 92°C and 97 percent r.h. led to a loss of absorptance (from 0.97 to 0.90) for both steel and aluminum substrate specimens. Scanning Election Microscopy (SEM) of laboratory exposed specimens showed degradation on the epoxide matrix during moisture exposure [2]. The same type of degradation was observed in outdoor exposure specimens from all three sites, but the extent of degradation was less after outdoor exposure than after 21 weeks laboratory exposure at 92°C and 97 percent r.h.

3.4.10 Silicone

Specimens of silicone coating exhibited little or no change in optical properties during the outdoor exposures. In the laboratory exposures, oven aging at 250°C and thermal cycling led to removal of the coating on some substrates. Oven aging at 150 and 200°C led to little or no change in optical properties.

3.4.11 Modified Polyester

As noted in sections 3.1 and 3.3 of this report, the outdoor exposures in Maryland and Florida led to "removal" of the modified polyester coating from the substrates. The data in tables 2 and 4, however, indicate that the absorptance was not significantly changed although the emittance increased. Oven aging at 250°C led to removal of the coating as did thermal cycling. During oven aging at 200°C, changes in absorptance of up to 0.06 units and changes in emittance of up to 0.04 units were noted.

3.4.12 Porcelain

The optical properties of porcelain specimens exhibited little or no change in either the outdoor exposures or the accelerated laboratory exposures.

4. CONCLUSIONS

1. The outdoor exposure data, developed using ASTM Standard Practice E781-81, show that simulated stagnation conditions degrade some materials typically used as absorptive coatings.
2. Degradation of absorptive coatings, such as change of optical properties or appearance that was observed during outdoor exposures, was also observed in one or more of the accelerated laboratory exposures included in ASTM E744-80. This indicates that the degradation processes induced by stagnation exposure are adequately addressed by the accelerated laboratory exposures.
3. Changes in properties were observed with accelerated laboratory exposures but not with outdoor exposures for the following coatings: Anodized aluminum (moisture exposure), Urethane (oven aging and thermal cycling), Alkyd (oven aging and moisture exposure), Epoxide (oven aging, thermal cycling and moisture exposure) and Silicone (oven aging and thermal cycling). This indicates that the accelerated laboratory exposures provide more severe exposure conditions than outdoor exposure. Frequently, 250°C oven aging of non-selective coatings induced changes that were not observed in oven aging at lower temperatures or in outdoor exposure tests. Since it is highly unlikely that non-selective absorption coatings would even be exposed to stagnation temperatures greater than 200°C, exposures at 250°C are probably far too severe to simulate actual in-service conditions.
4. Degradation of absorptive coatings, which can be observed visually or with microscopy, does not always result in a change in optical properties. This points out the need to visually inspect exposed coatings and to note observable changes.
5. The current exposure requirements in ASTM E781-81 stipulate a minimum solar irradiation of $6.2 \times 10^9 \text{ J/m}^2$, which is based upon the solar irradiation received in a 12 month period with an average daily value of $1.7 \times 10^7 \text{ J/m}^2$ (1500 Btu/ft²/day). The data obtained in this study show that, where degradation was observed, it occurred within the time required to achieve that total solar irradiation. Therefore, the current exposure requirements of ASTM E781-81 appear to be adequate.

5. BIBLIOGRAPHY

1. Skoda, L.F. and Masters, L.W., "Solar Energy Systems - Survey of Materials Performance," NBSIR 77-1314, National Bureau of Standards, Washington, D.C., 20234, October 1977.
2. Masters, Larry W., Seiler, James F., Embree, Edward J., and Roberts, Willard E., "Solar Energy Systems - Standards for Absorber Materials," NBSIR 81-2232, National Bureau of Standards, Washington, D.C., 20234, January 1981.
3. ASTM E744-80, Standard Practice for Evaluating Solar Absorptive Materials for Thermal Applications, Annual Book of Standards, Part 41, American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA, 19103.
4. ASTM E781-81, Standard Practice for Evaluating Absorptive Solar Receiver Materials When Exposed to Conditions Simulating Stagnation in Solar Collectors with Cover Plates, Annual Book of Standards, Part 41, American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA, 19103.
5. ASTM E424-71, Test for Solar Energy Transmittance and Reflectance (Terrestrial) of Sheet Materials, Annual Book of Standards, Part 41, American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA, 19103.
6. ASTM E408-71, Test for Total Normal Emittance of Surface Using Inspection Meter Techniques, Annual Book of Standards, Part 41, American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA, 19103.

Table 1. Absorptive Coatings and Substrates Used in the Study

<u>Code Number</u> ^{1/}	<u>Absorptive Coating</u>	<u>Substrate</u>
A8	Nickel coated foil	Aluminum, alodine
B6	Anodized aluminum	Aluminum, 6061, anodized
B7	Anodized aluminum	Aluminum, 1100, anodized
C5	Copper oxide	Copper
D2	Black chrome	Steel, cold-rolled ^{2/}
D4	Black chrome	Copper, DHP 123 ^{3/}
G9	Polyvinylidene fluoride	20 gage, G90, hot dipped galvanized steel
H1	Polyvinylidene fluoride	Steel, bonderized
H8	Polyvinylidene fluoride	Aluminum, alodine
I1	Urethane	Steel, bonderized
I4	Urethane	Copper, DHP 122
I8	Urethane	Aluminum, alodine
J1	Alkyd	Steel, bonderized
J4	Alkyd	Copper, DHP 122
J8	Alkyd	Aluminum, alodine
K1	Epoxide	Steel, bonderized
K4	Epoxide	Copper, DHP 122
K8	Epoxide	Aluminum, alodine
L1	Silicone	Steel, bonderized
L4	Silicone	Copper, DHP 122
L8	Silicone	Aluminum, alodine
M1	Modified polyester	Steel, bonderized
M4	Modified polyester	Copper, DHP 122
M8	Modified polyester	Aluminum, alodine
N2	Porcelain enamel	Steel, cold-rolled
N8	Porcelain enamel	Aluminum, alodine

^{1/} The letter refers to the absorptive coating and the number to the substrate.

^{2/} Includes 0.5 mil Nickel flash.

^{3/} Includes 0.1 - 0.2 mil Nickel flash.

Table 2. Results of Outdoor Exposure at Gaithersburg, Maryland

Cumulative Time of Exposure (Months)

Code Number	Absorptive Coating	Absorbance (α)						Emittance (ϵ)							
		Months						Months							
		0	41/	82/	123/	164/	205/	246/	0	41/	82/	123/	164/	205/	246/
A8	Nickel Foil	0.98	0.98	0.99	0.98	0.98	0.98	0.96	0.09	0.09	0.10	0.10	0.10	0.10	0.10
B6	Anodized	0.92	0.92	0.91	0.91	0.91	0.91	0.91	0.81	0.81	0.81	0.81	0.81	0.81	0.81
B7	Anodized	0.90	0.90	0.90	0.89	0.89	0.90	0.90	0.81	0.81	0.81	0.81	0.81	0.81	0.81
C5	Copper Oxide	0.95	0.92	0.91	0.91	0.90	0.90	0.90	0.747/	0.54	0.54	0.57	0.56	0.56	0.54
D2	Black Chrome	0.95	0.97	0.97	0.96	0.96	0.96	0.96	0.07	0.07	0.06	0.07	0.06	0.06	0.06
D4	Black Chrome	0.96	0.93	0.93	0.93	0.92	0.91	0.91	0.06	0.06	0.06	0.05	0.05	0.05	0.05
G9	Polyvinylidene Fluoride	0.95	0.95	0.95	0.95	0.95	0.94	0.94	0.85	0.84	0.85	0.85	0.85	0.84	0.84
H1	Polyvinylidene Fluoride	0.96	0.95	0.95	0.95	0.95	0.95	0.95	0.85	0.82	0.84	0.83	0.83	0.82	0.82
H8	Polyvinylidene Fluoride	0.96	0.96	0.96	0.95	0.96	0.95	0.95	0.88	0.85	0.87	0.87	0.86	0.85	0.85
I1	Urethane	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.92	0.92	0.92	0.92	0.92	0.92	0.92
I4	Urethane	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.92	0.92	0.92	0.92	0.92	0.93	0.92
I8	Urethane	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.92	0.92	0.92	0.92	0.92	0.93	0.92
J1	Alkyd	0.97	0.98	0.98	0.98	0.98	0.97	0.97	0.92	0.91	0.91	0.91	0.90	0.91	0.91
J4	Alkyd	0.97	0.98	0.98	0.98	0.98	0.97	0.97	0.91	0.91	0.91	0.90	0.91	0.91	0.91
J8	Alkyd	0.97	0.97	0.97	0.98	0.98	0.97	0.97	0.92	0.92	0.91	0.91	0.91	0.91	0.92
K1	Epoxide	0.97	0.98	0.98	0.98	0.98	0.97	0.97	0.90	0.91	0.91	0.91	0.90	0.90	0.90
K4	Epoxide	0.97	0.98	0.98	0.98	0.98	0.97	0.97	0.91	0.91	0.91	0.91	0.90	0.91	0.91
K8	Epoxide	0.97	0.98	0.98	0.98	0.98	0.97	0.97	0.91	0.91	0.90	0.90	0.90	0.90	0.90
L1	Silicone	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.88	0.87	0.88	0.87	0.87	0.87	0.87
L4	Silicone	0.97	0.97	0.97	0.97	0.96	0.96	0.96	0.87	0.87	0.87	0.87	0.87	0.87	0.87
L8	Silicone	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.88	0.87	0.88	0.87	0.87	0.87	0.88
M1	Mod. Polyester	0.93	0.94	0.94	0.94	0.95	0.94	0.94	0.86	0.88	0.90	0.91	0.91	0.91	0.91
M4	Mod. Polyester	0.89	0.90	0.91	0.91	0.92	0.92	0.92	0.84	0.85	0.88	0.90	0.91	0.90	0.91
M8	Mod. Polyester	0.90	0.90	0.91	0.90	0.90	0.90	0.90	0.81	0.84	0.88	0.90	0.90	0.89	0.91
N2	Porcelain	0.93	0.94	0.94	0.94	0.94	0.93	0.93	0.85	0.85	0.85	0.85	0.85	0.85	0.85
N8	Porcelain	0.93	0.94	0.94	0.93	0.93	0.93	0.93	0.84	0.84	0.84	0.84	0.84	0.84	0.84

1/ Exposed from 6/78 to 10/78.

2/ Exposed from 11/78 to 3/79.

3/ Exposed from 4/79 to 8/79.

4/ Exposed from 4/80 to 8/80.

5/ Exposed from 11/80 to 3/81.

6/ Exposed from 5/81 to 9/81.

7/ Emittance for 10 specimens of this sample varied from 0.65 to 0.80.

Table 3. Results of Outdoor Exposure at Phoenix, Arizona

Cumulative Time of Exposure (Months)

Code Number	Absorptive Coating	Absorbance (α) Months					Emittance (ϵ) Months						
		0	41/	82/	123/	164/	205/	0	41/	82/	123/	164/	205/
A8	Nickel Foil	0.98	0.99	0.98	0.98	0.98	0.98	0.09	0.09	0.09	0.09	0.08	0.08
B6	Anodized	0.92	0.92	0.91	0.91	0.91	0.91	0.81	0.81	0.81	0.81	0.81	0.81
B7	Anodized	0.90	0.90	0.89	0.89	0.89	0.90	0.82	0.81	0.81	0.80	0.81	0.81
C5	Copper Oxide	0.95	0.91	0.89	0.89	0.88	0.87	0.74 ^{6/}	0.54	0.56	0.55	0.56	0.56
D2	Black Chrome	0.95	0.97	0.96	0.96	0.95	0.95	0.07	0.07	0.06	0.06	0.06	0.06
D4	Black Chrome	0.96	0.97	0.95	0.96	0.95	0.94	0.06	0.09	0.08	0.07	0.08	0.07
G9	Polyvinylidene Fluoride	0.95	0.95	0.95	0.95	0.95	0.94	0.85	0.85	0.84	0.84	0.84	0.84
H1	Polyvinylidene Fluoride	0.96	0.95	0.95	0.95	0.96	0.95	0.85	0.83	0.80	0.81	0.83	0.83
H8	Polyvinylidene Fluoride	0.96	0.95	0.95	0.95	0.95	0.95	0.88	0.88	0.87	0.87	0.86	0.86
I1	Urethane	0.97	0.97	0.97	0.98	0.98	0.97	0.92	0.92	0.88	0.93	0.93	0.93
I4	Urethane	0.97	0.98	0.97	0.96	0.97	0.97	0.92	0.92	0.93	0.93	0.93	0.93
I8	Urethane	0.97	0.97	0.97	0.97	0.98	0.97	0.92	0.92	0.92	0.94	0.93	0.93
J1	Alkyd	0.97	0.98	0.98	0.98	0.98	0.97	0.92	0.91	0.91	0.91	0.91	0.91
J4	Alkyd	0.97	0.97	0.98	0.98	0.98	0.97	0.91	0.91	0.91	0.91	0.91	0.91
J8	Alkyd	0.97	0.97	0.98	0.98	0.98	0.97	0.92	0.91	0.91	0.91	0.91	0.92
K1	Epoxide	0.97	0.98	0.98	0.98	0.98	0.97	0.91	0.91	0.90	0.90	0.90	0.90
K4	Epoxide	0.97	0.98	0.98	0.98	0.98	0.97	0.91	0.91	0.90	0.90	0.90	0.91
K8	Epoxide	0.97	0.98	0.98	0.98	0.98	0.97	0.91	0.91	0.91	0.91	0.90	0.90
L1	Silicone	0.97	0.97	0.96	0.96	0.97	0.96	0.88	0.87	0.87	0.87	0.87	0.87
L4	Silicone	0.97	0.97	0.97	0.97	0.97	0.96	0.87	0.87	0.87	0.87	0.87	0.87
L8	Silicone	0.97	0.97	0.97	0.97	0.97	0.96	0.88	0.88	0.87	0.87	0.87	0.87
M1	Mod. Polyester	0.93	0.91	0.91	0.92	0.92	0.92	0.86	0.86	0.86	0.88	0.88	0.88
M4	Mod. Polyester	0.89	0.85	0.84	0.84	0.83	0.84	0.84	0.77	0.77	0.83	0.85	0.85
M8	Mod. Polyester	0.90	0.87	0.86	0.89	0.87	0.88	0.81	0.81	0.81	0.85	0.86	0.86
N2	Porcelain	0.93	0.94	0.93	0.94	0.93	0.93	0.85	0.85	0.85	0.85	0.85	0.85
N8	Porcelain	0.93	0.93	0.92	0.93	0.93	0.93	0.84	0.84	0.84	0.84	0.84	0.84

1/ Exposed from 11/78 to 3/79.

2/ Exposed from 4/79 to 8/79.

3/ Exposed from 5/80 to 9/80.

4/ Exposed from 11/80 to 3/81.

5/ Exposed from 5/81 to 9/81.

6/ Emittance for 10 specimens of this sample varied from 0.65 to 0.80.

7/ Coating delaminated.

Table 4. Results of Outdoor Exposure at Miami, Florida
Cumulative Time of Exposure (Months)

Code Number	Absorptive Coating	Absorbance (α)					Emittance (ϵ)								
		Months					Months								
		0	41/	82/	123/	164/	205/	246/	0	41/	82/	123/	164/	205/	246/
A8	Nickel Foil	0.98	0.99	0.98	0.98	0.98	0.98	0.97	0.09	0.05	0.08	0.08	0.08	0.09	0.10
B6	Anodized	0.92	0.92	0.92	0.91	0.91	0.91	0.91	0.81	0.81	0.81	0.81	0.81	0.81	0.81
B7	Anodized	0.90	0.90	0.90	0.89	0.89	0.89	0.90	0.82	0.81	0.80	0.81	0.81	0.80	0.81
C5	Copper Oxide	0.95	0.90	0.89	0.88	0.88	0.87	0.86	0.742/	0.50	0.53	0.52	0.52	0.53	0.54
D2	Black Chrome	0.95	0.97	0.96	0.95	0.95	0.95	0.94	0.07	0.04	0.07	0.06	0.06	0.07	0.08
D4	Black Chrome	0.96	0.94	0.93	0.92	0.92	0.92	0.91	0.06	0.06	0.06	0.06	0.05	0.06	0.07
G9	Polyvinylidene Fluoride	0.95	0.95	0.95	0.95	0.95	0.95	0.94	0.85	0.85	0.86	0.85	0.85	0.84	0.84
H1	Polyvinylidene Fluoride	0.96	0.95	0.95	0.95	0.95	0.95	0.95	0.85	0.82	0.85	0.83	0.84	0.83	0.83
H8	Polyvinylidene Fluoride	0.96	0.95	0.96	0.95	0.95	0.95	0.95	0.88	0.87	0.88	0.87	0.87	0.86	0.86
I1	Urethane	0.97	0.97	0.97	0.97	0.97	0.97	0.96	0.92	0.92	0.92	0.93	0.93	0.93	0.93
I4	Urethane	0.97	0.97	0.97	0.97	0.97	0.97	0.96	0.92	0.92	0.93	0.93	0.93	0.93	0.93
I8	Urethane	0.97	0.97	0.97	0.97	0.97	0.97	0.96	0.92	0.92	0.92	0.93	0.93	0.93	0.93
J1	Alkyd	0.97	0.98	0.98	0.98	0.98	0.98	0.97	0.92	0.91	0.91	0.91	0.90	0.90	0.90
J4	Alkyd	0.97	0.98	0.98	0.98	0.98	0.98	0.97	0.91	0.91	0.91	0.91	0.91	0.91	0.91
J8	Alkyd	0.97	0.97	0.98	0.98	0.98	0.98	0.97	0.92	0.91	0.91	0.91	0.91	0.91	0.91
K1	Epoxide	0.97	0.98	0.98	0.98	0.98	0.98	0.97	0.91	0.91	0.91	0.90	0.90	0.90	0.90
K4	Epoxide	0.97	0.98	0.98	0.98	0.98	0.98	0.97	0.91	0.91	0.91	0.90	0.90	0.90	0.90
K8	Epoxide	0.97	0.98	0.98	0.98	0.98	0.98	0.97	0.91	0.90	0.91	0.90	0.90	0.90	0.90
L1	Silicone	0.97	0.97	0.97	0.96	0.96	0.96	0.96	0.88	0.87	0.87	0.87	0.87	0.87	0.87
L4	Silicone	0.97	0.97	0.97	0.96	0.96	0.96	0.96	0.87	0.87	0.87	0.87	0.87	0.87	0.87
L8	Silicone	0.97	0.97	0.97	0.97	0.97	0.96	0.96	0.88	0.88	0.85	0.87	0.87	0.88	0.88
M1	Mod. Polyester	0.93	0.94	0.95	0.95	0.94	0.94	0.94	0.86	0.89	0.92	0.91	0.91	0.92	0.92
M4	Mod. Polyester	0.89	0.91	0.93	0.93	0.93	0.93	0.92	0.84	0.85	0.90	0.90	0.90	0.90	0.91
M8	Mod. Polyester	0.90	0.92	0.94	0.94	0.94	0.93	0.93	0.81	0.88	0.92	0.91	0.91	0.93	0.93
N2	Porcelain	0.93	0.94	0.94	0.93	0.94	0.94	0.91	0.85	0.85	0.85	0.85	0.84	0.85	0.85
N8	Porcelain	0.93	0.93	0.92	0.92	0.92	0.93	0.92	0.84	0.84	0.85	0.84	0.84	0.84	0.84

1/ Exposed from 6/78 to 10/78.

2/ Exposed from 11/78 to 5/79 (with a 2 mo. non-exposure period)

3/ Exposed from 7/79 to 11/79.

4/ Exposed from 5/80 to 9/80.

5/ Exposed from 12/80 to 4/81.

6/ Exposed from 5/81 to 9/81.

7/ Emittance for 10 specimens of this sample varied from 0.65 to 0.80.



Figure 1. Test box used for outdoor exposures

U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET (See Instructions)		1. PUBLICATION OR REPORT NO. NBSIR 82-2583	2. Performing Organ. Report No.	3. Publication Date October 1982
4. TITLE AND SUBTITLE Outdoor Exposure Tests of Solar Absorptive Coatings				
5. AUTHOR(S) Larry W. Masters, James F. Seiler and Willard E. Roberts				
6. PERFORMING ORGANIZATION (If joint or other than NBS, see instructions) NATIONAL BUREAU OF STANDARDS DEPARTMENT OF COMMERCE WASHINGTON, D.C. 20234			7. Contract/Grant No.	8. Type of Report & Period Covered
9. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS (Street, City, State, ZIP) U.S. Department of Energy Office of Solar Applications for Buildings Washington, D.C. 20585				
10. SUPPLEMENTARY NOTES <input type="checkbox"/> Document describes a computer program; SF-185, FIPS Software Summary, is attached.				
11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here) This report is a follow up to an earlier report (NBSIR 81-2232, January 1981) in which data on the performance of selected absorptive coatings in both accelerated laboratory exposures and outdoor exposures at three sites were presented. The research presented in this report focuses upon the results obtained by continuing the outdoor exposures of absorptive coatings using ASTM E781-81, Standard Practice for Evaluating Absorptive Solar Receiver Materials When Exposed to Conditions Simulating Stagnation in Solar Collectors with Cover Plates. Comparison of the results of the outdoor exposures with those obtained in accelerated laboratory exposures indicated that 1) the accelerated exposures, as described in ASTM E744-80, Standard Practice for Evaluating Solar Absorptive Materials for Thermal Applications, provide more severe exposure conditions than outdoor exposures, and 2) the degradation processes induced by outdoor exposure are adequately addressed by the accelerated laboratory exposures.				
12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons) Absorptive coatings; accelerated laboratory exposures; degradation; outdoor exposures; simulated stagnation exposure; solar energy				
13. AVAILABILITY <input checked="" type="checkbox"/> Unlimited <input type="checkbox"/> For Official Distribution. Do Not Release to NTIS <input type="checkbox"/> Order From Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402. <input checked="" type="checkbox"/> Order From National Technical Information Service (NTIS), Springfield, VA. 22161			14. NO. OF PRINTED PAGES 22	
			15. Price \$6.00	

