NBS TECHNICAL NOTE 1170

U.S. DEPARTMENT OF COMMERCE/National Bureau of Standards

# Weathering Performance of Cover Materials for Flat Plate Solar Collectors

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NBS technical note

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# ABSTRACT

Weathering studies were performed to obtain data on the performance and durability of cover plate materials for flat plate solar collectors used in solar heating and cooling systems. Ten materials were evaluated to assess their durability after natural weathering and artificial weathering with a xenon arc light. The materials were weathered for four years on small mini-collectors in Arizona, Florida, and Maryland after which the solar energy transmittance and the effect of dirt on the transmittance were measured. The tensile properties of selected film materials were also assessed after weathering. The effects of the natural weathering are compared: (1) for materials exposed as inner and outer cover plates for each weathering site; (2) for the three weathering sites; and (3) with materials artificially weathered with a xenon arc light.

Key words: artificial weathering; cover plate materials; durability; natural weathering; solar collectors; solar energy; solar energy transmittance; tensile properties; weathering of cover plates.

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# 1. INTRODUCTION

## 1.1 BACKGROUND

In 1976, due to a lack of durability data for solar collector cover materials, the National Bureau of Standards (NBS) initiated a study, sponsored by the Department of Energy (DoE), to obtain data as the technical basis for standards for solar collector cover plate materials. A report on the study [1]* issued in 1980 assessed problems with cover plate materials, listed performance requirements, described cover plate properties, and outlined factors which cause material degradation. It also contained data comparing cover materials after heat aging, artificial weathering with a xenon arc light, and two years natural outdoor weathering on minicollectors at three geographic locations. The materials were evaluated by measurement of transmittance, linear dimensions, and warpage. The report also contained two proposed standards for weathering and evaluation of cover plate materials.

This is the final report on the study. The objective of the work described in this report was: 1) to obtain additional natural weathering data for comparison with data from accelerated laboratory tests, and 2) to assess changes in mechanical properties of a limited number of materials.

This report discusses the effects of four years of natural weathering on cover plate materials. Comparisons are made with materials weathered artificially with xenon arc light. Solar transmittance was measured to assess the effect of the weathering and the effect of dirt. Tensile properties of three film materials were also measured after outdoor weathering, xenon arc artificial weathering, and heat aging.

The earlier report [1] contained data on exposure of cover materials to heat aging at 75, 100, 125, and 150°C, artificial aging with xenon arc light, and natural aging for two years on minicollectors.

## 1.2 RELATED DEVELOPMENTS

Since 1976 progress has been made in identification and use of more durable cover plate materials in solar collectors. In response to greater emphasis on material durability, increased efforts have been placed in development of standards for evaluating cover plate materials for solar collectors, in generating data regarding durability of cover plate materials, and in writing criteria or guidelines for cover plate materials in solar systems. Of critical significance has been the development of uniform methods to measure long-term performance of cover plate materials and to evaluate relative durabilities.

Progress in standards development has also been evidenced by activity in the American Society for Testing and Materials (ASTM). In 1978 ASTM formed Committee E 44 on Solar Energy Conversion with an active task group on Cover Plate Standards. Since then, the following new ASTM standards relating to

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* Figures in brackets refer to references in Section 7.

cover plate materials have been approved: E 765, Practice for Evaluation of Cover Materials for Flat Plate Solar Collectors [2]; E 782, Practice for Exposure of Cover Materials for Solar Collectors to Natural Weathering Under Conditions Simulating Operational Mode [3]; E 822, Practice for Determining Resistance of Solar Collector Covers to Hail by Impact with Propelled Ice Balls [4]; and E 881, Practice for Exposure of Solar Collector Cover Materials to Natural Weathering Under Conditions Simulating Stagnation Mode [5]. Standards E 765 and E 881 are based on work reported in [1] while initial work on Standard E 822 is described in [6] and [7]. Other standards are also being developed in Committee E 44. These standards represent significant progress in the development of uniform methods to measure long-term performance and to evaluate relative durabilities of cover plate materials.

Other data on durability of cover plate materials have also been published since 1976. Optical and mechanical property data of a number of cover plate materials are listed in [8, 9]. The materials were weathered at ambient temperatures, rather than the higher temperatures attained in solar collectors. Consequently, a user of these durability data should keep in mind that most materials are less durable at high temperatures.

Several efforts have also been made to assist designers, manufacturers, or builders in selecting reliable components and materials [10, 11, 12, 13, 14]. Design guidelines or performance criteria for materials in solar systems are provided, and reference 14 contains a chapter discussing the properties of glazing materials.

# 2. LABORATORY STUDIES AND FIELD EXPOSURES

## 2.1 MATERIALS

The cover plate materials utilized in this study were typical of those commercially available in 1976. The properties of materials currently on the market may differ from those described in this report. Properties of cover plate materials can be altered by changes in minor consitutents (i.e., iron oxide content, stabilizers, plasticizers, antioxidants) or in processing techniques. Many cover plate materials are marketed, and in order to improve their performance, manufacturers sometimes modify the materials. The reader is cautioned against direct application of the data in this report to materials currently marketed.

The ten cover plate materials selected for testing were representative of the materials and thicknesses used in solar collectors. Two of the materials were glass sheet. They differ in iron oxide content which directly affects the solar energy transmittance. Four of the materials were plastic films and four materials were plastic sheet, two of which were fiber reinforced plastics (FRP). These FRP materials were from separate manufacturers and contained different resins. They are distinguished in this report by their thicknesses. The ten materials are listed in table 1 along with their solar energy transmittance values. Greater description of the materials along with graphs of the initial spectral transmittance and the infrared transmittance are given in the earlier report [1].

## 2.2 WEATHERING PROCEDURES

### 2.2.1 Natural Weathering

The cover plate materials were weathered on small insulated boxes (i.e. minicollectors) (240 by 140 by 83 mm) which were designed to elevate the exposure temperature and thereby provide an exposure environment simulating that in a collector. Both single and double cover assemblies were used. The design of the minicollector is shown in figure 1.

The minicollectors were weathered at three sites: New River, Arizona; Miami, Florida; and Gaithersburg, Maryland. The Arizona site had a hot, dry desert climate while the Florida site was a hot, humid tropical climate with some industrial exposure. The Maryland site had a hot, humid subtropical climate. A variable angle exposure was utilized to maximize solar radiation incident upon the minicollectors. Details of the minicollector construction and weathering exposure are contained in the earlier report [1].

A set of test specimens was removed for evaluation at 3, 6, 12, 18, 24, 36, and 48 month intervals. In some cases, duplicate sets of test specimens were removed. The exposure schedule and the solar radiation accumulated during exposure are summarized in table 2. Comparing the solar radiation accumulated at the three sites during simultaneous exposure, it is observed that the test specimens received approximately 50 percent more solar radiation at New River than at Gaithersburg, and about 25 percent more solar radiation at New River

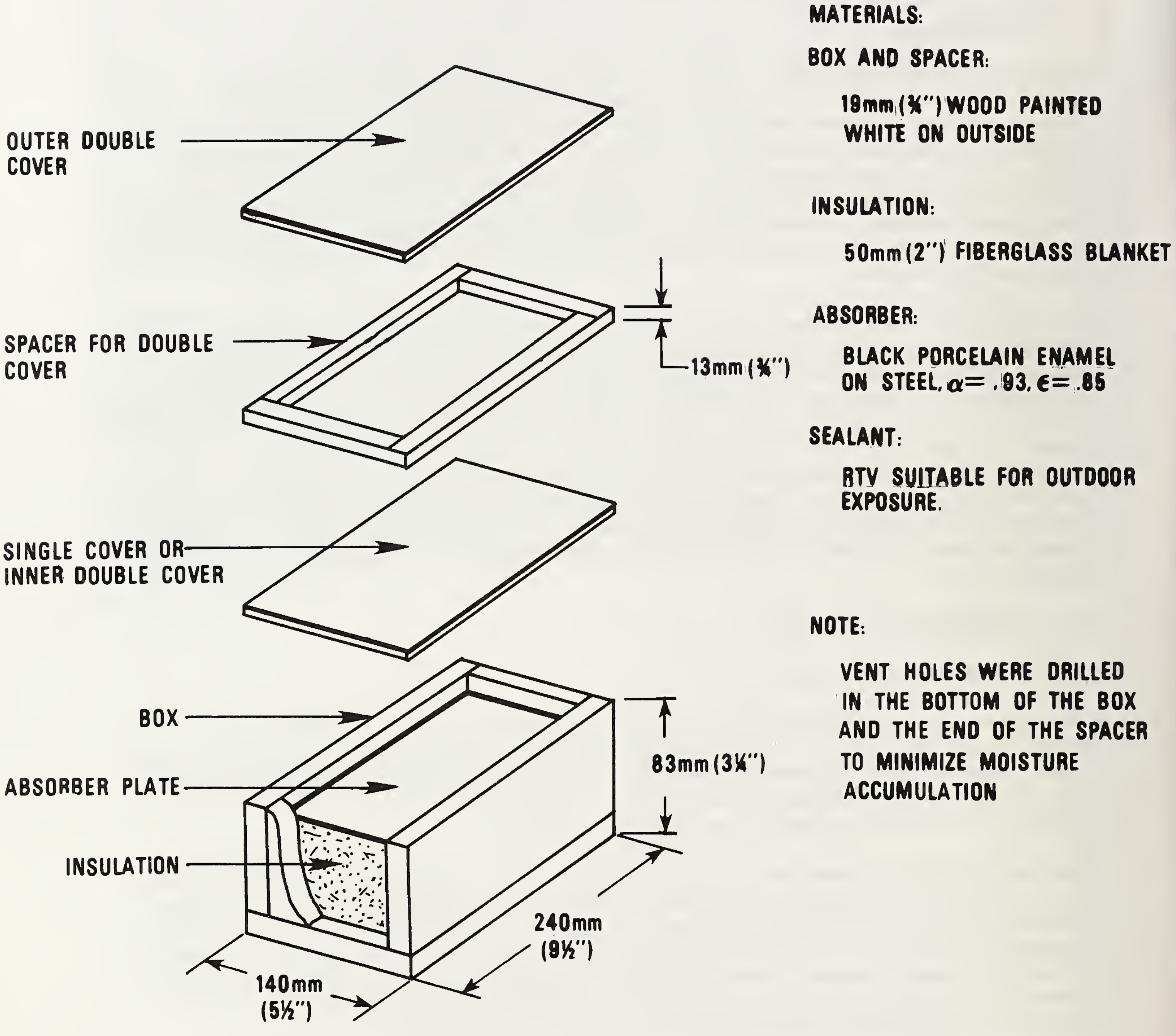

Figure 1. Minicollector for natural weathering exposure

Table 1. Solar Energy Transmittance of Unweathered Cover Plate Materials

| Material | Nominal Thickness mm | Solar Energy Transmittance Control Test Specimens | | | Average | Standard Deviation |
|---|---|---|---|---|---|---|
| Glass (0.01% iron oxide) | 3.2 | 90.5<br>90.8 | 90.5<br>91.0 | 90.9<br>90.7 | 90.7 | 0.2 |
| Glass (0.10% iron oxide) | 3.2 | 87.4 | 87.4 | 87.5 | 87.4 | 0.1 |
| Fluorinated (ethylene propylene) copolymer | 0.025 | 95.9 | 96.1 | 96.1 | 96.0 | 0.1 |
| Poly(vinyl fluoride) | 0.10 | 92.7 | 92.4 | 92.4 | 92.5 | 0.1 |
| Poly(ethylene terephthalate) | 0.13 | 86.4 | 86.4 | 86.3 | 86.3 | 0.1 |
| Acrylic | 0.076 | 90.6 | 90.8 | 90.7 | 90.7 | 0.1 |
| Poly(methyl methacrylate) | 1.5 | 91.0 | 91.0 | 91.1 | 91.0 | 0.1 |
| Polycarbonate | 1.02 | 88.2 | 88.0 | 88.2 | 88.1 | 0.1 |
| Fiber reinforced plastic | 1.02 | 86.5 | 86.3 | 86.2 | 86.3 | 0.1 |
| Fiber reinforced plastic | 1.5 | 81.7<br>77.2 | 80.0<br>77.8 | 74.6<br>79.5 | 78.5 | 2.3 |

Spectral transmittance was measured with an integrating sphere spectrophotometer. The solar energy transmittance was calculated for air mass 2. Transmittance is expressed in percentage.

Table 2. Natural Weathering Exposure Data for Minicollectors

| | | Solar Radiation ($GJ/m^2$) | | |
|---|---|---|---|---|
| Months Exposure | Dates | Gaithersburg, Maryland | Miami, Florida | New River, Arizona |
| 3 | 9/1/77-12/1/77 | 1.176 | 1.455 | 2.012 |
| | 12/20/77-3/20/78 | | | 1.422 |
| 6 | 9/1/77-3/1/78 | 2.251 | 2.864 | 3.487 |
| | 3/24/78-9/24/78 | | | 5.123 |
| 12 | 9/1/77-9/1/78 | 5.477 | 6.344 | 8.006 |
| | 3/1/78-3/1/79 | 5.429 | | |
| | 4/1/78-4/1/79 | | 6.523 | |
| | 7/29/78-7/29/79 | | | 8.259 |
| 18 | 9/1/77-3/1/79 | 7.680 | 9.333 | 11.642 |
| 24 | 9/1/77-9/1/79 | 10.720 | 13.125 | 16.370 |
| 36 | 9/1/77-9/1/80 | 16.402 | 19.398 | 24.414 |
| | 4/1/78-4/1/81 | | 19.859 | |
| | 4/17/78-4/17/81 | 16.693 | | |
| 48 | 9/1/77-9/1/81 | 22.076 | 26.333 | 33.038 |

than at Miami. Similarly, the test specimens at Miami received about 20 percent more solar radiation than those at Gaithersburg.

### 2.2.2 Artificial Weathering with Xenon Arc Light

Cover plate materials were exposed to xenon arc light in an artificial weathering device using ASTM Method D 2565, Recommended Practice for Operating Xenon Arc-Type (Water-Cooled) Light-Exposure Apparatus With and Without Water for Exposure of Plastics [15]. A Type B apparatus was used with the irradiance regulated through the use of a continuously controlling monitor that automatically maintained uniform intensity at preselected wavelengths of 340, 420, and 580 nm. A borosilicate glass filter with suitable transmittance was used to filter the light and to provide radiation which simulated the solar spectrum at sea level. Test specimens were exposed to a continuous light cycle without water spray. The ambient temperature within the chamber was approximately 40-50°C.

Test specimens were about 45 cm from the light source. Periodically, test specimens were repositioned to essentially achieve uniform radiation. A set was removed for evaluation at time intervals ranging from 250 to 4000 hours. The spectral energy distribution of a xenon arc light in an artificial weathering device is shown in figure 2. In the ultraviolet and visible region it closely simulates the spectral distribution of sunlight (expecially air mass 1) also shown in figure 2, although there are some differences in the near infrared region.

To facilitate comparison of the effects of natural weathering with xenon arc artificial weathering, the energy deposited on materials during xenon arc exposure was calculated. Although it is the ultraviolet radiation which causes damage to polymeric materials, these comparisons were done with total solar energy because no measurements of only ultraviolet energy were available for the outdoor weathering. The spectral curve of the 6500 Joule (6500 Watt) xenon arc lamp [16] run at a controlled lamp output of 52 μJ was used to calculate energy deposited. Integration under the curve and adjustment for distance (45 cm) of specimen from the lamp produced a value of 1140 $J/m^2$ at the test specimen. The hours of xenon arc exposure in the artificial weathering device and the corresponding calculated energy values are shown in table 3.

## 2.3 PROPERTY TESTS

### 2.3.1 Solar Energy Transmittance

The solar energy transmittance of the materials was determined using Method A of ASTM E 424-71, Standard Test Methods for Solar Energy Transmittance and Reflectance (Terrestrial) of Sheet Materials [17]. The spectral transmittance

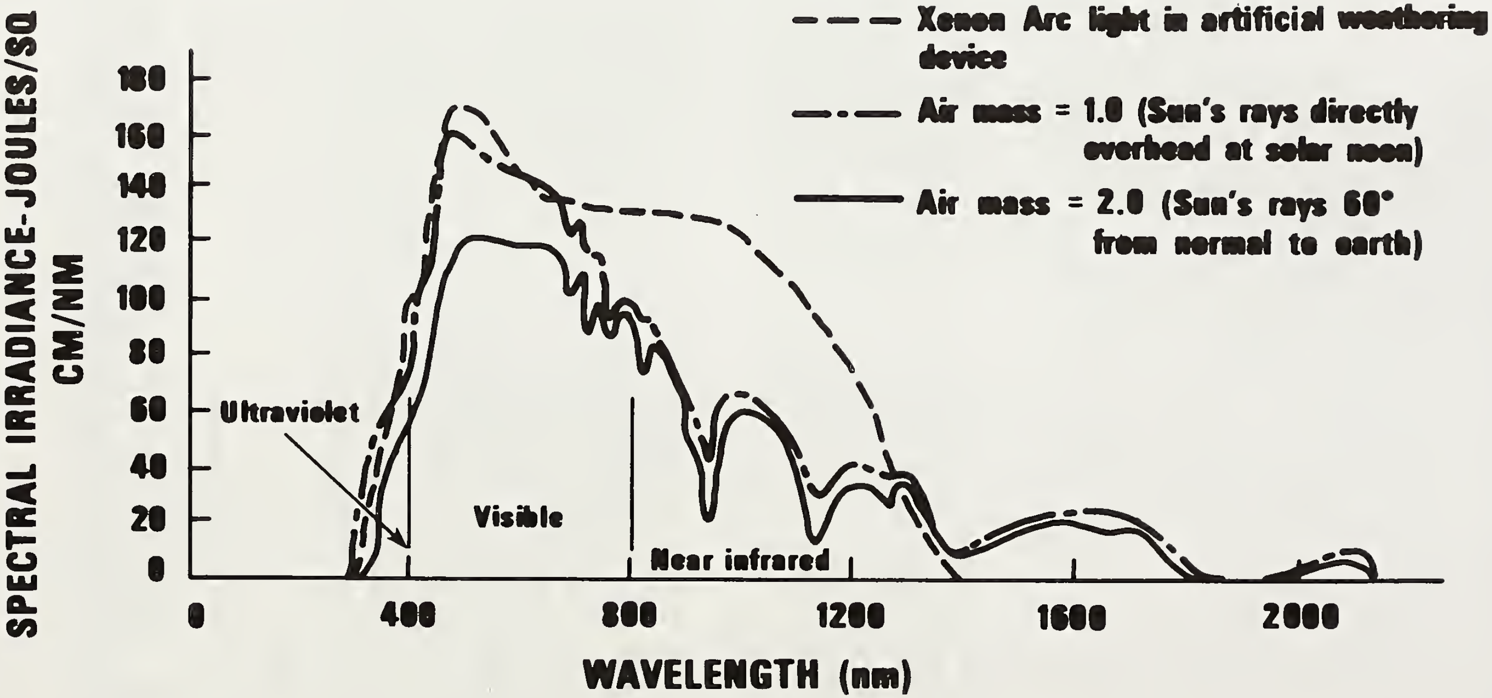

Figure 2. Spectral distribution of energy from the sun and for a xenon arc light

Table 3. Calculated Values for Energy Deposited on Cover Materials During Artificial Weathering with Xenon Arc Light

| Hours of Exposure | Energy Deposited (Calculated) GJ/m$^2$ |
|---|---|
| 250 | 1.030 |
| 499 | 2.055 |
| 758 | 3.122 |
| 1000 | 4.118 |
| 2012 | 8.286 |
| 3000 | 12.355 |
| 4010 | 16.515 |

of the cover plate materials was measured utilizing a Cary 17D Spectrophotometer[1] with a 76 mm diameter integrating sphere. Measurements of spectral transmittance were made over the spectral range from 300 to 2150 nm. The solar energy transmitted was obtained by integrating over the solar energy distribution, as reported by Parry Moon [18], for sea level and air mass 2 (AM 2). The weighted ordinates calculation method from ASTM E 424 was used to integrate the solar energy distribution at 50 nm intervals, normalized to 100. Further details of the transmittance measurement are given in the earlier report [1].

#### 2.3.1.1 Cleaning Procedure

The cover materials weathered outdoors were cleaned after the weathering to determine the effect of dirt accumulation on transmittance. No cleaning was done during weathering. The cleaning procedure consisted of immersing the test specimens in a 0.1 percent solution of detergent in distilled water. A soft brush was used to clean both sides of the test specimen which was then rinsed with distilled water and air dried. Care was taken to avoid scratching or stretching the plastic materials.

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[1] Certain trade names and company products are identified in order to adequately specify the experimental procedure. In no case does such identification imply recommendation or endorsement by the National Bureau of Standards, nor does it imply that the products are necessarily the best available for the purpose.

### 2.3.2 Tensile Properties

The tensile properties of fluorinated (ethylene propylene) copolymer, poly(vinyl fluoride), and poly (ethylene terephthalate) films were measured using ASTM D 882, Methods for Tensile Properties of Thin Plastic Sheeting [19]. The tensile properties which were calculated were breaking factor, tensile strength, elongation at break, yield strength, and elongation at yield. Tensile specimens of 13 by 100 mm were cut from the weathered materials. Where sufficient material was available, five tensile specimens were taken from both the longitudinal and the transverse directions. This was done to obtain data regarding the anisotropic nature of the films. Tensile testing was performed only on selected test specimens from the heat aging at 125°C, artificial weathering with xenon arc, and outdoor weathering at Arizona and Florida (poly(ethylene terephthalate) only).

## 3. RESULTS AND DISCUSSION

### 3.1 VISUAL OBSERVATIONS

The test specimens were visually examined during removal from the minicollector boxes. Some of each type of glass test specimen had broken during the exposure. This breakage was apparently due to the manner in which the boxes were held on the exposure rack. It appeared not to be due to impact. Several test specimens were cracked when they were removed from the test boxes. Both types of glass were annealed. The test specimens had been cut from large sheets and the edges had not been treated to reduce the stress levels. It is doubtful cracking would have occurred with tempered glass which is generally used in solar collectors.

With the fluorinated (ethylene propylene) copolymer, there was little change in appearance other than the accumulation of dirt. However, several of the double cover minicollectors (some from Miami and some from Gaithersburg) developed small holes 20-40 mm from the edge. The holes were reported to be caused by birds pecking at the cover plates. The minicollectors in Arizona suffered damage due to a hail storm. Damage ranged from dents to holes of 10-30 mm diameter.

The poly(vinyl fluoride) became extremely taut across the boxes, apparently caused by shrinkage of the material. The test specimens gradually yellowed as the exposure continued. The inner cover of the double cover minicollectors exposed for 18 to 48 months in Arizona and for 24 to 48 months in Florida became so brittle that they ruptured. The single and outer double covers accumulated dirt that could not be washed off with the cleaning procedure used in this test program. However, it was noted that the dirt could be removed with adhesive tape. (When the specimens were placed in the spectrophotometer for transmittance measurements, adhesive tape was used to hold the material in place. When the tape was removed, the dirt came off cleanly from under the tape. It appeared that some of the outer degraded polymer that was holding the dirt also came off the cover plate.)

The poly(ethylene terephthalate) outer covers exposed for one year and longer in Miami developed a white, opaque appearance. Although the material was transparent prior to exposure, it became a milky white. Closer examination of the test specimens found that the white material was present only on the exterior surface. Apparently the environmental factors in Miami, e.g., more moisture and an industrial atmosphere, caused changes in the outer surface exposed directly to the weather. The white material was not present on the interior side of the outer cover nor on the inner cover. Examination of outer surface with a scanning electron microscope indicated minute cracking on the surface. Figure 3a illustrates the small cracks seen after one year of weathering in Miami, Florida.

The poly(ethylene terephthalate) test specimens from Arizona were damaged apparently by a hailstorm. All of the outer double cover and single cover poly(ethylene terephthalate) test specimens on exposure at that time had holes and cracks in them. The material had become extremely brittle. The inner cover remained intact. All but one of the minicollectors with poly(ethylene

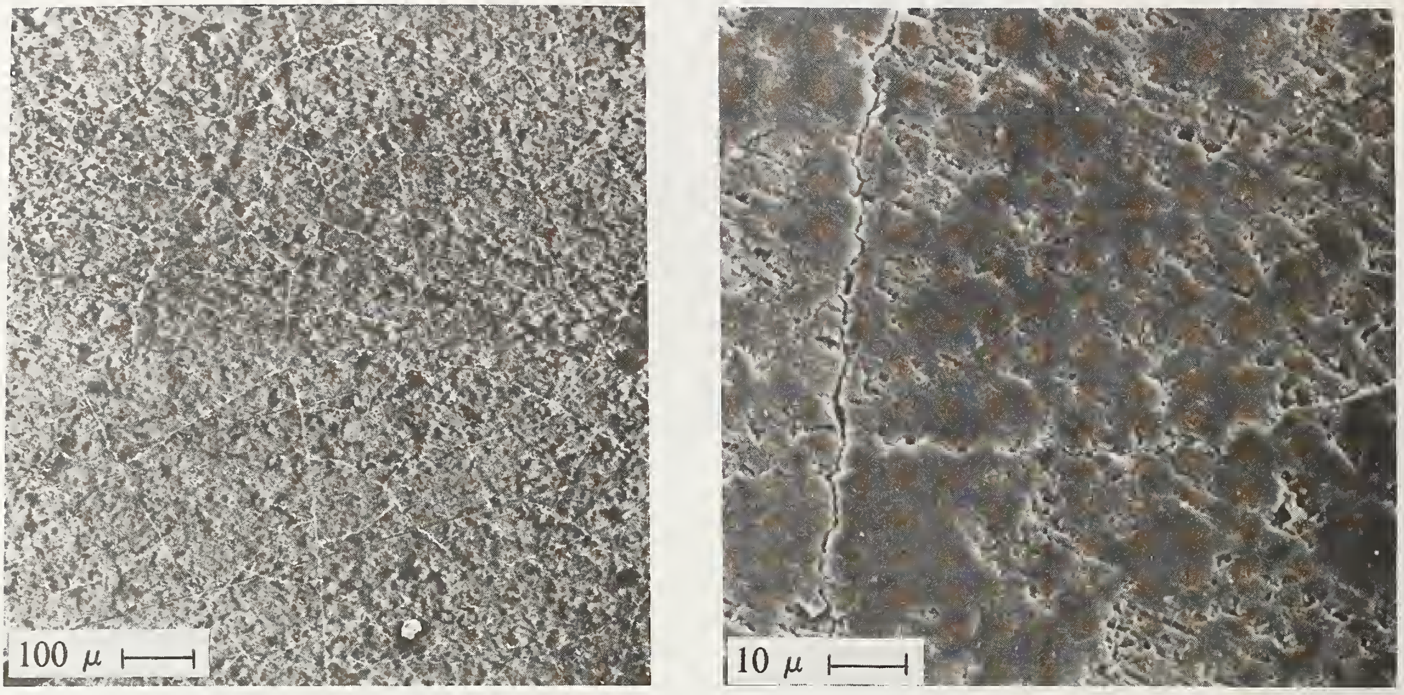


Figure 3a. Scanning electron micrographs of poly(ethylene terephthalate) after one year weathering in Miami, Florida

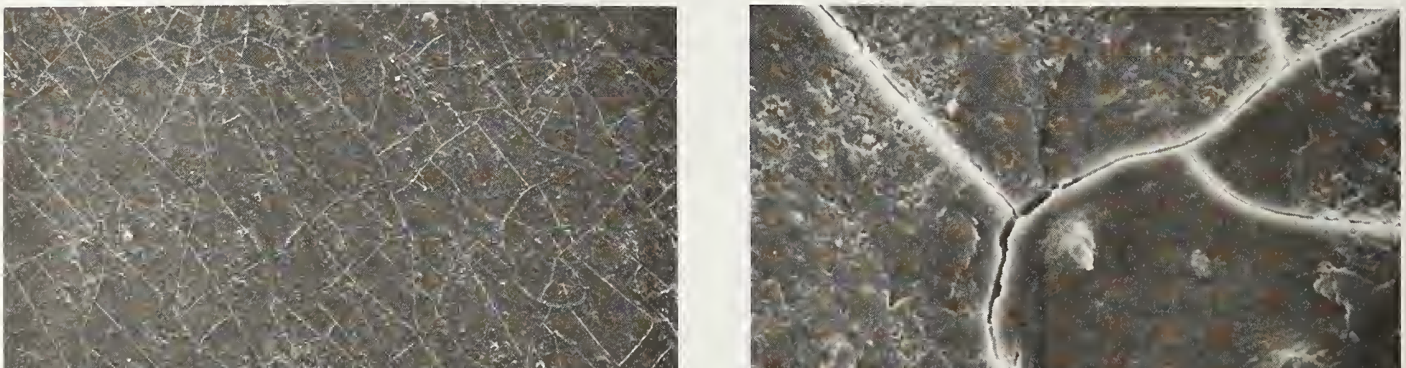


Figure 3b. Scanning electron micrographs of polycarbonate after one year weathering in Miami, Florida

terephthalate) from Arizona were terminated after 18 months due to damage. The remaining minicollector suffered similar serious damage in a hail storm during the 29th month of exposure.

The acrylic film was the first material to physically deteriorate during the exposure. It cracked and broke into pieces at all three exposure sites. The material failed most rapidly in Arizona, followed by Florida and Maryland. The outer cover test specimen deteriorated more rapidly than the inner one. After 18 months exposure in Arizona and Florida, the outer covers had completely disintegrated and blown away. The inner cover and single cover test specimens exhibited somewhat less damage. All minicollectors with the acrylic film were terminated at 18 or 24 months due to material failure.

The polycarbonate material visibly yellowed as it was exposed. In addition, the test specimens exposed in Florida developed deposits on the outer surface. The deposits were not washed off during the cleaning. Similar deposits developed on the Maryland samples but not to the extent that they occurred on the Florida specimens. Examination of the surface with a scanning electron microscope showed small cracks after one year. These are seen in figure 3b. However, no measure of physical properties was made to determine if the material was weakened.

Both of the fiber reinforced materials yellowed during the outdoor exposure, with the 1.5 mm FRP changing the most. The resin of this material also progressively developed a whitish appearance when weathered in Florida. This change may be attributed to either moisture or the industrial atmosphere. After 36 months exposure, the 1.5 mm fiber reinforced material exhibited a very significant amount of "fiber bloom" on the outer covers while the 1.0 mm fiber reinforced material showed a smaller amount. "Fiber bloom" occurs when fibers break away from the resin and protrude from the surface. The greatest amount of "fiber bloom" occurred on the test specimens from Arizona. The "fiber bloom" and yellowing continued to increase for both fiber reinforced materials through the 48 months exposure.

## 3.2 SOLAR TRANSMITTANCE

### 3.2.1 Gaithersburg, Maryland Exposure

The solar energy transmittance of single and double covers after natural weathering in Gaithersburg is compared for each cover material in figures 4a to 4j. The lines represent a least squares, best fit equation drawn through the data. The test specimens were washed prior to transmittance measurements. All materials suffered some loss in transmittance although the amount of the loss varied among the materials. In general, the inner cover transmittance changed the least. For most materials there was almost no change in the inner cover; however, both fiber reinforced plastics show a significant decline indicating their temperature sensitivity. Usually the rate of decline for the single and outer double covers was similar with the single cover transmittance, generally, slightly worse than the outer cover. One notable exception to this was the fluorinated (ethylene propylene) copolymer (fig. 4c) where the outer double cover decreased more. The single and outer double covers were exposed to

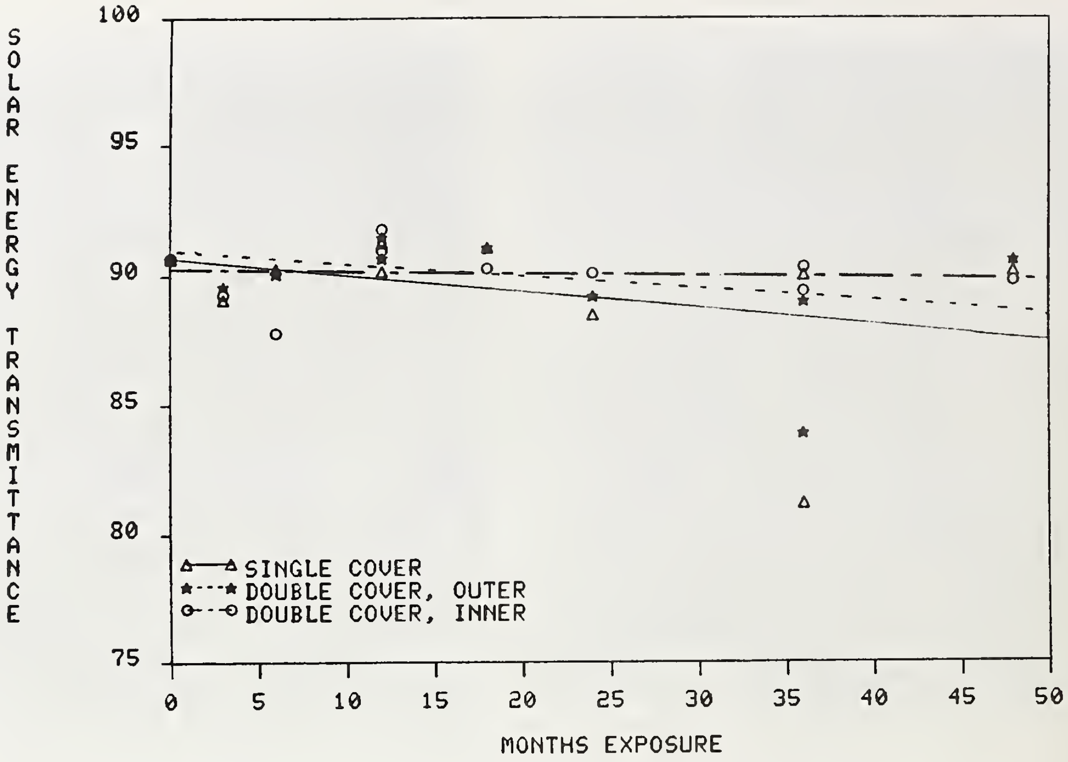


Figure 4a. Solar energy transmittance of glass (0.01% iron oxide) after weathering on minicollectors in Gaithersburg, Maryland

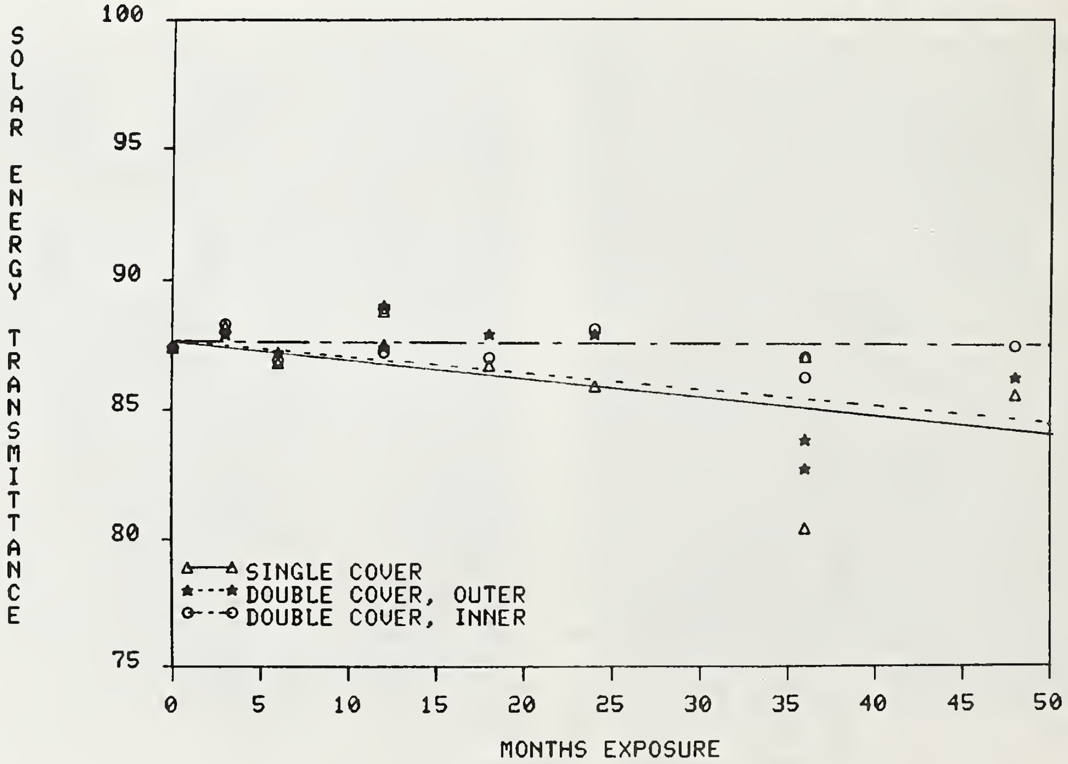


Figure 4b. Solar energy transmittance of glass (0.10% iron oxide) after weathering on minicollectors in Gaithersburg, Maryland

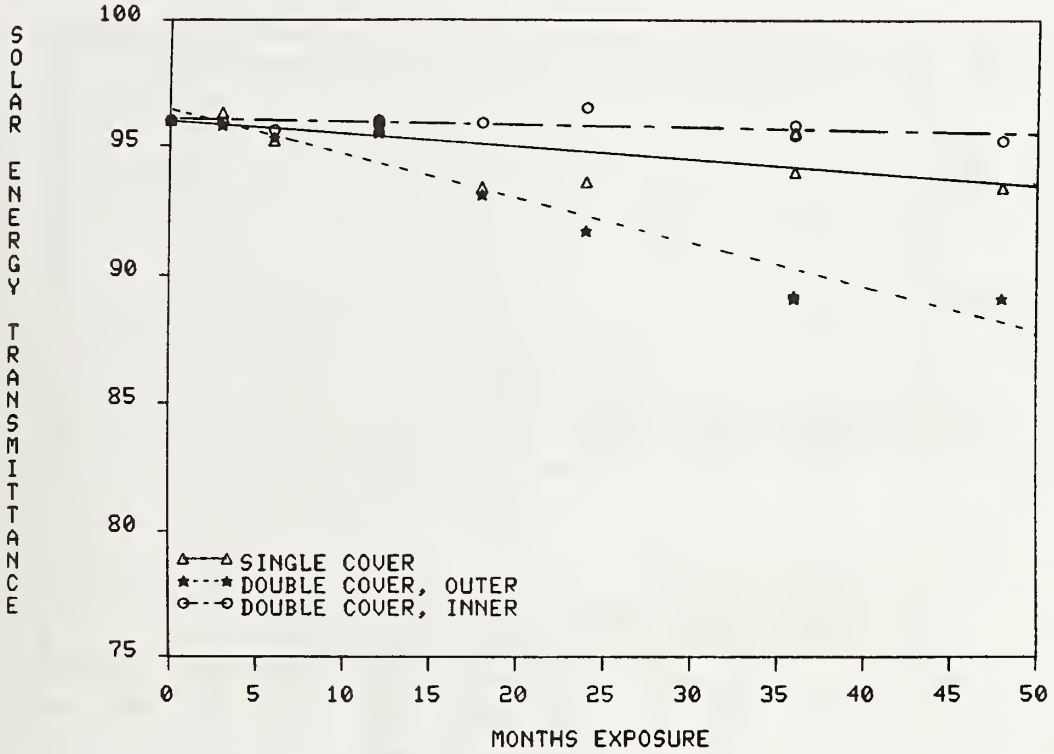


Figure 4c. Solar energy transmittance of fluorinated (ethylene propylene) copolymer after weathering on minicollectors in Gaithersburg, Maryland

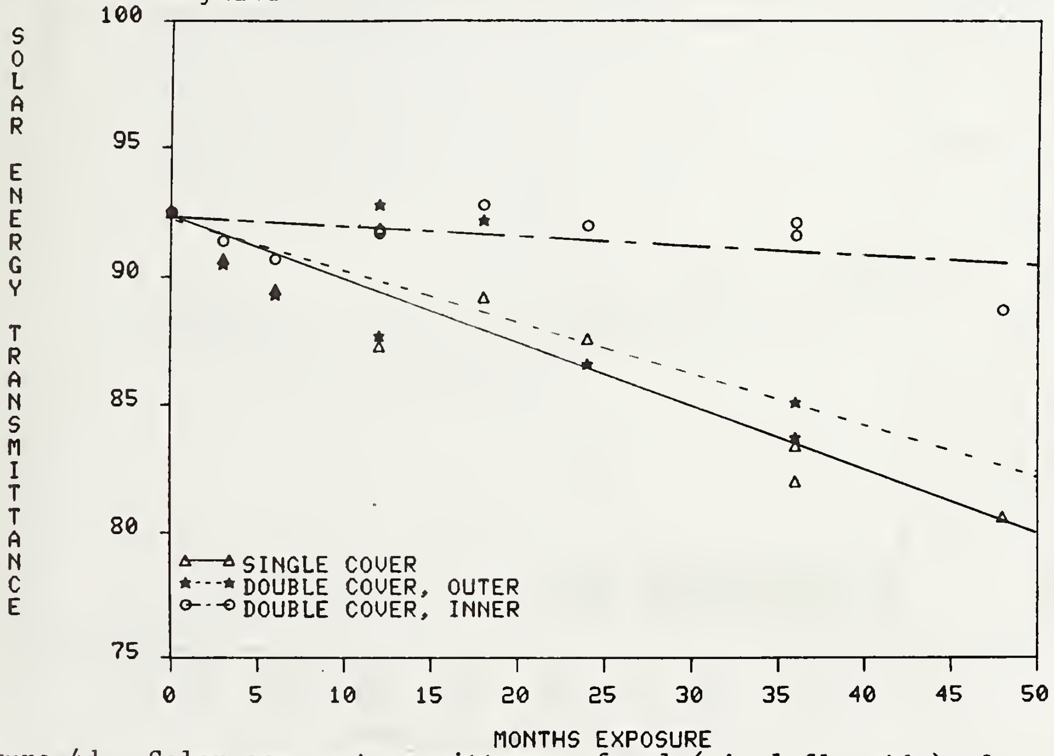


Figure 4d. Solar energy transmittance of poly(vinyl fluoride) after weathering on minicollectors in Gaithersburg, Maryland

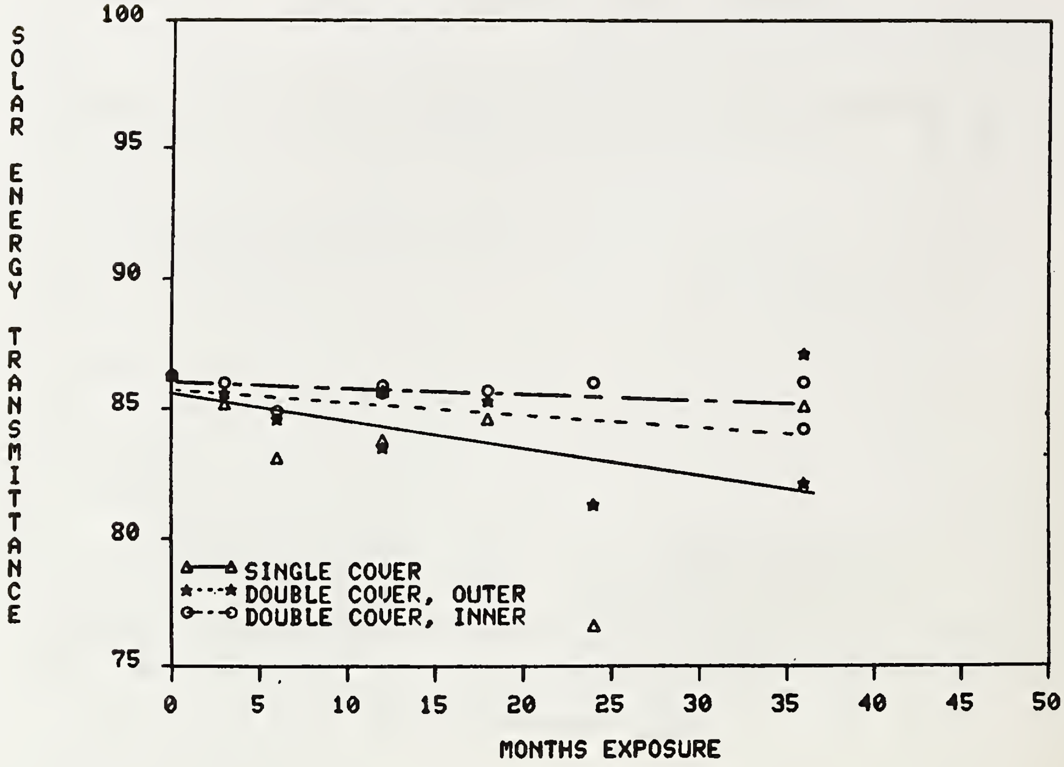


Figure 4e. Solar energy transmittance of poly(ethylene terephthalate) after weathering on minicollectors in Gaithersburg, Maryland

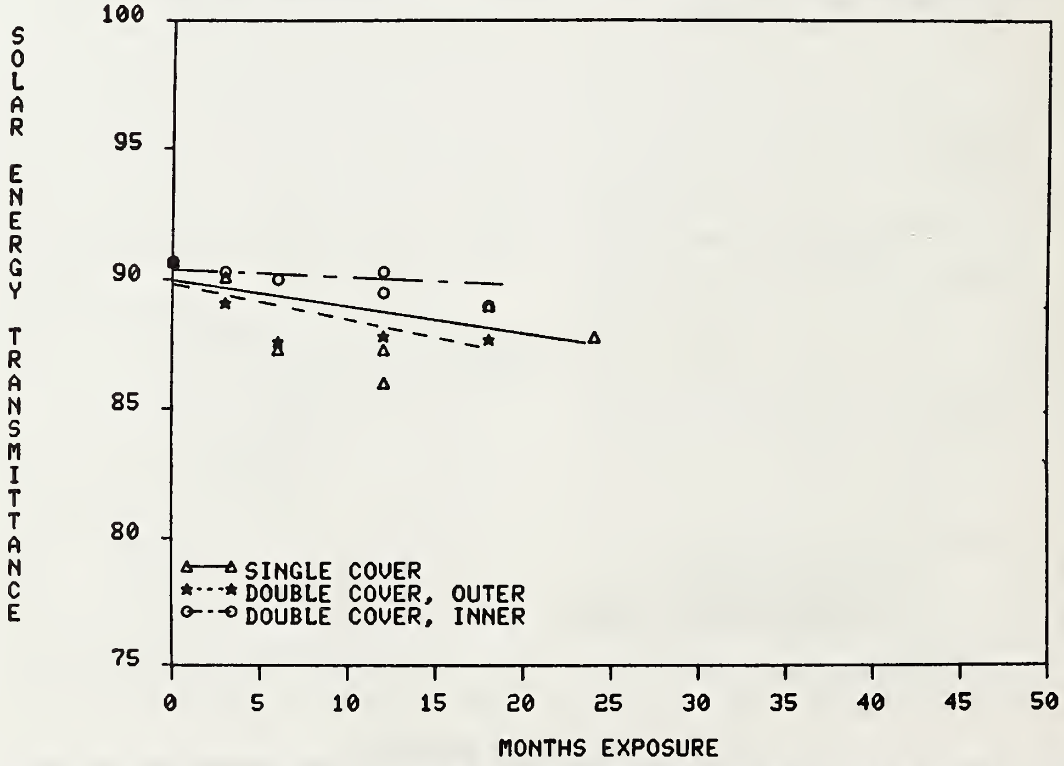


Figure 4f. Solar energy transmittance of acrylic film after weathering on minicollectors in Gaithersburg, Maryland

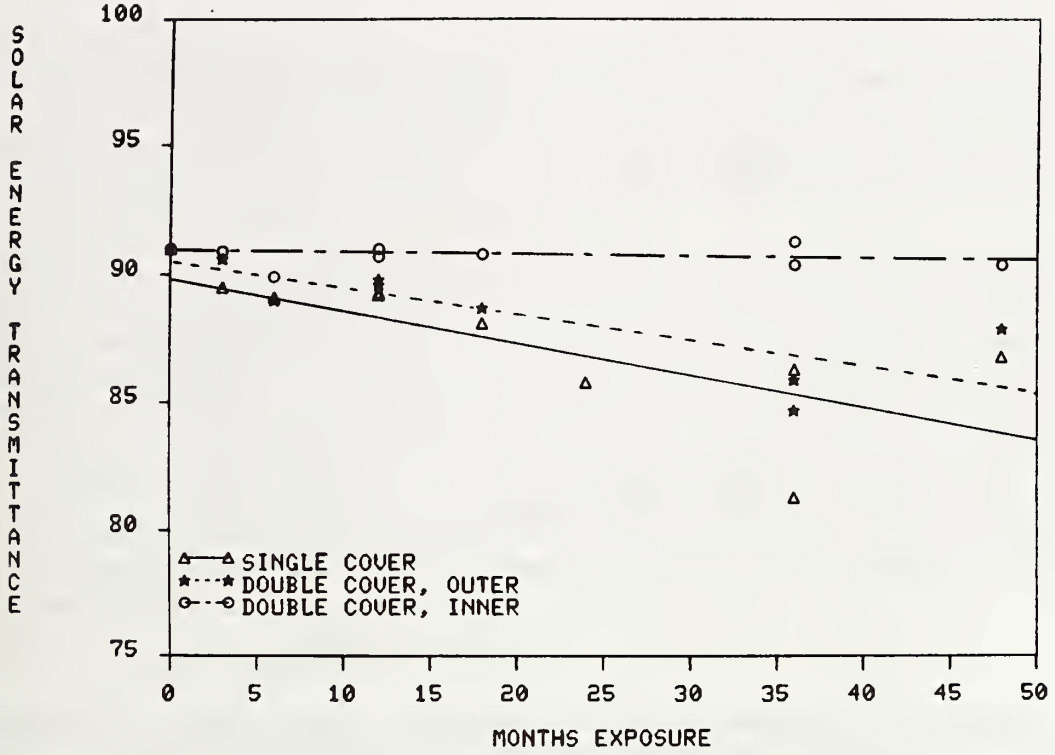


Figure 4g. Solar energy transmittance of poly(methyl methacrylate) after weathering on minicollectors in Gaithersburg, Maryland

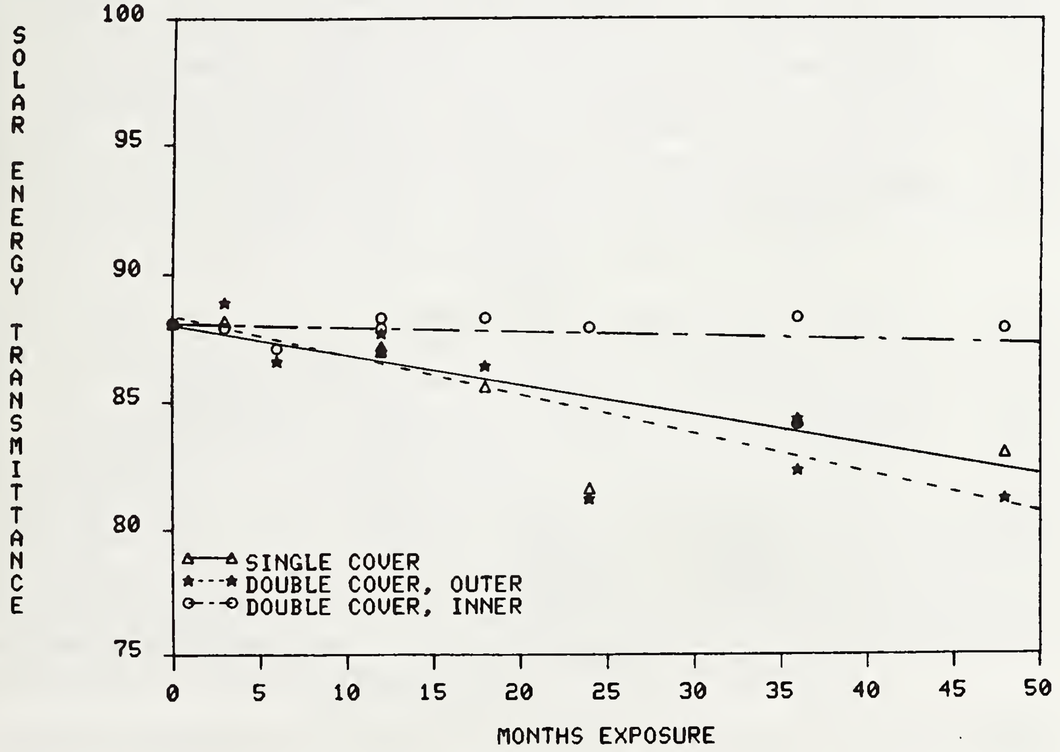


Figure 4h. Solar energy transmittance of polycarbonate after weathering on minicollectors in Gaithersburg, Maryland

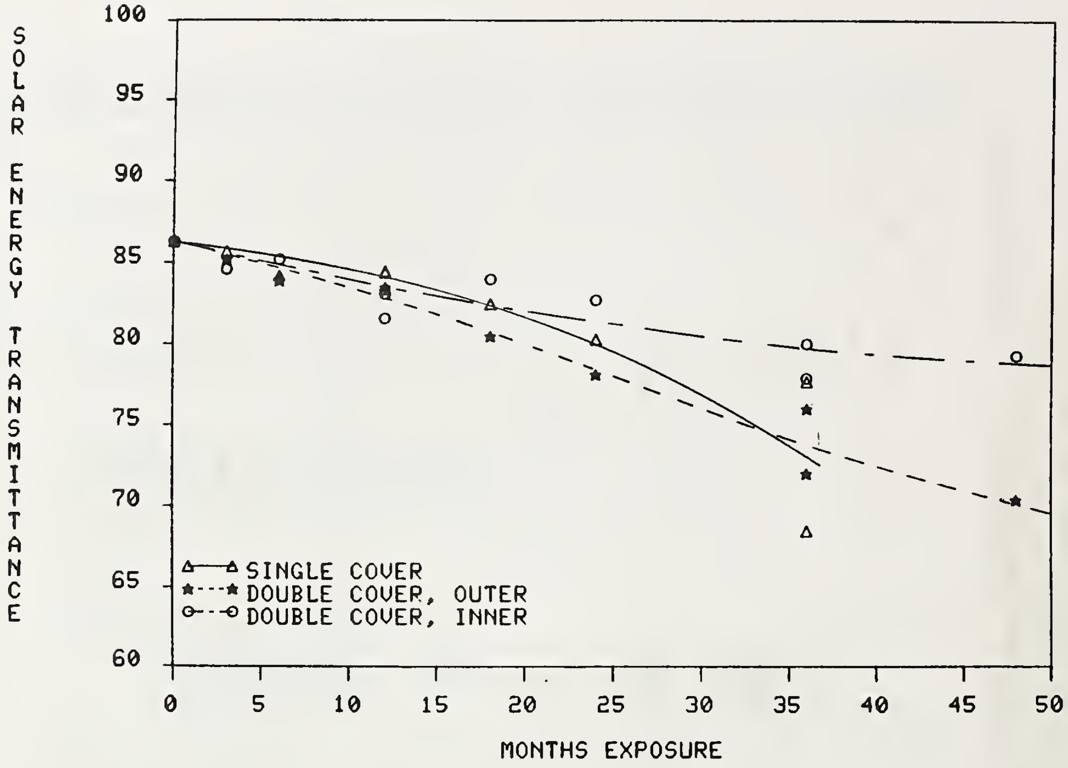


Figure 4i. Solar energy transmittance of fiber reinforced plastic (1.00 mm) after weathering on minicollectors in Gaithersburg, Maryland

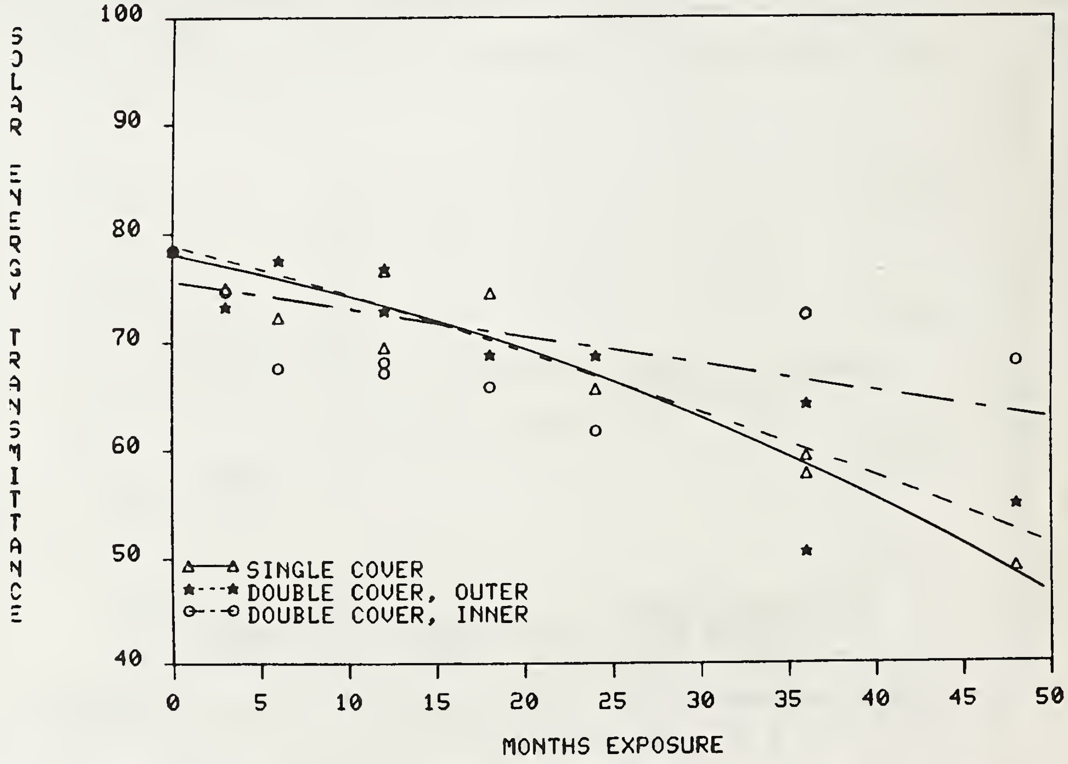


Figure 4j. Solar energy transmittance of fiber reinforced plastic (1.5 mm) after weathering on minicollectors in Gaithersburg, Maryland

identical weathering with the exception of temperature. With the minicollector exposure the single cover attains a higher temperature than the outer double cover. Since the combination of elevated temperature and sunlight can have synergistic effects in degrading materials, the somewhat higher temperature of single covers is probably the cause of the greater losses of the single covers than the double outer covers.

Data for the solar transmittance values are given in Appendix A. The solar energy transmittance after weathering in Gaithersburg is tabulated in table A1 for single covers and in table A2 for double covers. Transmittance losses due to weathering are listed in table A3 for single covers and table A4 for double covers. The solar energy transmittance losses due to the surface dirt on the materials are listed in table A5 for single covers and table A6 for double covers. For the single and outer double covers the dirt accumulation increased for the first 12 months after which it tended to level off or decrease. For the inner double covers the transmittance losses were generally less than one percent and were not cumulative with time, except for the fluorinated (ethylene propylene) copolymer.

### 3.2.2 Miami, Florida Exposure

The solar energy transmittance of single and double covers after natural weathering in Miami is compared for each cover material in figures 5a to 5j. The transmittance measurements were made after the test specimens were washed. Again, in general, the inner cover lost the least transmittance. For the glass materials there was little loss of transmittance. For the other materials, the outer double and single covers showed greater transmittance losses, the rates generally being similar. Contrary to most of the other materials, the outer double polycarbonate and FRP covers had a greater rate of loss than the single covers. The two fiber reinforced plastics suffered significant deterioration, apparently due to the combination of moisture, heat, and sunlight. For both FRP materials the transmittance of the inner cover decreased substantially while the outer and single covers declined at faster rates. Figures 5i and 5j illustrate the losses in the FRP materials.

The solar energy transmittance values after weathering in Miami are tabulated in table A7 for single covers and table A8 for double covers. Transmittance losses due to weathering are given in tables A9 and A10 for single and double covers. The solar energy transmittance losses due to accumulation of dirt are given in table A11 for single covers and table A12 for double covers. Dirt caused decreases in transmittance for a number of materials. For any given time period, all the materials seemed to be high or low, comparatively, in the transmittance loss. This may have been related to the most recent rainfall prior to completion of the weathering. Transmittance losses for the inner covers seemed to increase as the weathering continued. The poor conditions of the minicollector boxes after many months of weathering may have permitted dirt to enter and accumulate during the weathering.

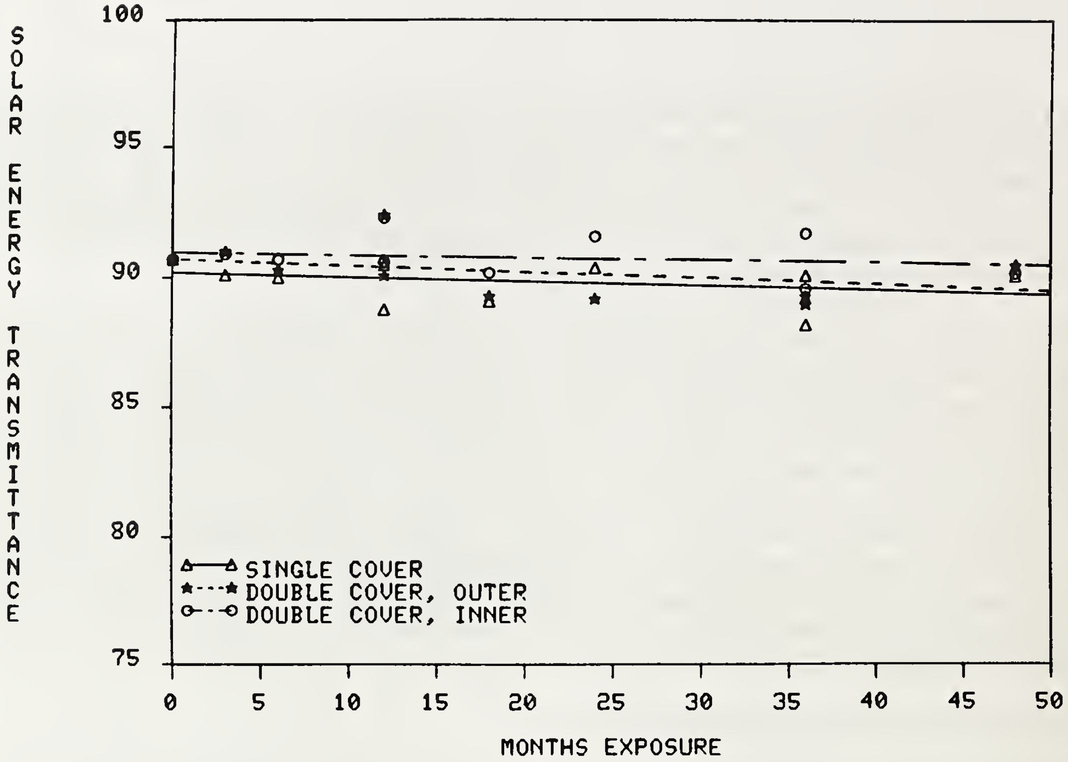


Figure 5a. Solar energy transmittance of glass (0.01% iron oxide) after weathering on minicollectors in Miami, Florida

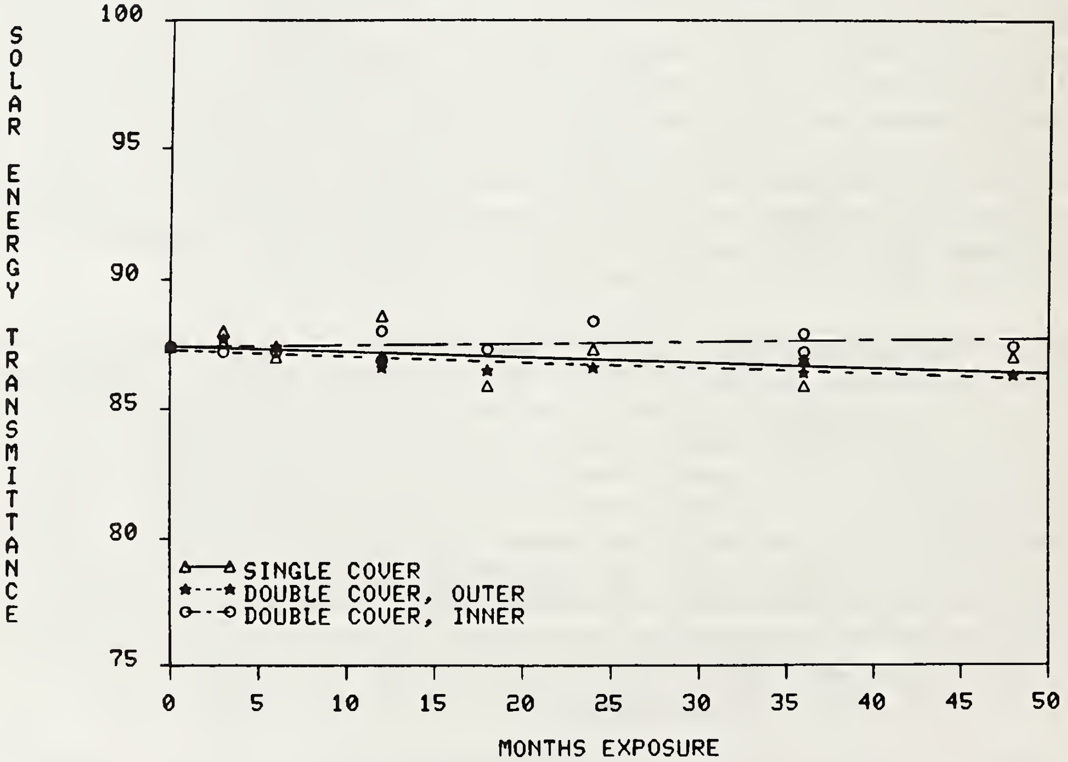
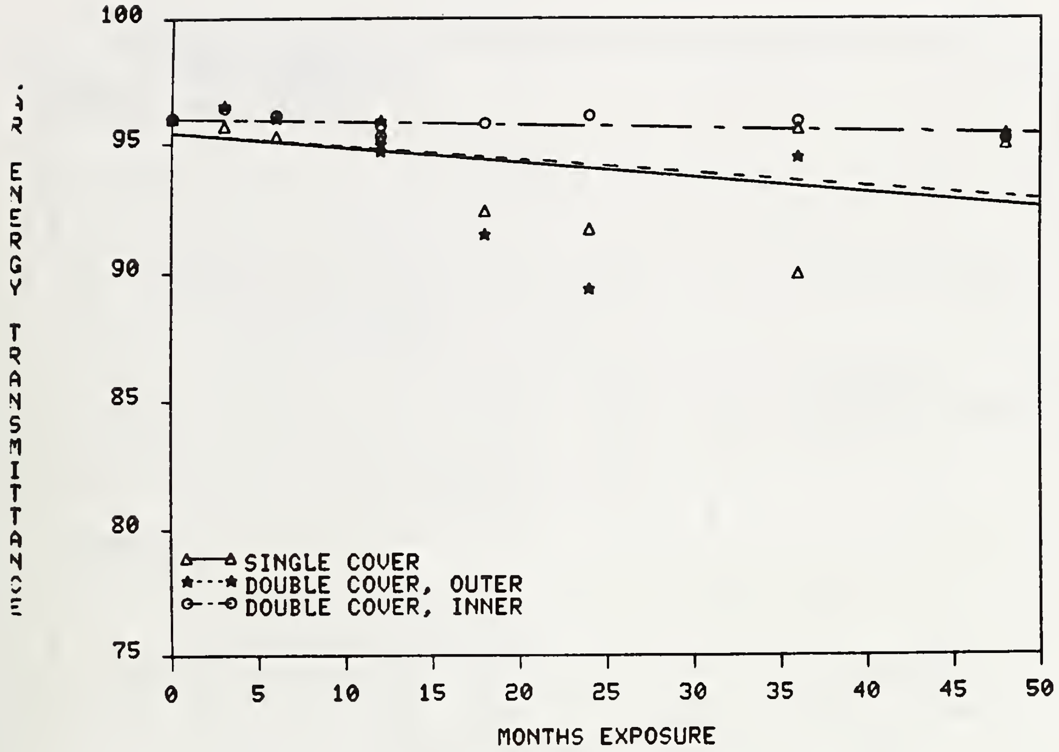


Figure 5b. Solar energy transmittance of glass (0.10% iron oxide) after weathering on minicollectors in Miami, Florida



igure 5c. Solar energy transmittance of fluorinated (ethylene propylene) after weathering on minicollectors in Miami, Florida

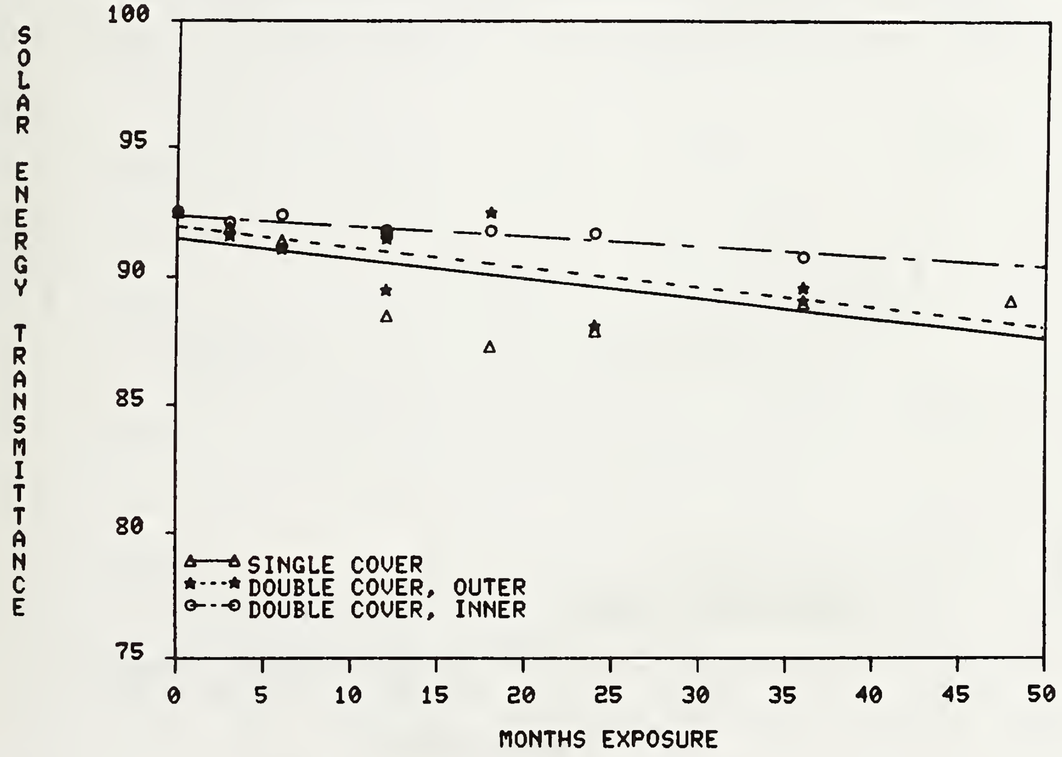


Figure 5d. Solar energy transmittance of poly(vinyl fluoride) after weathering on minicollectors in Miami, Florida

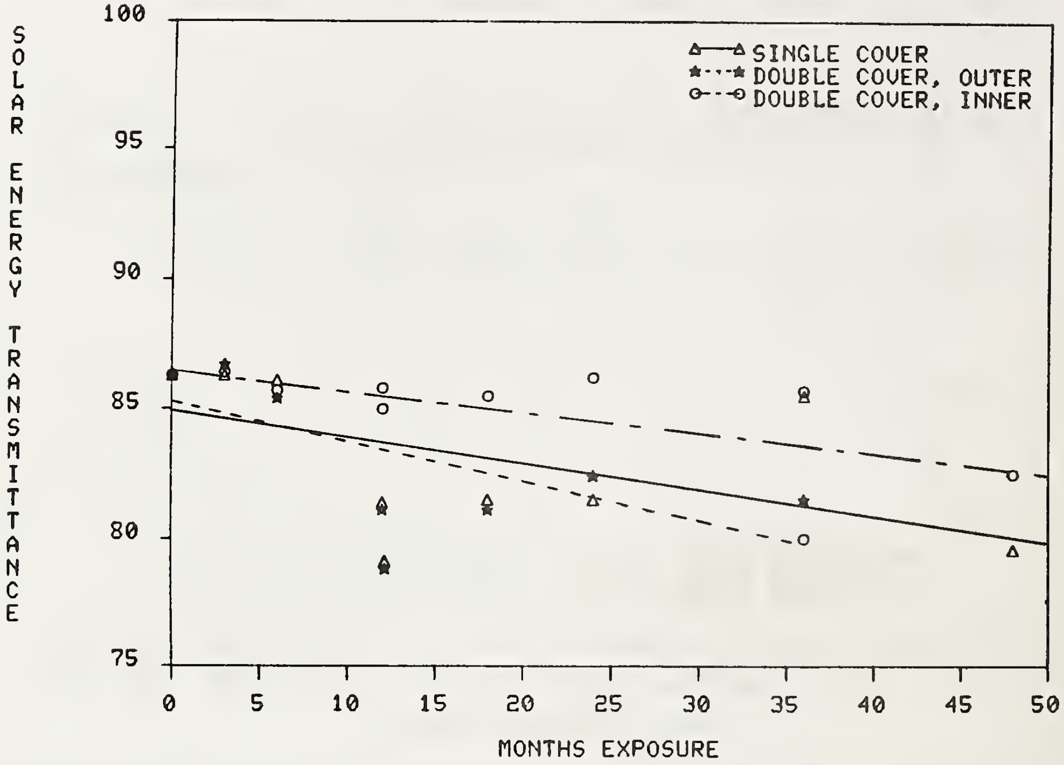


Figure 5e. Solar energy transmittance of poly(ethylene terephthalate) weathering on minicollectors in Miami, Florida

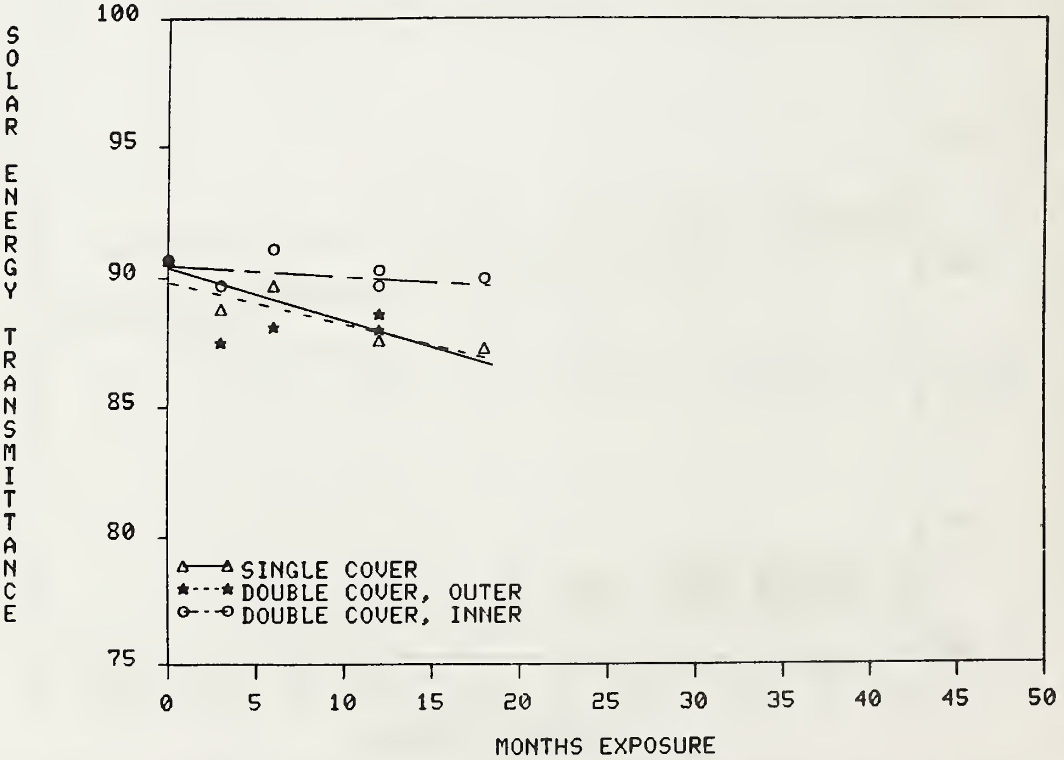


Figure 5f. Solar energy transmittance of acrylic film after weathering on minicollectors in Miami, Florida

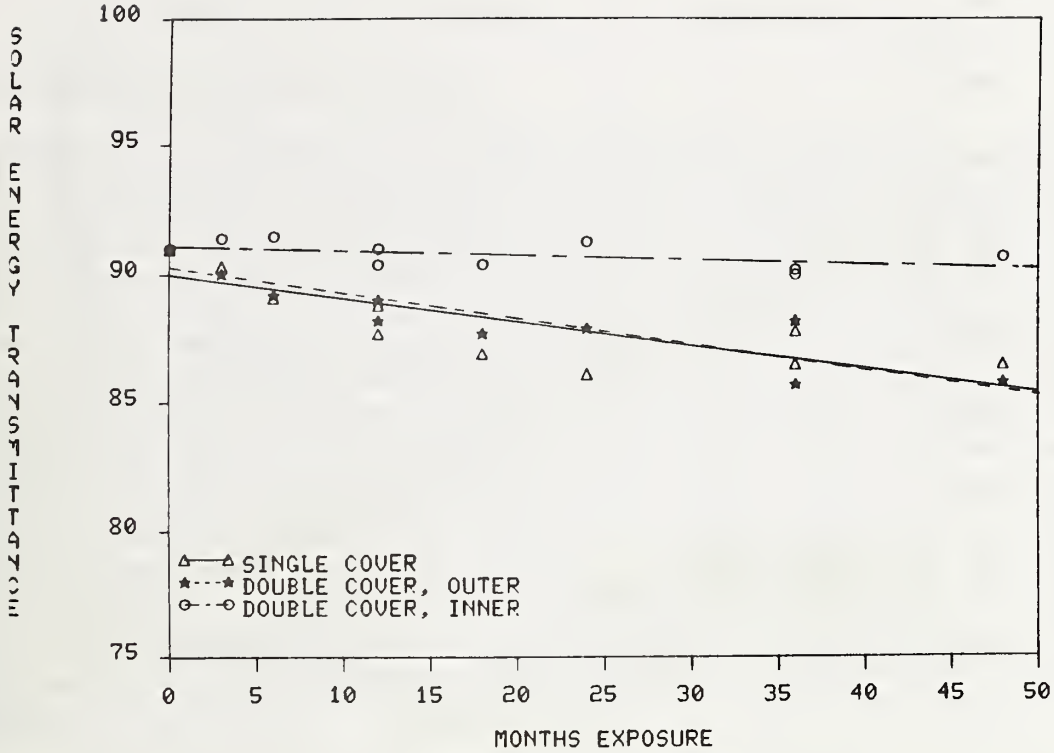


Figure 5g. Solar energy transmittance of poly(methyl methacrylate) after weathering on minicollectors in Miami, Florida

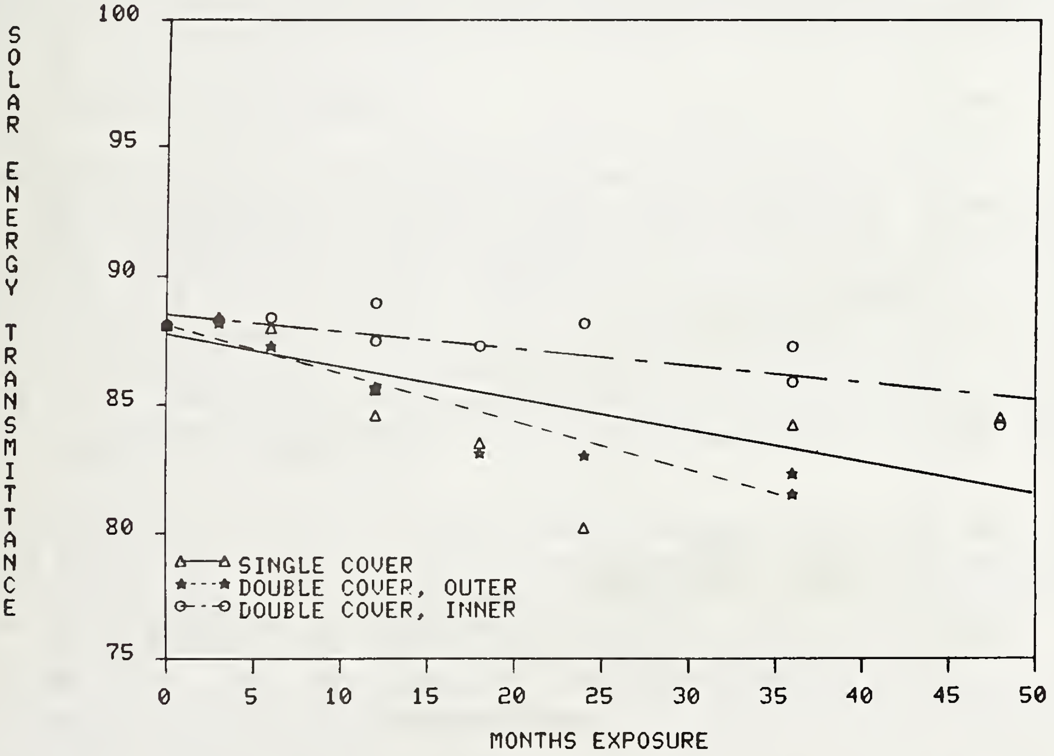


Figure 5h. Solar energy transmittance of polycarbonate after weathering on minicollectors in Miami, Florida

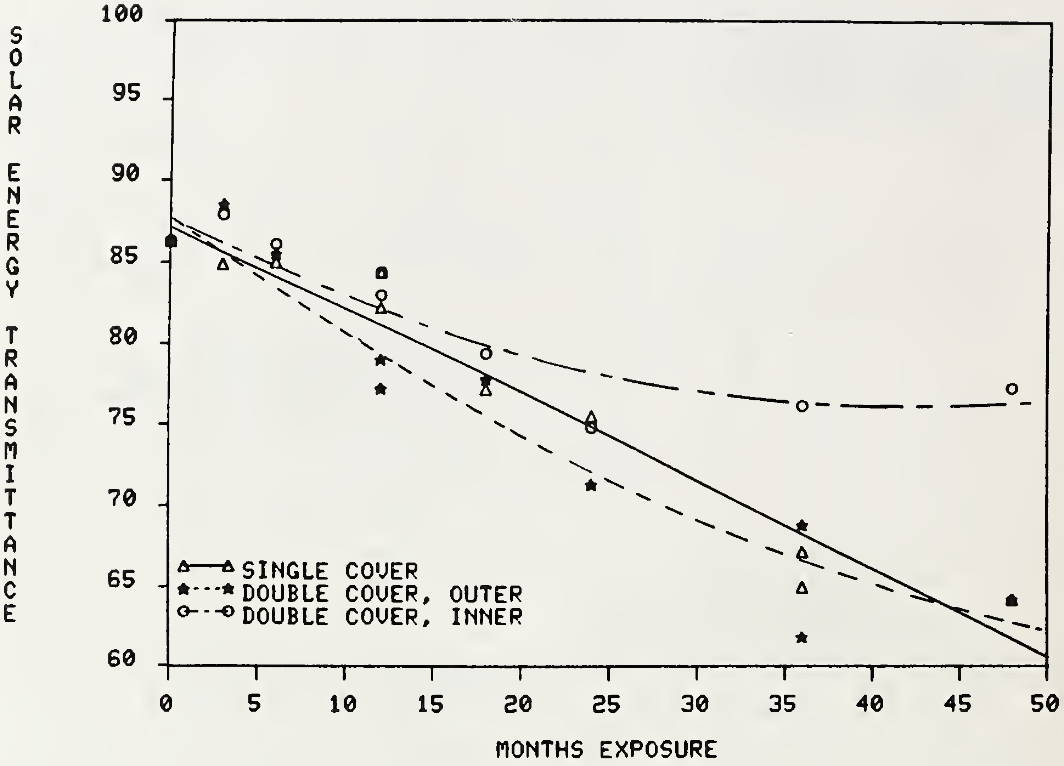


Figure 5i. Solar energy transmittance of fiber reinforced plastic (1.0 mm) after weathering on minicollectors in Miami, Florida

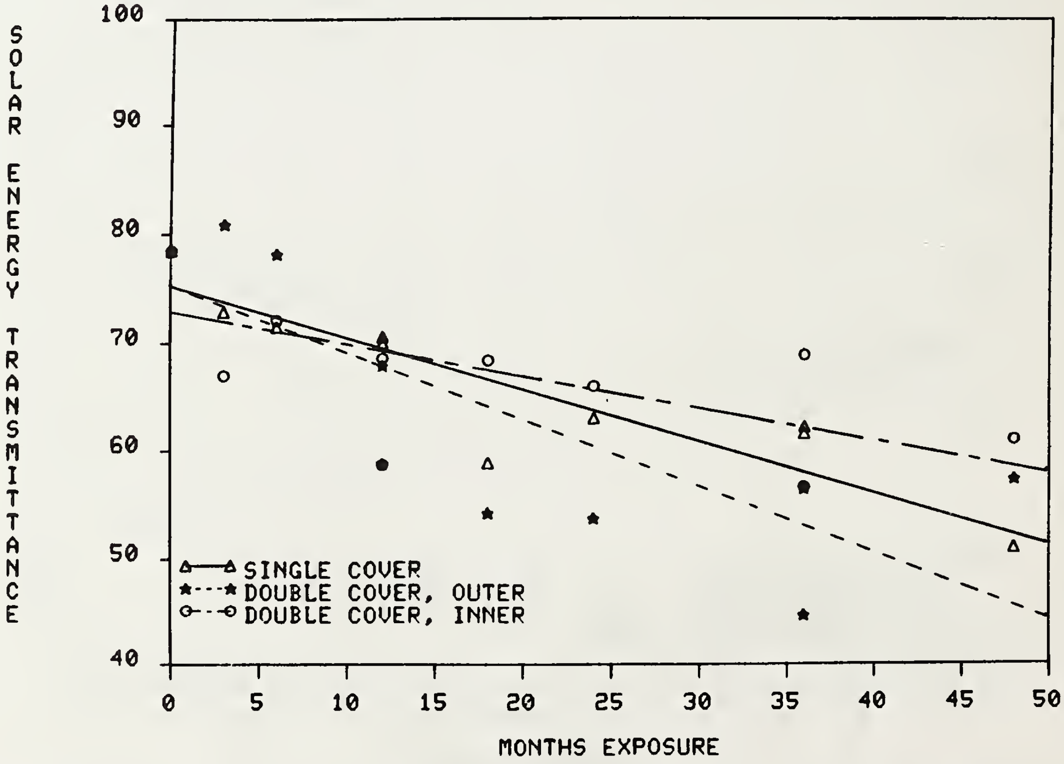


Figure 5j. Solar energy transmittance of fiber reinforced plastic (1.5 mm) after weathering on minicollectors in Miami, Florida

### 3.2.3 New River, Arizona Exposure

The solar energy transmittance of single and double covers after natural weathering in New River is compared for each cover material in figures 6a to 6j. The materials were washed prior to these measurements. The corresponding solar energy transmittance values are tabulated in tables A13 for single covers and table A14 for double covers. The values for the transmittance losses caused by the weathering are listed in tables A15 and A16. With the exception of fluorinated (ethylene propylene) copolymer, the film materials did not hold up well in the weathering. Most of the film test specimens failed by the 18th month of exposure. The glass materials and the fluorinated (ethylene propylene) copolymer showed very little change in transmittance. For the other materials the inner cover generally declined less than the covers exposed directly to sunlight. The single and outer double covers usually decreased at at rates much faster than the inner cover. The fiber reinforced materials had the greatest transmittance losses, exceeding 12 percent for the single and outer double covers after 48 months. Figure 6j illustrates that the outer cover of the 1.5 mm fiber reinforced plastic declined less than the inner and single covers. This indicates that the transmittance loss is caused by more than sunlight. The early drop in the inner cover values point toward elevated temperature as a factor.

Transmittance losses resulting from dirt accumulation are listed in table A17 for single covers and table A18 for double covers. Dirt accumulation fluctuated somewhat for the various time periods. For the longest periods, the fiber reinforced materials and the fluorinated (ethylene propylene) copolymer seemed to collect the most dirt.

### 3.2.4 Comparison of Exposures

The materials followed the same general trends at all three locations. The glass cover plate materials were not changed significantly by the weathering. The fluorinated (ethylene propylene) transmittance shown in figure 7a remained virtually unchanged after natural weathering as an inner cover and artificial weathering with a xenon arc light. However, both the outer and single cover specimens declined about five percent at Florida and Gaithersburg. Figure 7b illustrates this declined. Both figures 7a and 7b have the transmittance plotted versus cumulative solar radiation at each site, rather than months exposure. This was done to illustrate the effects of total sunlight exposure rather than total time exposure.

The inner poly(vinyl fluoride) cover deteriorated most rapidly at New River, followed by Miami. The deterioration caused the material to become brittle and crumble. The transmittance of the outer and single poly(vinyl fluoride) specimens decreased more at Gaithersburg and Miami than at New River.

The transmittance of the poly(ethylene terephthalate) declined more at Miami and Gaithersburg than at New River; however, the material became brittle at New River in about twelve months.

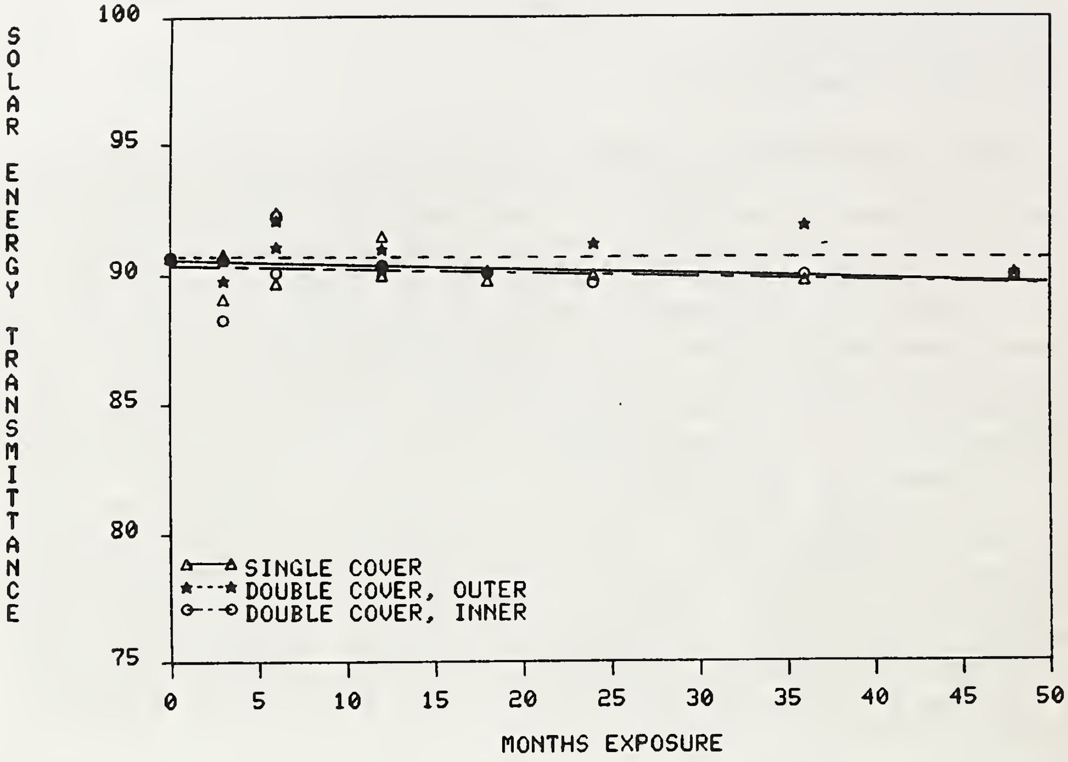


Figure 6a. Solar energy transmittance of glass (0.01% iron oxide) after weathering on minicollectors in New River, Arizona

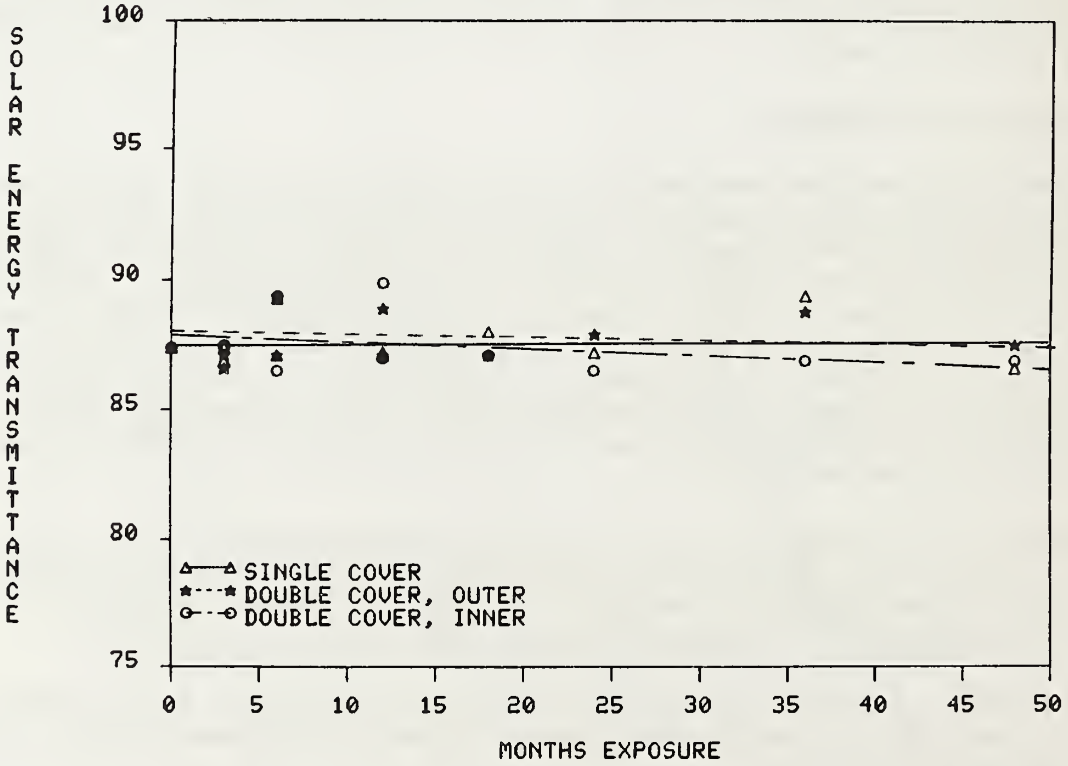


Figure 6b. Solar energy transmittance of glass (0.10% iron oxide) after weathering on minicollectors in New River, Arizona

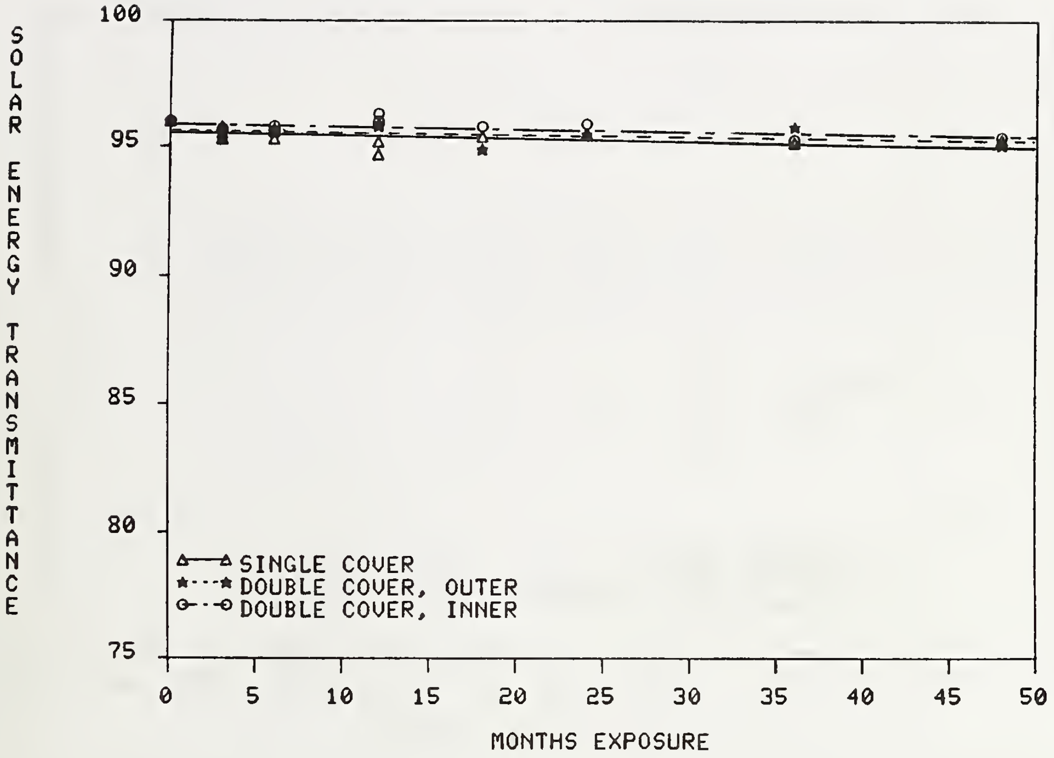


Figure 6c. Solar energy transmittance of fluorinated (ethylene propylene) copolymer after weathering on minicollectors in New River, Arizona

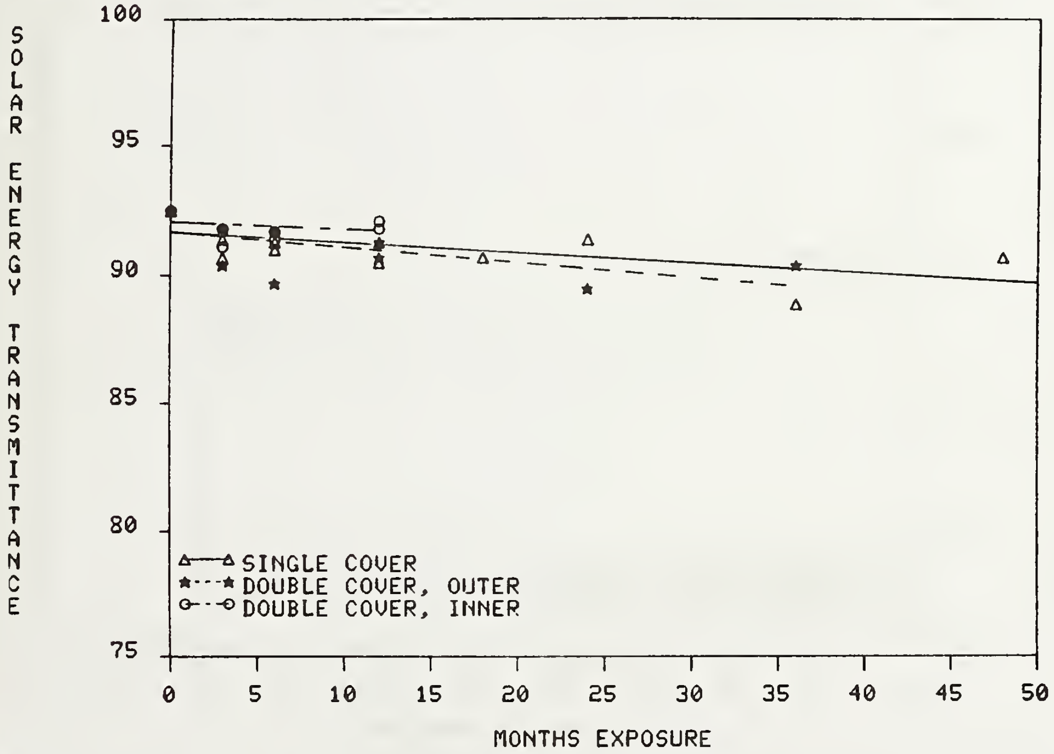


Figure 6d. Solar energy transmittance of poly(vinyl fluoride) after weathering on minicollectors in New River, Arizona

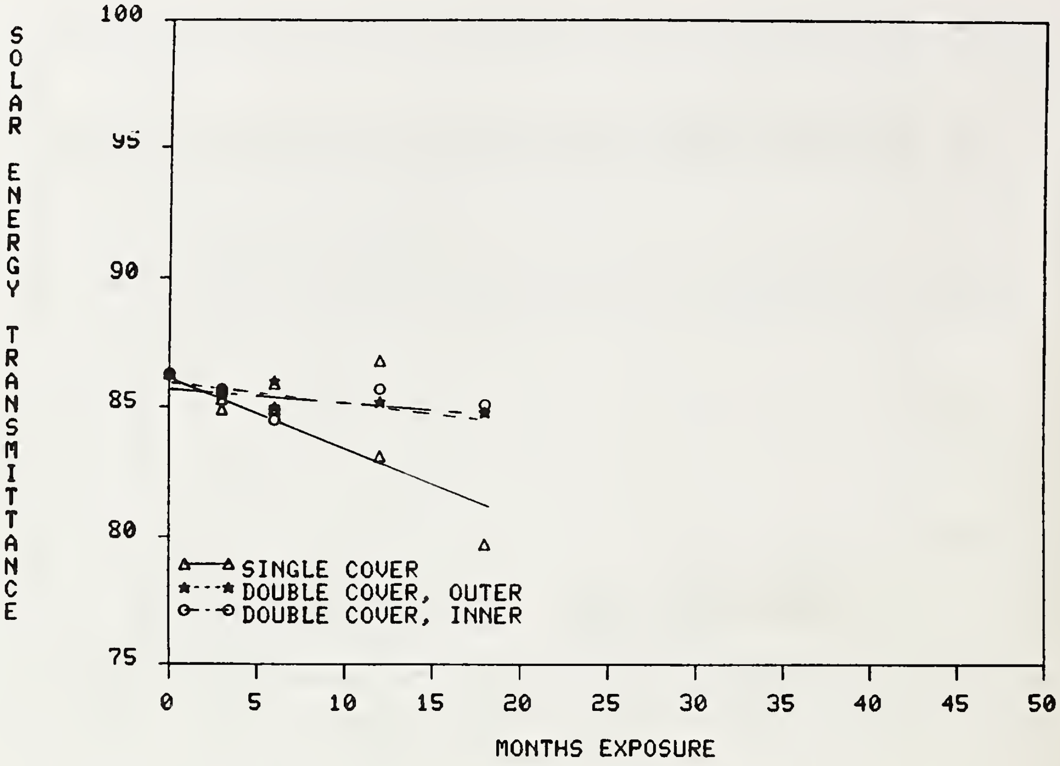


Figure 6e. Solar energy transmittance of poly(ethylene terephthalate) after weathering on minicollectors in New River, Arizona

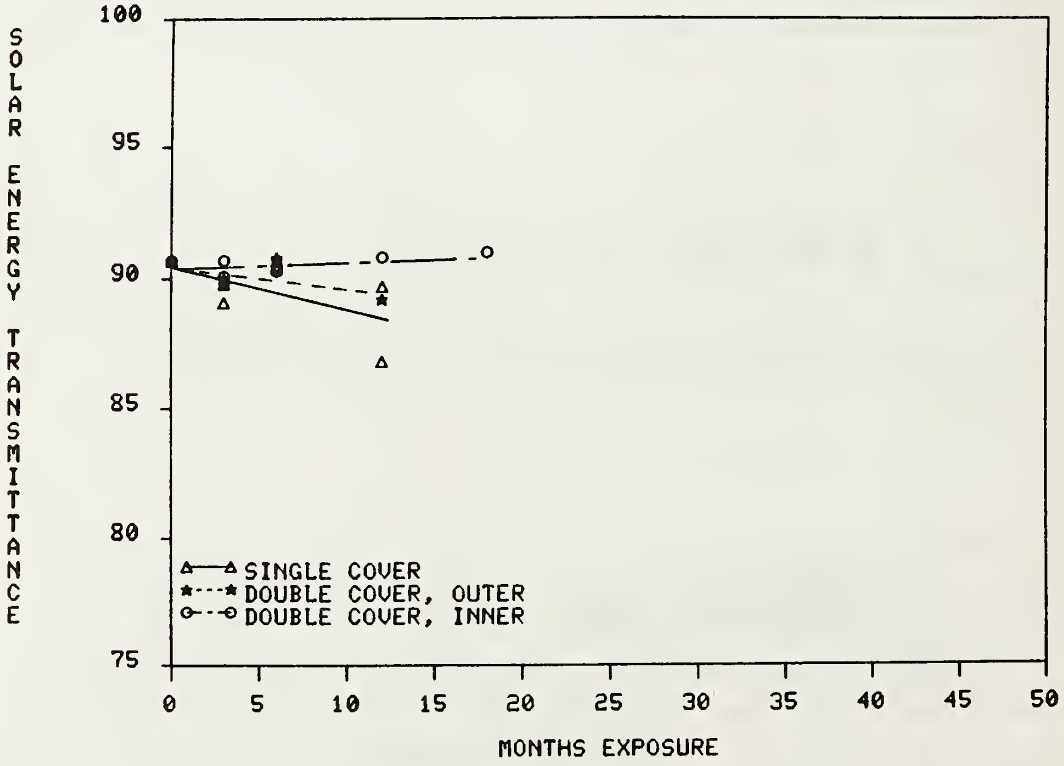


Figure 6f. Solar energy transmittance of acrylic film after weathering on minicollectors in New River, Arizona

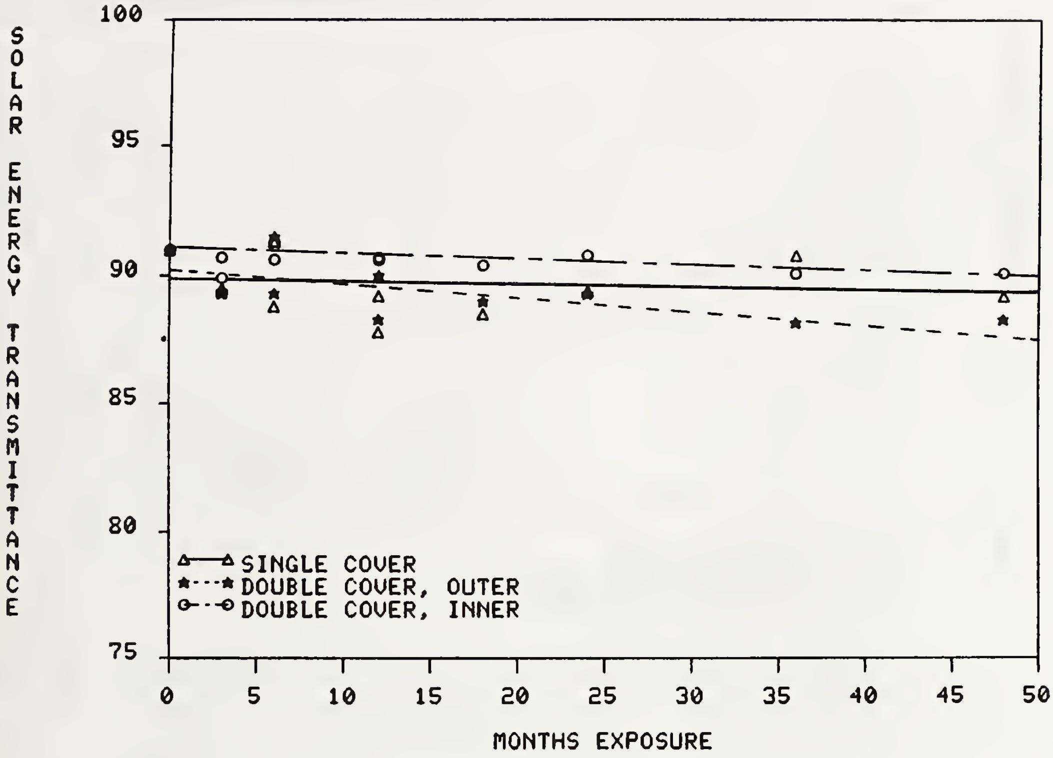


Figure 6g. Solar energy transmittance of poly(methyl methacrylate) after weathering on minicollectors in New River, Arizona

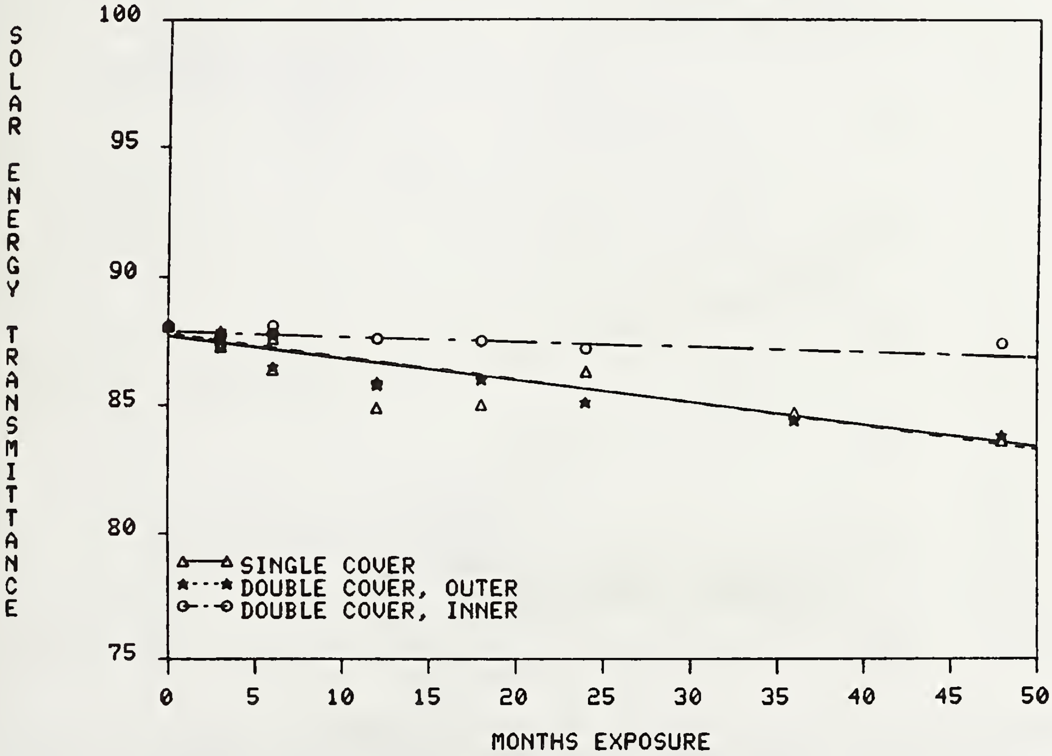


Figure 6h. Solar energy transmittance of polycarbonate after weathering on minicollectors in New River, Arizona

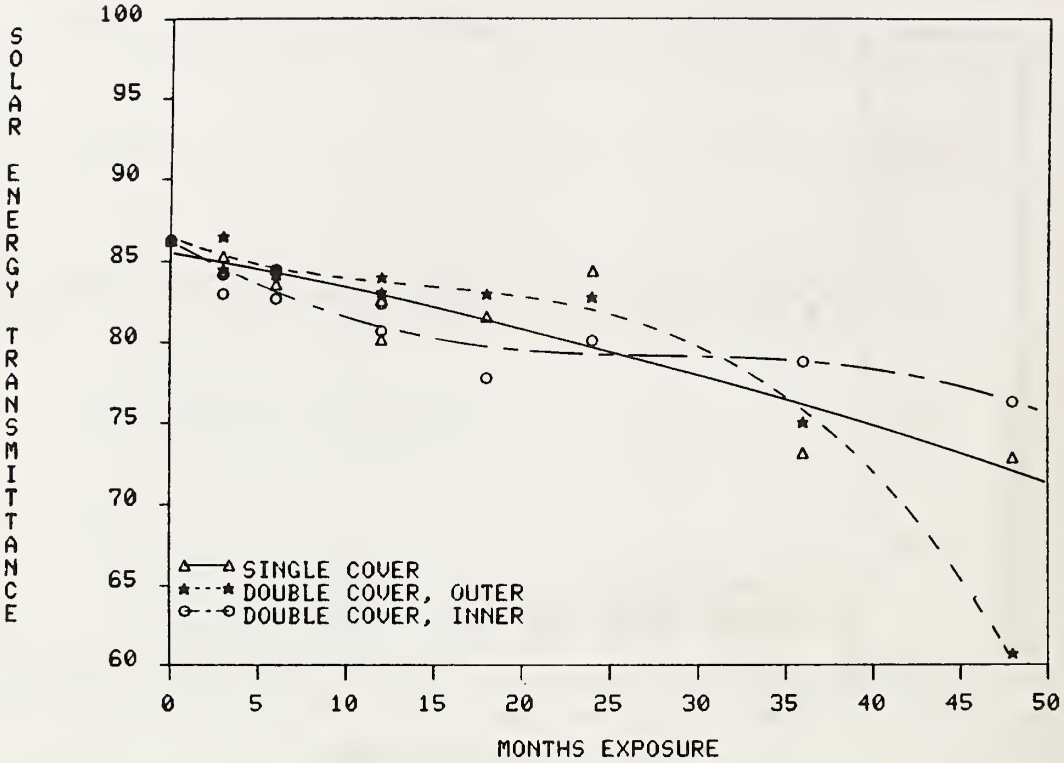


Figure 6i. Solar energy transmittance of fiber reinforced plastic (1.0 mm) after weathering on minicollectors in New River, Arizona

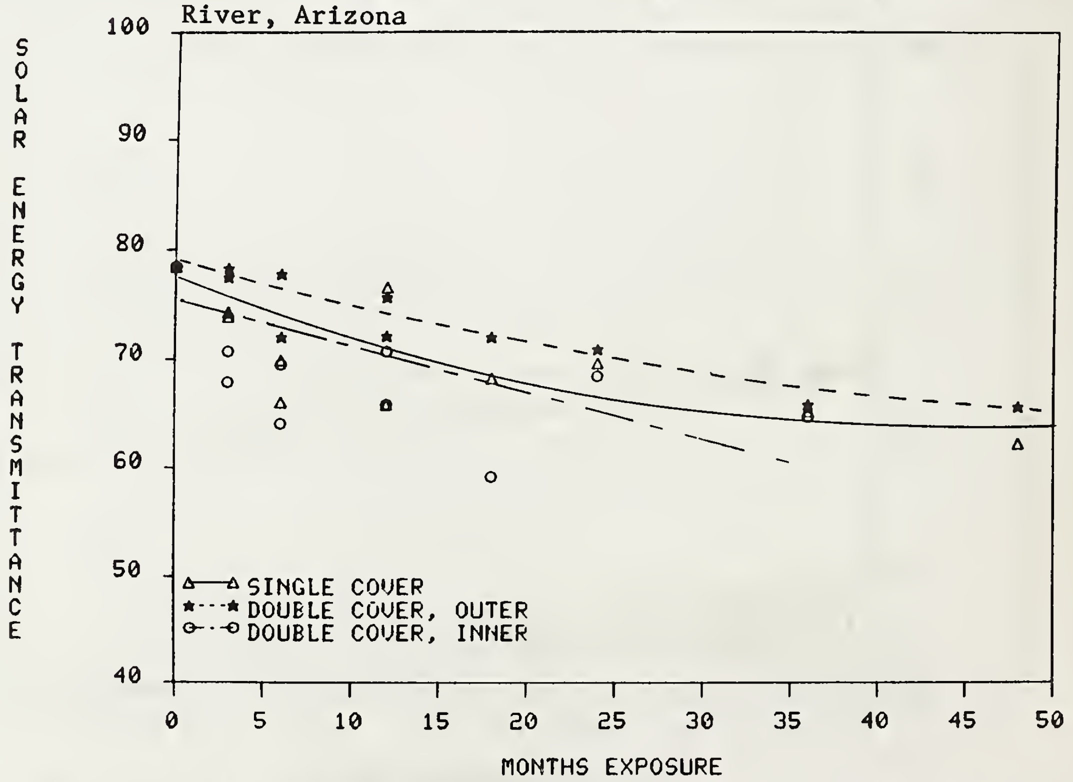


Figure 6j. Solar energy transmittance of fiber reinforced plastic (1.5 mm) after weathering on minicollectors in New River, Arizona

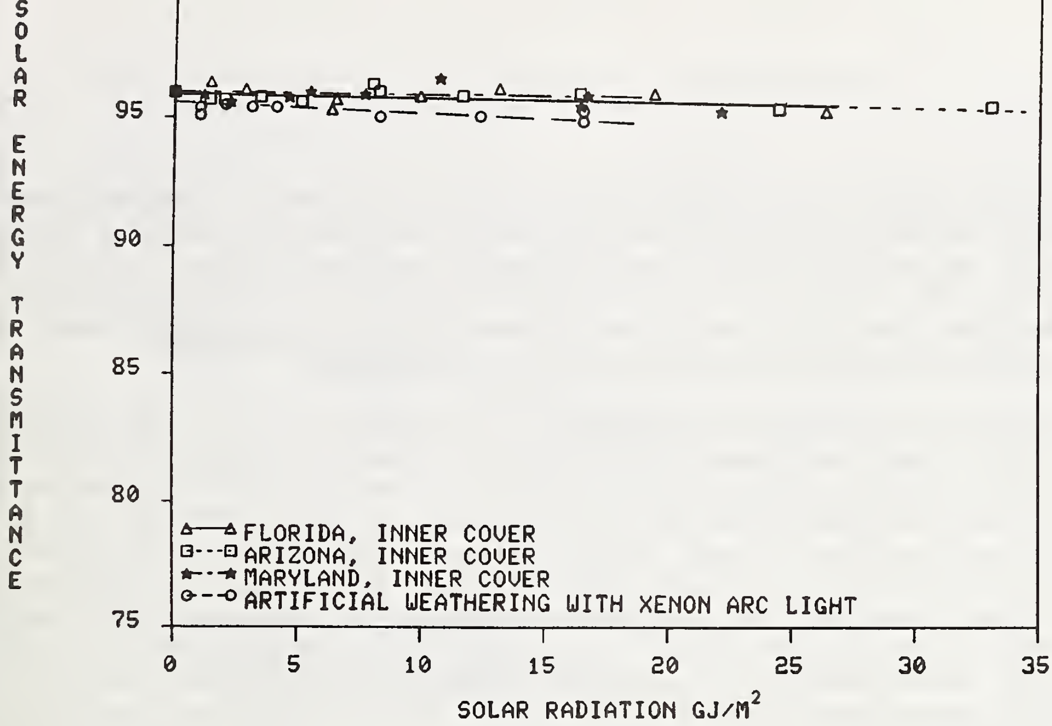


Figure 7a. Comparison of solar transmittance of fluorinated (ethylene propylene) copolymer after natural weathering as the inner cover of a minicollector and artificial weathering with xenon arc light

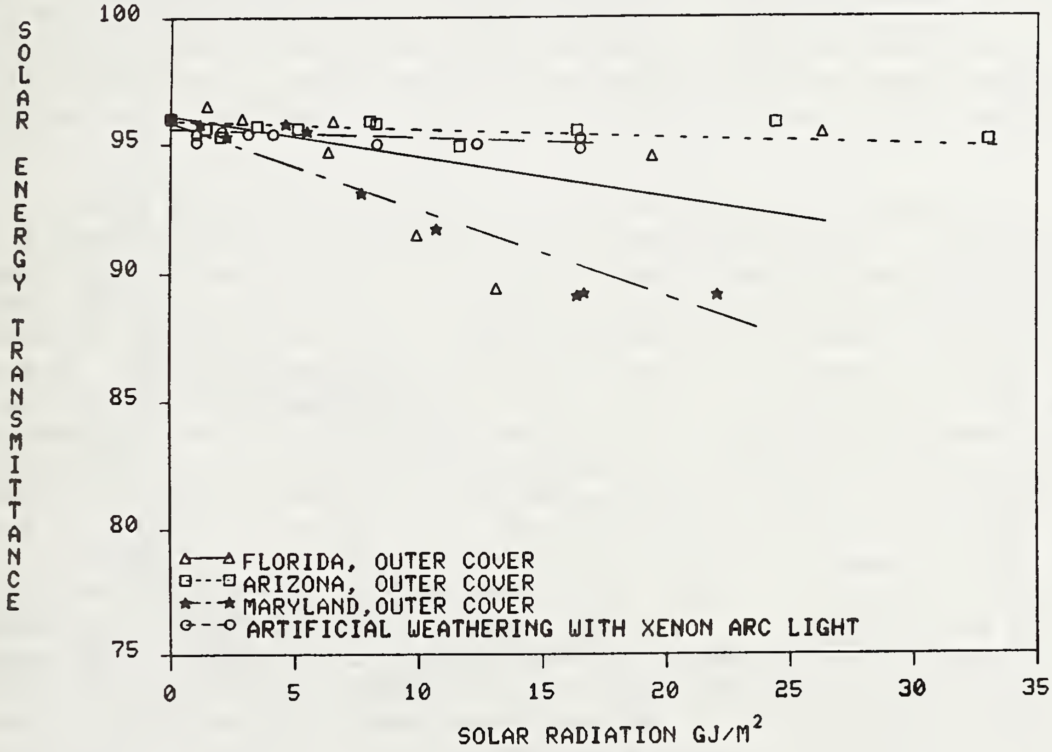


Figure 7b. Comparison of solar transmittance of fluorinated (ethylene propylene) copolymer after natural weathering as an outer cover of a minicollector and artificial weathering with xenon arc light

The acrylic film did not weather well at any of the sites. Failure occurred when the material physically deteriorated by cracking or crumbling into pieces. Generally, the material failed by the time it had been exposed to 12 GJ/$m^2$ of solar radiation. Failure occurred at New River first, followed by Miami. This indicates that the solar energy was interacting with the chemical bonds in the acrylic polymer resulting in degradation of the film.

The poly(methyl methacrylate) weathered comparatively well on the minicollectors. As an inner cover the transmittance remained relatively unchanged (<1%). For equal solar radiation exposure at the three sites, transmittance losses for the outer and single covers were one to three percent higher at Miami and Gaithersburg than at New River. These changes compared well with the data from artificial weathering with a xenon arc light. Figure 8 compares the transmittance of the outer covers and the specimens from xenon arc exposure. The rate of change was essentially the same for the test specimens from New River and the artificial weathering. Both represent exposures of high solar energy intensity with minimal moisture. (Arizona has little rain and the artificial weathering was done without water spray.) The decreases in transmittance from Miami and Gaithersburg exposures were similar. These exposures involved moisture from rain, dew, and humidity.

Polycarbonate also weathered comparatively well. The outer and single cover materials lost somewhat more transmittance at Miami and Gaithersburg than at New River, for equal solar radiation exposure. The decrease in transmittance at New River compared well with the xenon arc data. Again the transmittance decreases at Miami and Gaithersburg were similar. The transmittance of the outer covers and the test specimens from xenon arc exposure are compared in figure 9.

The fiber reinforced plastics showed the greatest decreases in solar transmittance. The transmittance of the inner covers of both materials declined less than the single and outer covers. The 1.5 mm material changed significantly more than the 1.0 mm material. For equal solar radiation exposure as single or outer double covers, the Florida and Maryland exposures caused greater decreases in solar transmittance than did Arizona. This seems to indicate that factors in additional to sunlight and heat were causing the changes. Most likely, the presence of more moisture at these locations contributed to the deterioration. Figure 10a shows the solar transmittance as a function of solar radiation exposure for the 1.0 mm FRP material as an outer cover, and figure 10b illustrates the same as a function of months of exposure. Figures 10a illustrates that the transmittance loss due to artificial weathering with xenon arc light exposure (sunlight with minimal heat and no moisture) was less than for exposures at any of the three outdoor weathering sites. Clearly, the degradation is not due to sunlight alone. When comparing the transmittance as a function of solar radiation (figure 10a), the rate of decline was rapid at Miami, followed by Gaithersburg and New River. However when comparing transmittance as a function of months exposure (figure 10b), the rate of decline for New River is greater than Gaithersburg. Nevertheless, by comparing figures 10a and 10b it can be seen that the same trends (rapid decline in solar transmittance) occurred.

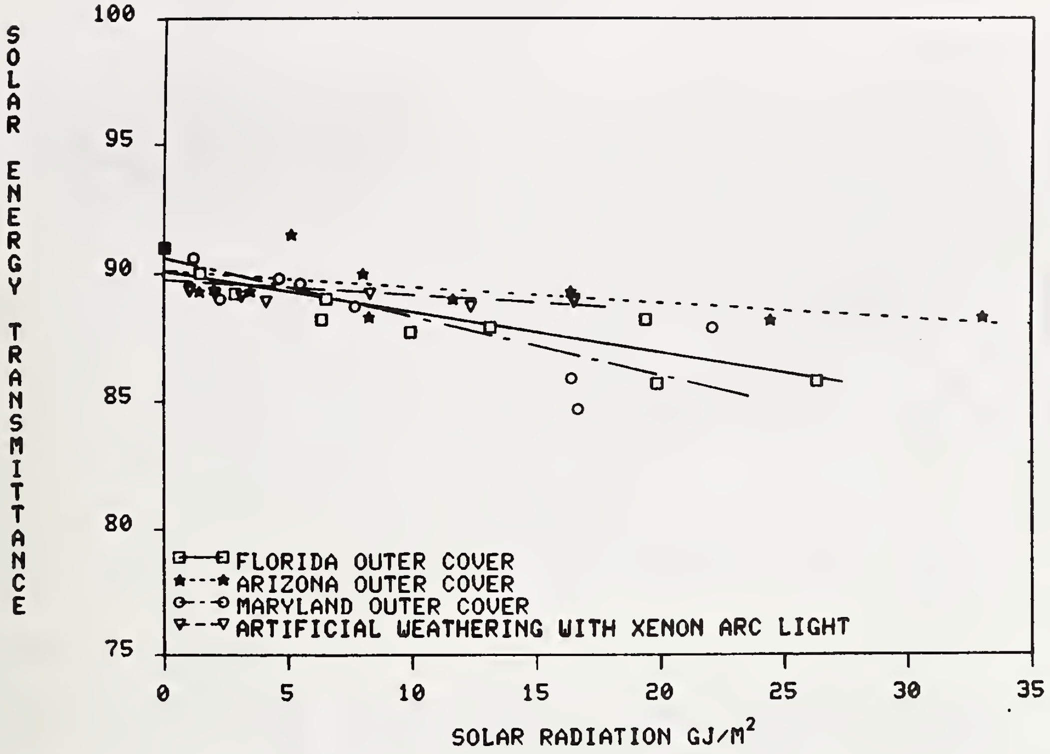


Figure 8. Comparison of solar transmittance of poly(methyl methacrylate) after weathering on a minicollector as an outer cover and in an artificial weathering device with xenon arc light

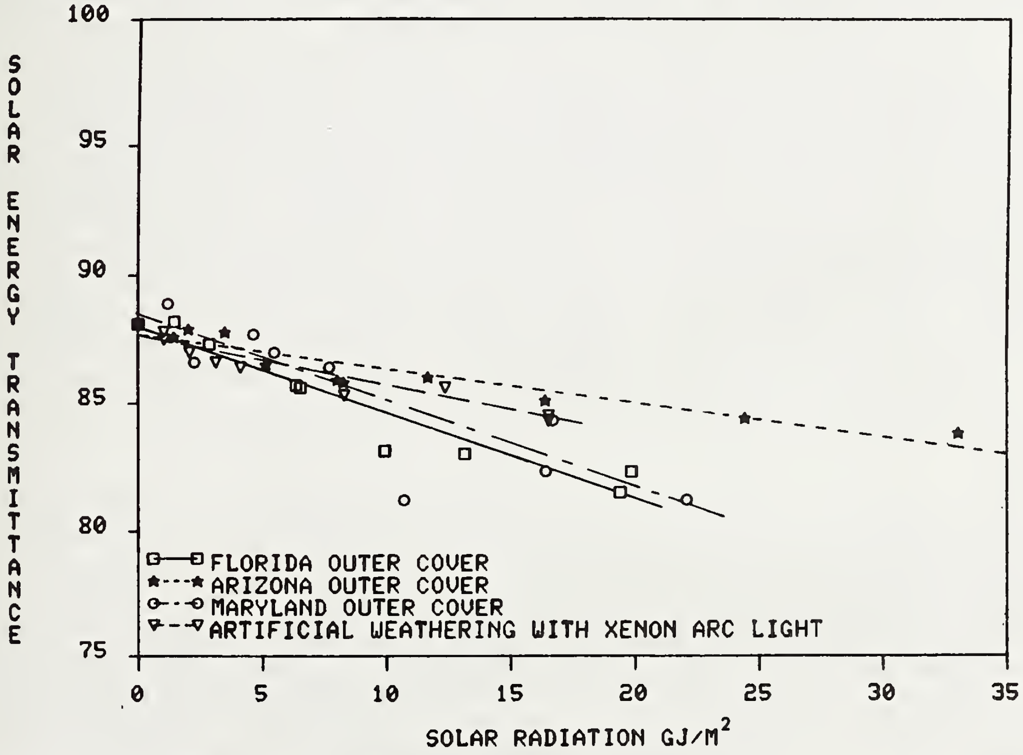


Figure 9. Comparison of solar transmittance of polycarbonate after weathering on a minicollector as an outer cover and in an artificial weathering device with xenon arc light

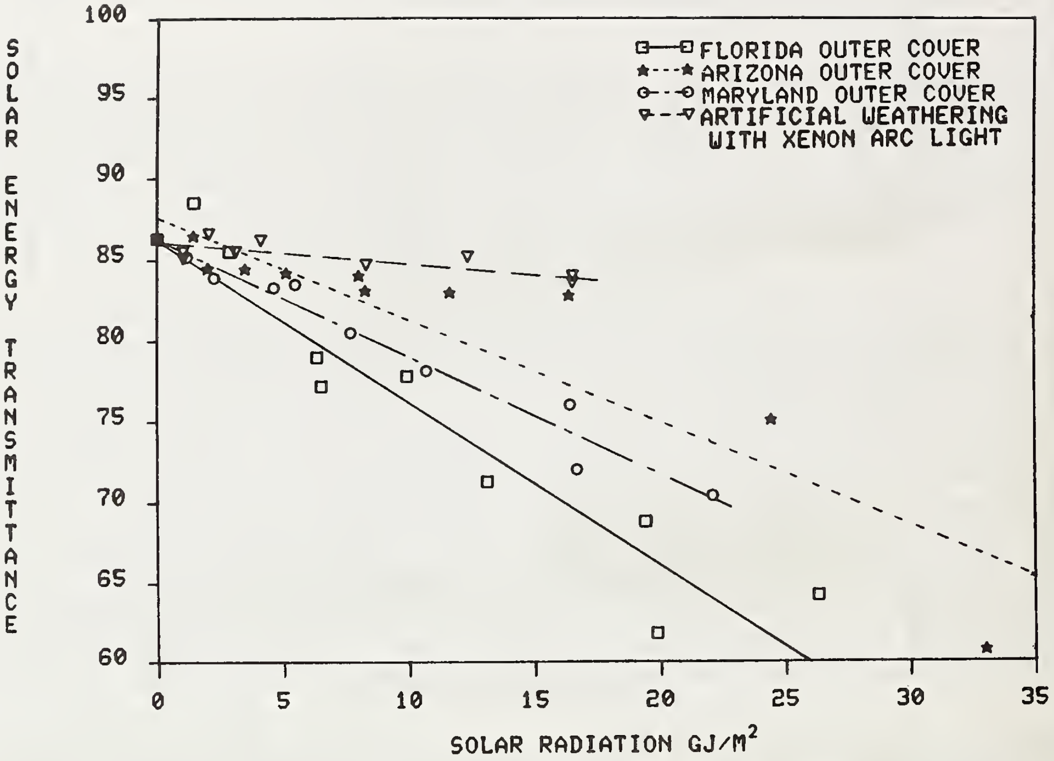


Figure 10a. Solar transmittance of fiber reinforced plastic (1.0 mm) as a function of solar radiation exposure

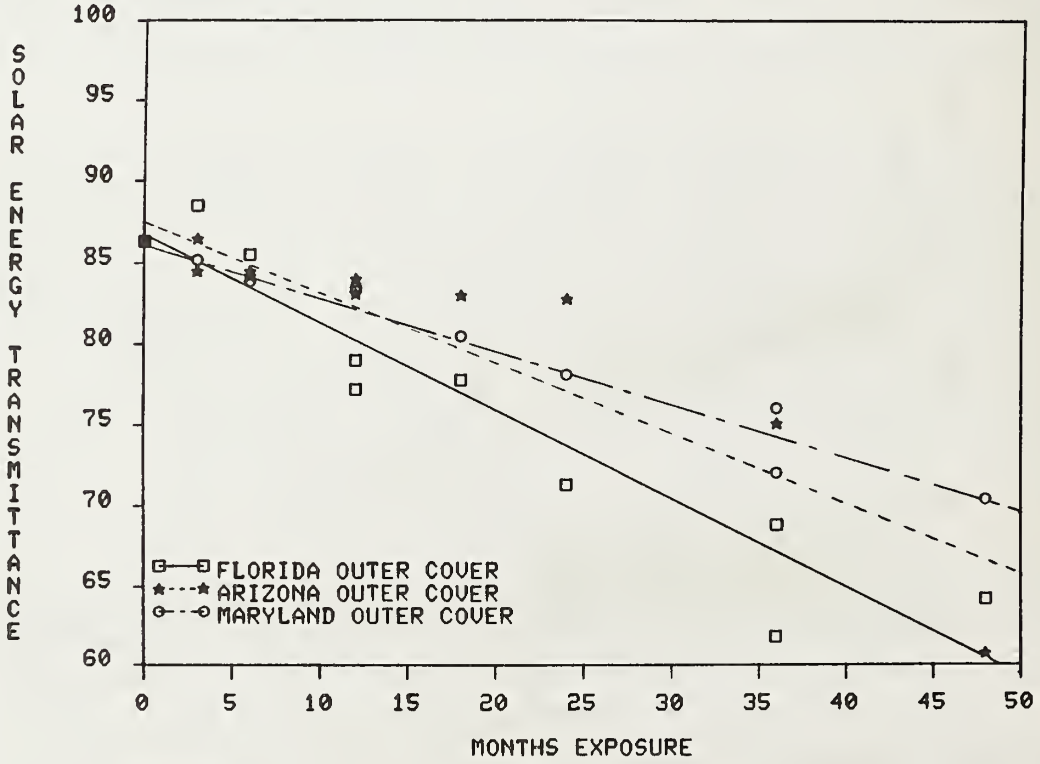


Figure 10b. Solar transmittance of fiber reinforced plastic (1.0 mm) as a function of months of exposure

In comparing the effects of dirt for all samples, the general trend was for the transmittance loss due to dirt to increase for about 12 to 18 months, then to decrease and/or level off. A possible reason for this is that, when the sample is new or only outdoors for a short period of time, the dirt comes off relatively easily with the washing procedure used. As the material ages, the dirt is embedded deeper in the surface and cannot be washed off by the procedure that was used. That could explain the leveling off or decrease in the apparent amount of dirt on the surface. Also, the samples were exposed to various amounts of rain. The specimens were brought indoors on a set schedule, if there was any rain in the preceeding days or weeks, a decrease in the amount of dirt on the surface may result.

The dirt seemed to accumulate most on the fluorinated (ethylene propylene) and on the fiber reinforced materials which became rough as their surfaces weathered.

## 3.3 TENSILE PROPERTIES

Tensile properties of three plastic films (i.e. fluorinated (ethylene propylene) copolymer, poly(vinyl fluoride) and poly(ethylene terephthalate)) were measured following exposure to heat aging at 125°C, artificial weathering with xenon arc light, and natural weathering in New River, Arizona (for up to 36 months) and Miami, Florida for three months (poly(ethylene terephthalate) only). Breaking factor, tensile strength elongation at break, yield strength, and elongation at yield were calculated from the tensile data.

None of the tensile properties of the fluorinated (ethylene propylene) copolymer changed dramatically. Tensile strength and yield strength data are presented in table 4. The tensile strength typically decreased about 25 percent in the longitudinal direction during each exposure, but with the sizable standard deviations it is difficult to say how meaningful this was. The fluorinated (ethylene propylene) was very thin, consequently, cutting it into tensile strips without edge flaws was difficult. This and the thinness of the material undoubtedly are the cause of the large standard deviations. The breaking factor and the elongation at break data are given in table 5. The elongation at break decreased about 35 percent in the xenon arc artificial weathering but a corresponding decrease was not observed in the Arizona weathering.

The tensile strength and yield strength of poly(vinyl fluoride) are presented in table 6. Heat aging at 125°C for 2000 hours caused the tensile strength to decrease about 15 percent and xenon arc exposure for 4000 hours resulted in about 10 percent loss. Outdoor weathering for 36 months caused about 25 percent drop in tensile strength of the outer and single covers. The inner cover tensile strength declined about 50 percent in the first year. The inner covers exposed for longer periods of time become brittle and disintegrated during exposure. The breaking factor and elongation at break are given in table 7. Both of these parameters showed declines similar to the tensile strength.

Table 4. Tensile Strength and Yield Strength of Weathered Fluorinated(ethylene propylene) Copolymer

| Exposure | Number of Test Specimens[a] L/T | Tensile Strength (MPa) | | | | Yield Strength (MPa) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Longitudinal[b] | | Transverse[b] | | Longitudinal[b] | | Transverse[b] | |
| | | $\bar{x}$ | σ | $\bar{x}$ | σ | $\bar{x}$ | σ | $\bar{x}$ | σ |
| None | 5/5 | 25.96 | 6.20 | 19.25 | 5.17 | 9.95 | 0.27 | 10.66 | 0.59 |
| Heat Aging - 125°C | | | | | | | | | |
| 100 hours | 5/5 | 27.60 | 9.11 | 19.05 | 3.06 | 10.32 | 0.96 | 9.21 | 0.91 |
| 250 hours | 5/5 | 23.97 | 5.16 | 19.96 | 1.68 | 4.61 | 0.28 | 4.90 | 0.25 |
| 1000 hours | 5/6 | 23.34 | 2.02 | 16.68 | 3.18 | 5.02 | 0.21 | 4.66 | 0.35 |
| 2000 hours | 11/11 | 19.80 | 5.76 | 16.83 | 4.49 | 5.67 | 0.39 | 5.51 | 0.25 |
| Xenon Arc Light | | | | | | | | | |
| 500 hours | 6 | 23.71 | 5.28 | | | 8.70 | 1.02 | | |
| 1000 hours | 5 | 25.80 | 0.77 | | | 8.23 | 0.57 | | |
| 3000 hours | 6 | 19.54 | 5.27 | | | 6.33 | 1.16 | | |
| 4000 hours | 10 | 21.94 | 5.01 | | | 5.60 | 0.32 | | |
| Arizona - Outer Double Cover | | | | | | | | | |
| 3 months | 5/4 | 26.14 | 1.98 | 19.36 | 0.62 | 5.22 | 0.62 | 5.02 | 0.26 |
| 6 months | 6/5 | 27.70 | 4.06 | 25.15 | 1.74 | 5.13 | 0.53 | 5.46 | 0.36 |
| 12 months | 5/5 | 24.84 | 2.04 | 21.24 | 5.25 | 5.32 | 0.47 | 4.42 | 0.44 |
| 18 months | 6/6 | 28.11 | 3.72 | 24.36 | 2.78 | 5.65 | 0.53 | 5.28 | 0.15 |
| 24 months | 4 | 23.76 | 3.41 | | | 8.73 | 0.73 | | |
| 36 months | 5 | 19.73 | 3.31 | | | 8.98 | 0.20 | | |
| Arizona - Inner Double Cover | | | | | | | | | |
| 6 months | 6/6 | 23.21 | 6.54 | 19.71 | 3.22 | 5.02 | 0.49 | 4.42 | 0.16 |
| 12 months | 6/6 | 26.66 | 1.91 | 22.78 | 4.08 | 5.00 | 1.00 | 5.38 | 0.25 |
| 18 months | 5/6 | 24.65 | 4.01 | 19.34 | 4.42 | 4.30 | 0.25 | 4.48 | 0.33 |
| 24 months | 5 | 20.05 | 4.18 | | | 8.50 | 0.31 | | |
| 36 months | 5 | 18.34 | 4.99 | | | 7.88 | 0.56 | | |
| Arizona - Single Cover | | | | | | | | | |
| 3 months | 4/5 | 23.58 | 6.60 | 22.04 | 3.47 | 5.67 | 0.16 | 5.77 | 0.43 |
| 6 months | 6/6 | 25.27 | 5.51 | 23.02 | 1.92 | 5.44 | 0.34 | 5.39 | 0.38 |
| 12 months | 6/5 | 27.17 | 5.59 | 24.09 | 2.40 | 4.36 | 0.78 | 4.90 | 0.36 |
| 24 months | 5 | 20.85 | 4.68 | | | 8.07 | 0.52 | | |
| 36 months | 5 | 19.56 | 3.49 | | | 8.75 | 0.18 | | |

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[a] Number of specimens indicate number of strips obtained from weathered material. L = Longitudinal direction, T = Transverse direction.

[b] $\bar{x}$ = average, σ = standard deviation.

Table 5. Breaking Factor and Elongation at Break of Weathered Fluorinated(ethylene propylene) Copolymer

| Exposure | Number of Test Specimens[a] L/T | Breaking Factor (N/m) | | | | Elongation at Break (%) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Longitudinal[b] | | Transverse[b] | | Longitudinal[b] | | Transverse[b] | |
| | | $\bar{x}$ | $\sigma$ | $\bar{x}$ | $\sigma$ | $\bar{x}$ | $\sigma$ | $\bar{x}$ | $\sigma$ |
| None | 5/5 | 646 | 156 | 488 | 131 | 257 | 45 | 272 | 160 |
| Heat Aging - 125°C | | | | | | | | | |
| 100 hours | 5/5 | 632 | 205 | 402 | 75 | 221 | 75 | 246 | 77 |
| 250 hours | 5/5 | 609 | 131 | 507 | 42 | 204 | 65 | 340 | 21 |
| 1000 hours | 5/6 | 604 | 61 | 462 | 81 | 217 | 43 | 243 | 106 |
| 2000 hours | 11/11 | 555 | 86 | 460 | 84 | 211 | 65 | 276 | 79 |
| Xenon Arc Light | | | | | | | | | |
| 500 hours | 6 | 566 | 143 | | | 225 | 52 | | |
| 1000 hours | 5 | 672 | 171 | | | 254 | 104 | | |
| 3000 hours | 6 | 495 | 133 | | | 170 | 71 | | |
| 4000 hours | 10 | 557 | 126 | | | 161 | 74 | | |
| Arizona - Outer Double Cover | | | | | | | | | |
| 3 months | 5/4 | 646 | 65 | 492 | 16 | 265 | 14 | 355 | 21 |
| 6 months | 6/5 | 749 | 100 | 674 | 42 | 253 | 28 | 372 | 15 |
| 12 months | 5/5 | 681 | 31 | 593 | 147 | 355 | 16 | 209 | 65 |
| 18 months | 6/6 | 644 | 212 | 492 | 215 | 252 | 28 | 340 | 35 |
| 24 months | 4 | 718 | 75 | | | 379 | 35 | | |
| 36 months | 5 | 576 | 75 | | | 335 | 42 | | |
| Arizona - Inner Double Cover | | | | | | | | | |
| 6 months | 6/6 | 676 | 108 | 500 | 82 | 261 | 31 | 327 | 50 |
| 12 months | 6/6 | 676 | 49 | 385 | 103 | 260 | 31 | 288 | 100 |
| 18 months | 5/6 | 671 | 100 | 513 | 107 | 264 | 40 | 325 | 75 |
| 24 months | 5 | 513 | 107 | | | 318 | 91 | | |
| 36 months | 5 | 572 | 159 | | | 301 | 119 | | |
| Arizona - Single Cover | | | | | | | | | |
| 3 months | 4/5 | 542 | 129 | 560 | 89 | 185 | 34 | 332 | 45 |
| 6 months | 6/6 | 642 | 140 | 584 | 49 | 238 | 82 | 311 | 21 |
| 12 months | 6/5 | 737 | 126 | 672 | 72 | 266 | 45 | 343 | 14 |
| 24 months | 5 | 630 | 140 | | | 339 | 99 | | |
| 36 months | 5 | 497 | 89 | | | 316 | 45 | | |

[a] Number of specimens indicate number of strips obtained from weathered material. L = Longitudinal direction, T = Transverse direction.

[b] $\bar{x}$ = average, $\sigma$ = standard deviation.

Table 6. Tensile Strength and Yield Strength of Weathered Poly(vinyl fluoride)

| Exposure | Number of Test Specimens[a] L/T | Tensile Strength (MPa) | | | | Yield Strength (MPa) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Longitudinal[b] | | Transverse[b] | | Longitudinal[b] | | Transverse[b] | |
| | | $\bar{x}$ | $\sigma$ | $\bar{x}$ | $\sigma$ | $\bar{x}$ | $\sigma$ | $\bar{x}$ | $\sigma$ |
| None | 9/9 | 78.63 | 6.65 | 74.92 | 3.46 | 36.30 | 4.14 | 35.25 | 2.08 |
| Heat Aging - 125°C | | | | | | | | | |
| 100 hours | 4/5 | 77.64 | 1.72 | 73.81 | 5.69 | 35.26 | 0.99 | 36.67 | 3.72 |
| 250 hours | 5/4 | 71.70 | 2.42 | 70.29 | 2.87 | 32.34 | 3.54 | 33.41 | 1.40 |
| 1000 hours | 3/3 | 68.99 | 4.58 | 64.70 | 3.07 | 36.63 | 1.63 | 36.52 | 0.36 |
| 2000 hours | 9/9 | 66.71 | 4.35 | 63.04 | 4.11 | 37.67 | 2.88 | 35.32 | 2.63 |
| Xenon Arc Light | | | | | | | | | |
| 500 hours | 4 | 70.72 | 2.73 | | | 31.98 | 0.63 | | |
| 1000 hours | 3 | 69.10 | 0.63 | | | 33.35 | 0.72 | | |
| 3000 hours | 3 | 68.08 | 3.74 | | | 33.98 | 0.36 | | |
| 4000 hours | 9 | 70.04 | 4.29 | | | 35.37 | 2.28 | | |
| Arizona - Outer Double Cover | | | | | | | | | |
| 3 months | 5/5 | 70.39 | 2.61 | 67.25 | 2.99 | 35.08 | 1.52 | 34.31 | 0.69 |
| 12 months | 4/5 | 70.69 | 4.02 | 68.47 | 3.09 | 32.77 | 2.09 | 32.42 | 0.53 |
| 24 months | 4 | 69.75 | 1.57 | | | 31.88 | 1.98 | | |
| 36 months | 5 | 61.05 | 5.09 | | | 34.50 | 2.67 | | |
| Arizona - Inner Double Cover | | | | | | | | | |
| 3 months | 4/5 | 69.95 | 3.58 | 66.25 | 1.23 | 38.15 | 1.08 | 35.59 | 1.92 |
| 12 months | 2 | 42.90 | 1.12 | | | 37.05 | 0.45 | | |
| Arizona - Single Cover | | | | | | | | | |
| 3 months[c] | 4/5 | 69.74 | 3.78 | 67.22 | 6.35 | 34.83 | 0.89 | 33.69 | 1.92 |
| 3 months[c] | 4/5 | 76.70 | 6.84 | 69.25 | 3.83 | 35.46 | 1.79 | 34.19 | 1.00 |
| 6 months | 5/5 | 74.65 | 2.79 | 64.60 | 2.43 | 32.91 | 0.96 | 32.68 | 0.76 |
| 12 months | 5/4 | 63.09 | 5.73 | 59.18 | 10.07 | 34.81 | 2.00 | 34.86 | 1.41 |
| 18 months | 6/5 | 67.14 | 3.49 | 58.01 | 5.39 | 30.91 | 1.61 | 30.11 | 0.99 |
| 24 months | 4 | 63.07 | 4.17 | | | 32.01 | 0.56 | | |
| 36 months | 3 | 58.17 | 4.44 | | | 34.54 | 1.04 | | |

[a] Number of specimens indicate number of strips obtained from weathered material.
L = Longitudinal direction, T = Transverse direction.

[b] $\bar{x}$ = average, $\sigma$ = standard deviation.

[c] Two sets of minicollectors were exposed the same period of time but different dates.

Table 7. Breaking Factor and Elongation at Break of Weathered Poly(vinyl fluoride)

| Exposure | Number of Test Specimens[a] L/T | Breaking Factor (N/m) |  |  |  | Elongation at Break (%) |  |  |  |
|---|---|---|---|---|---|---|---|---|---|
|  |  | Longitudinal[b] |  | Transverse[b] |  | Longitudinal[b] |  | Transverse[b] |  |
|  |  | $\bar{x}$ | σ | $\bar{x}$ | σ | $\bar{x}$ | σ | $\bar{x}$ | σ |
| None | 9/9 | 7655 | 506 | 7258 | 221 | 205 | 13.0 | 191 | 11.1 |
| Heat Aging - 125°C |  |  |  |  |  |  |  |  |  |
| 100 hours | 4/5 | 8357 | 185 | 7626 | 586 | 229 | 8.6 | 204 | 22.4 |
| 250 hours | 5/4 | 7408 | 249 | 7263 | 303 | 221 | 6.6 | 198 | 8.9 |
| 1000 hours | 3/3 | 7317 | 408 | 6685 | 320 | 187 | 29.6 | 219 | 16.9 |
| 2000 hours | 9/9 | 6762 | 422 | 6483 | 455 | 195 | 11.5 | 175 | 14.1 |
| Xenon Arc Light |  |  |  |  |  |  |  |  |  |
| 500 hours | 4 | 8182 | 284 |  |  | 216 | 3.9 |  |  |
| 1000 hours | 3 | 7139 | 66 |  |  | 212 | 2.6 |  |  |
| 3000 hours | 3 | 7033 | 385 |  |  | 204 | 22.7 |  |  |
| 4000 hours | 9 | 6951 | 168 |  |  | 192 | 9.6 |  |  |
| Arizona - Outer Double Cover |  |  |  |  |  |  |  |  |  |
| 3 months | 5/5 | 7272 | 270 | 6947 | 310 | 193 | 7.5 | 194 | 15.8 |
| 12 months | 4/5 | 7303 | 415 | 7002 | 373 | 216 | 16.9 | 214 | 6.5 |
| 24 months | 4 | 6923 | 82 |  |  | 183 | 7.4 |  |  |
| 36 months | 5 | 6345 | 529 |  |  | 176 | 19.0 |  |  |
| Arizona - Inner Double Cover |  |  |  |  |  |  |  |  |  |
| 3 months | 4/5 | 7226 | 369 | 6845 | 126 | 204 | 14.4 | 195 | 9.4 |
| 12 months | 2 | 4433 | 116 |  |  | 101 | 47.8 |  |  |
| Arizona - Single Cover |  |  |  |  |  |  |  |  |  |
| 3 months[c] | 4/5 | 7214 | 408 | 6844 | 657 | 201 | 14.4 | 202 | 21.1 |
| 3 months[c] | 4/5 | 7925 | 706 | 7154 | 396 | 211 | 28.7 | 202 | 13.7 |
| 6 months | 5/5 | 7713 | 287 | 6675 | 252 | 224 | 8.6 | 205 | 9.6 |
| 12 months | 5/4 | 6519 | 592 | 6114 | 1040 | 175 | 32.8 | 181 | 54.9 |
| 18 months | 6/5 | 7214 | 369 | 6303 | 545 | 213 | 19.8 | 220 | 58.8 |
| 24 months | 4 | 6161 | 352 |  |  | 160 | 12.4 |  |  |
| 36 months | 3 | 5592 | 429 |  |  | 149 | 25.5 |  |  |

[a] Number of specimens indicate number of strips obtained from weathered material. L = Longitudinal direction, T = Transverse direction.

[b] x = average, σ = standard deviation.

[c] Two sets of minicollectors were exposed the same period of time but different dates.

The tensile properties of the poly(ethylene terephthalate) changed more than either of the other films. The tensile and yield strengths are presented in table 8. Figure 11 displays the tensile strength (longitudinal) as a function of solar radiation in Arizona and in artificial weathering. (The hours and months of exposure in table 8 can be converted to solar radiation using tables 2 and 3.) As seen in this figure, the tensile strength shows a dramatic decline after exposure in the xenon arc artificial weathering and in the outdoor weathering. The tensile strength of the outer double and single covers dropped about 50 percent after only 3 months exposure in Arizona and Florida and 500 hours in the xenon arc exposure. The inner covers, which were weathered simultaneously, showed minor changes. The outer covers apparently absorbed most of the ultraviolet radiation which was causing the material to degrade. Consequently the inner cover degraded much more slowly. After 18 months the single and outer double covers retained only about 20 percent of their original strength, while the inner cover had dropped to about 60 percent. At that point, the material was very brittle. A hail storm at the New River test site broke holes in all of the remaining poly (ethylene terephthalate) minicollectors.

The breaking factor and elongation break are listed in table 9. Both factors dropped rapidly in the specimens exposed directly to sunlight and more slowly in the inner covers. In just 3 months the elongation at break dropped from 82 percent to 2.7 percent. The changes in the elongation at break are illustrated in figure 12 for poly(ethylene terephthalate) exposed in Arizona and in an artificial weathering device with xenon arc. A scanning electron micrograph of the surface of poly(ethylene terephthalate) after 12 months outdoor exposure in Miami is shown in figure 3a. Many small cracks can be seen. These indicate degradation of the material and are certainly related to the loss of strength.

From reviewing the data for the tensile properties, it is evident that all three of the films were anisotropic (i.e., properties were not the same in transverse and longitudinal directions). Of the five properties which were calculated from the tensile measurements, it appears that the elongation at break and tensile strength are the most sensitive factors in determining the degradation in mechanical properties caused by weathering.

Table 8. Tensile Strength and Yield of Weathered Poly(ethylene terephthalate)

| Exposure | Number of Test Specimens[a] L/T | Tensile Strength (MPa) | | | | Yield Strength (MPa) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Longitudinal[b] | | Transverse[b] | | Longitudinal[b] | | Transverse[b] | |
| | | $\bar{x}$ | σ | $\bar{x}$ | σ | $\bar{x}$ | σ | $\bar{x}$ | σ |
| None | 10/12 | 213.28 | 10.75 | 159.37 | 6.71 | 85.17 | 2.77 | 90.15 | 4.79 |
| Heat Aging - 125°C | | | | | | | | | |
| 250 hours | 5/6 | 202.55 | 5.04 | 158.68 | 21.59 | 79.39 | 1.85 | 79.02 | 2.92 |
| 1000 hours | 6/3 | 199.82 | 4.34 | 153.39 | 2.36 | 81.33 | 4.28 | 81.82 | 2.30 |
| 2000 hours | 5/6 | 178.08 | 3.79 | 140.39 | 4.70 | 79.36 | 11.48 | 79.36 | 2.11 |
| Xenon Arc Light | | | | | | | | | |
| 500 hours | 4 | 112.03 | 1.24 | | | 84.29 | 2.10 | | |
| 1000 hours | 4 | 103.69 | 3.25 | | | 70.87 | 6.83 | | |
| 3000 hours | 4 | 56.98 | 6.87 | | | | | | |
| 4000 hours | 7 | 35.27 | 5.21 | | | | | | |
| Arizona - Outer Double Cover | | | | | | | | | |
| 3 months | 6/6 | 96.47 | 10.40 | 49.31 | 1.79 | | | | |
| 12 months | 6/6 | 72.01 | 3.41 | 45.23 | 2.36 | | | | |
| 18 months | 4 | 49.86 | 9.98 | | | | | | |
| Arizona - Inner Double Cover | | | | | | | | | |
| 3 months | 6/4 | 195.14 | 3.14 | 141.02 | 3.84 | 104.90 | 3.19 | 109.24 | 4.82 |
| 12 months | 6 | 167.49 | 16.82 | 106.71 | 37.84 | 96.65 | 2.63 | 82.85 | 1.56 |
| 18 months | 6/6 | 130.13 | 10.04 | | | 85.53 | 9.31 | | |
| Arizona - Single Cover | | | | | | | | | |
| 3 months[c] | 2/6 | 82.20 | 4.61 | 43.72 | 2.73 | | | | |
| 3 months[c] | 6/4 | 185.61 | 2.99 | 185.48 | 3.39 | | | | |
| 6 months | 6/6 | 85.23 | 10.34 | 43.16 | 12.88 | | | | |
| 12 months | 5 | 27.89 | 2.70 | | | 88.92 | 2.61 | | |
| 18 months | 3 | 45.52 | 6.71 | | | 84.35 | 1.41 | | |
| Florida - 3 months | | | | | | | | | |
| Single Cover | 5/6 | 103.23 | 2.47 | 54.37 | 2.55 | | | | |
| Outer Double | 6/4 | 115.94 | 3.03 | 62.18 | 5.24 | 105.68 | 1.85 | | |
| Inner Double | 6/4 | 207.50 | 3.72 | 155.90 | 5.92 | 101.13 | 3.81 | 103.89 | 2.08 |

[a] Number of specimens indicate number of strips obtained from weathered material. L = Longitudinal direction, T = Transverse direction.

[b] $\bar{x}$ = average, σ =standard deviation.

[c] Two sets of minicollectors were exposed the same period of time but different dates.

Table 9. Breaking Factor and Elongation at Break of Weathered Poly(ethylene terephthalate)

| Exposure | Number of Test Specimens[a] L/T | Breaking Factor (N/m) | | | | Elongation at Break (%) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Longitudinal[b] | | Transverse[b] | | Longitudinal[b] | | Transverse[b] | |
| | | $\bar{x}$ | σ | $\bar{x}$ | σ | $\bar{x}$ | σ | $\bar{x}$ | σ |
| None | 10/12 | 26110 | 812 | 19889 | 742 | 82.0 | 6.6 | 123.1 | 10.9 |
| Heat Aging - 125°C | | | | | | | | | |
| 250 hours | 5/6 | 25356 | 597 | 19812 | 2668 | 81.2 | 12.3 | 115.7 | 18.7 |
| 1000 hours | 6/3 | 24885 | 541 | 19101 | 320 | 91.5 | 8.6 | 138.8 | 2.6 |
| 2000 hours | 5/6 | 23011 | 485 | 17529 | 530 | 74.3 | 5.6 | 115.8 | 7.7 |
| Xenon Arc Light | | | | | | | | | |
| 500 hours | 4 | 14233 | 147 | | | 10.4 | 3.6 | | |
| 1000 hours | 4 | 13307 | 499 | | | 6.7 | 1.8 | | |
| 3000 hours | 4 | 7246 | 868 | | | 2.1 | 0.4 | | |
| 4000 hours | 7 | 4386 | 616 | | | 1.3 | 0.3 | | |
| Arizona - Outer Double Cover | | | | | | | | | |
| 3 months | 6/6 | 12207 | 1334 | 6168 | 201 | 2.8 | 0.2 | 1.7 | 0.2 |
| 12 months | 6/6 | 9089 | 353 | 5687 | 280 | 2.1 | 0.1 | 1.6 | 0.1 |
| 18 months | 5 | 6566 | 1285 | | | 5.3 | 0.3 | | |
| Arizona - Inner Double Cover | | | | | | | | | |
| 3 months | 6/4 | 24253 | 380 | 17545 | 462 | 78.7 | 6.9 | 116.0 | 16.5 |
| 12 months | 6 | 21222 | 2218 | | | 42.3 | 19.9 | | |
| 18 months | 6/6 | 16949 | 1490 | 14533 | 3852 | 28.8 | 22.5 | 13.8 | 6.2 |
| Arizona - Single Cover | | | | | | | | | |
| 3 months[c] | 2/6 | 10246 | 560 | 5436 | 355 | 2.7 | | 1.4 | 0.1 |
| 3 months[c] | 6/4 | 23654 | 285 | 23552 | 440 | 57.9 | 5.0 | 56.8 | 6.0 |
| 6 months | 6/6 | 10640 | 1251 | 5279 | 1534 | 2.4 | 0.4 | 1.4 | 0.1 |
| 12 months | 5 | 3487 | 371 | | | 1.0 | 0.1 | | |
| 18 months | 3 | 5900 | 867 | | | 3.8 | 0.7 | | |
| Florida - 3 months | | | | | | | | | |
| Single Cover | 5/6 | 12636 | 348 | 6631 | 310 | 3.1 | 0.04 | 1.9 | 0.2 |
| Outer Double | 6/4 | 14205 | 400 | 7721 | 609 | 4.2 | 0.2 | 2.2 | 0.2 |
| Inner Double | 6/4 | 25809 | 464 | 13483 | 739 | 80.2 | 5.9 | 131.3 | 9.8 |

[a] Number of specimens indicate number of strips obtained from weathered material. L = Longitudinal direction, T = Transverse direction.

[b] $\bar{x}$ = average, σ = standard deviation.

[c] Two sets of minicollectors were exposed the same period of time but different dates.

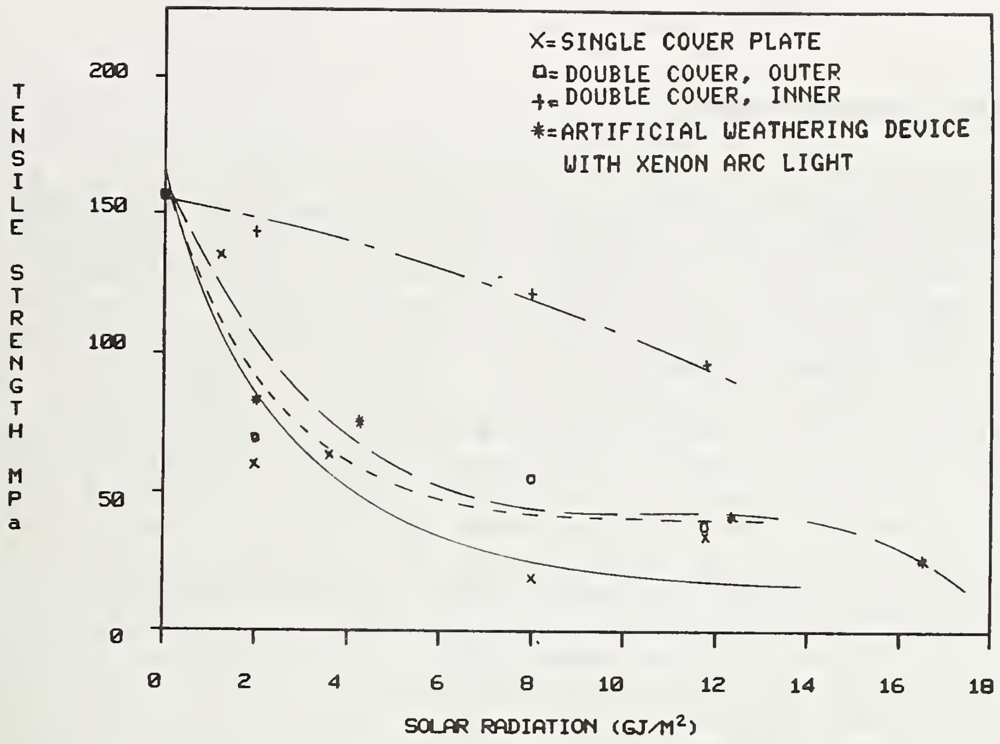

Figure 11. Tensile Strength of Poly(ethylene terephthalate) After Natural Weathering in Arizona and Artificial Weathering with Xenon Arc Light

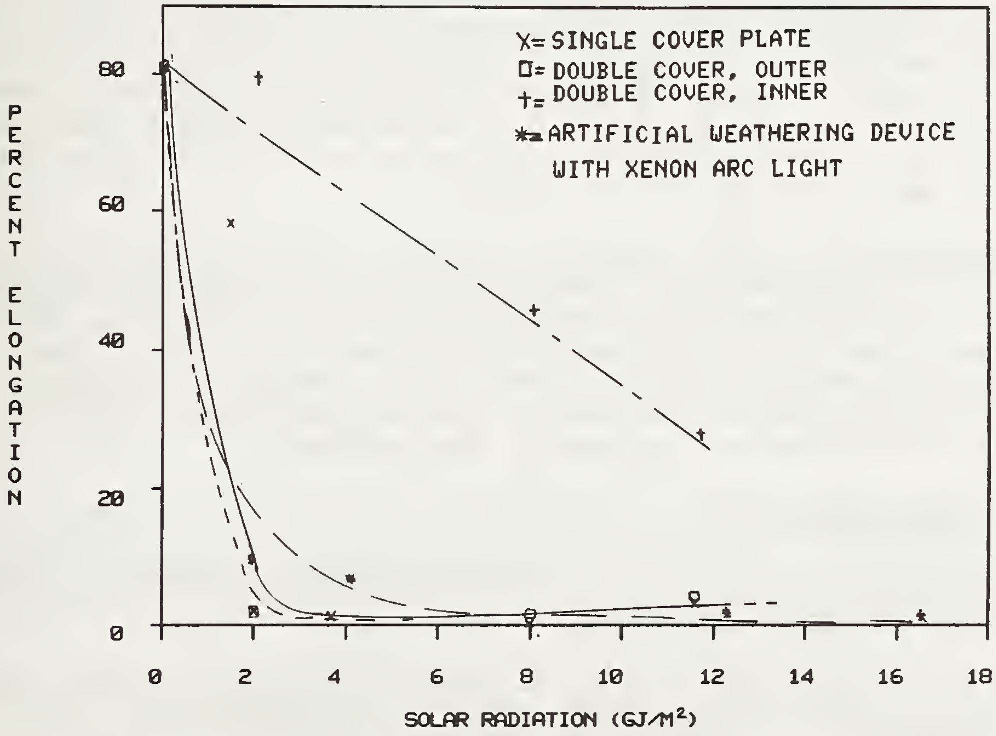

Figure 12. Elongation at Break of Poly(ethylene terephthalate) After Natural Weathering in Arizona and Artificial Weathering with Xenon Arc Light

## 4. SUMMARY AND CONCLUSIONS

The key objective of this entire study described in this report and an earlier report [1] was to obtain data needed as the technical basis for standards for cover plate materials. An underlying assumption in the development of the standards was that they should provide the user with a means to evaluate the relative durabilities of potential cover plate materials. During the course of this research, cover plate materials were aged using natural and artificial weathering techniques, and an assessment of their performance was obtained by measuring optical, physical and mechanical properties before and after weathering. The natural and artificial weathering techniques were carefully chosen to simulate one or more environmental conditions reached by the cover material of a solar collector. The material properties which were measured were selected because they were considered both critical to the performance of a solar collector and likely to be affected by weathering. The cover plate materials used were typical of those commercially available in 1976.

The large body of data which was assembled during the study now permits reevaluation of the weathering procedures and property tests to determine their adequacy. As a side benefit, while not being an objective of the study, examination of the data also provides information on the durability of the specific cover plate materials used in this study. However, the reader is cautioned against direct extrapolation of these data to materials currently on the market. The cover plate materials in this study are representative of those on the market in 1976. No attempt was made to evaluate all types of cover plate materials since this was not the purpose of the research. Many cover plate materials are marketed and manufacturers sometimes modify their materials in order to improve performance. Since the properties of cover plate materials can be changed by alteration in minor constituents or processing techniques, the properties of cover plate materials currently on the market may differ from those described in this report.

The conclusions given below are drawn from the work in this report and they relate to weathering procedures, property tests, and the effects of weathering on cover materials. Additional conclusions reached in the earlier phase of the research are contained in the first report [1] on this project. Those conclusions address the measurement of transmittance, accelerated laboratory testing, and outdoor weathering, and are not repeated here unless additional data supporting the conclusions are included in this report.

### 4.1 WEATHERING PROCEDURES

1. Exposure of materials on minicollectors provided data useful in evaluating candidate cover plate materials.

(a) Minicollectors provide a means of simultaneously exposing cover plate materials to sunlight, elevated temperatures, moisture, and other natural environmental conditions encountered by a cover plate on actual solar collectors. Since material degradation generally occurs more rapidly at elevated temperatures, a device which simultaneously exposes materials to elevated temperatures and natural sunlight is an advance over the commonly employed methods of natural weathering which involve exposure at ambient temperature.

(b) Minicollectors provide a means to generate data to evaluate materials in both inner and outer cover plate applications. Due to their location in a solar collector, inner and outer covers encounter somewhat different weathering. In some ways, the differences may be inconsequential; however, other differences can be important. Outer cover plates experience higher intensities of solar radiation but lower temperatures than inner cover plates. In addition, outer cover plates generally have more exposure to moisture and air pollutants. After minicollector exposure, differences were observed between materials exposed as inner covers and those exposed directly to the sun. Materials susceptible to damage caused by sunlight and by heat were distinguished.

2. Artificial weathering with xenon arc light is helpful in distinguishing materials sensitivity to natural sunlight. Polycarbonate and both fiber reinforced plastics yellowed and had the largest solar transmittance losses after both exposure in the xenon arc light and 48 months weathering in Arizona. Similarly with the tensile property measurements, poly(ethylene terephthalate) had a dramatic decrease in tensile strength and elongation at break after just 500 hours of xenon arc exposure. Rapid declines in tensile properties also occurred in the test specimens exposed to natural sunlight. Susceptibility of materials to property changes due to damage from sunlight alone could be determined in shorter periods of real time using artificial weathering with xenon arc. However, periods of exposure in an artificial weathering device must be sufficiently lengthy, with property measurements being made at regular intervals, to establish a definite rate of degradation.

## 4.2 PROPERTY TESTS

1. Evaluation of materials for cover plates should include measurement of both optical and mechanical properties. It must be emphasized that both are critical to the performance of a cover plate material and a significant decrease in either can cause the material to be unsuitable for use in a solar collector. Evaluation of weathered materials has shown that optical properties may change little while mechanical properties decline rapidly leading to failure of the material.

2. Tensile strength and elongation at break are useful parameters for monitoring changes in mechanical properties of plastic film cover plate materials caused by weathering. Mechanical property losses induced by weathering on the minicollectors appear to be either: (1) a function of accumulated exposure to sunlight (e.g., poly(ethylene terephthalate) and acrylic film), or (2) a combination of elevated temperature and accumulated exposure to sunlight (e.g., poly(vinyl fluoride) inner covers). Deterioration of mechanical properties occurred most rapidly in Arizona. Of the tensile properties studied, tensile strength and elongation at break were the most sensitive in determining material degradation. Significant information

relating to strength as well as ductibility (or brittleness) can be extracted from the data from tensile measurements.

## 4.3 EFFECTS OF WEATHERING ON MATERIALS

1. Significant solar energy transmittance losses result from retention of dirt and dust on the cover plate surfaces. For most materials, the transmittance loss due to dirt increased for 12 to 18 months, then decreased or leveled off. These transmittance losses, which can be regained by washing the material, were generally three to six percent, although, in a few cases, they reached 17-20 percent.

2. The rates of material degradation vary at different geographic locations. Sun, heat, moisture, and air pollutants can cause material degradation either independently or synergistically. The varied influence of these multiple weather factors is illustrated by the different rates of degradation for materials weathered simultaneously at three separate sites. The data clearly indicate that weather parameters in addition to sunlight are causing degradation. Although the materials weathered in Arizona were exposed to the most sun and the highest temperatures, they did not usually have the greatest transmittance losses. The materials from Florida and Maryland suffered greater transmittance losses. This seems to indicate that moisture contributed to the material degradation. The effect of pollutants is difficult to assess quantitatively since their concentrations were not monitored.

3. Degradation rates vary among the cover plate materials. Comparison of all materials at one site indicates that some cover plate materials degrade more rapidly than others. Similarly, comparison of a material at one site exposed as single cover, and as inner and outer covers shows that the type of use in a solar collector can influence the rate of degradation.

4. Outdoor weathering caused no significant degradation of the glass cover plate materials. Solar transmittance measurements of the two glass materials did not decline significantly.

5. The fluorinated(ethylene propylene) copolymer film was the only one of the four films which did not suffer serious degradation in either the optical or mechanical properties during either accelerated or natural weathering. Although the test specimens exposed in Gaithersburg had a solar transmittance loss of seven percent after three and four years exposure, examination of the material indicated the likely cause was permanent deposits of dirt or pollutants on the surface.

6. Poly(vinyl fluoride) was susceptible to deterioration resulting from the combination of sunlight and heat. The inner covers became brittle and disintegrated in some cases.

7. The mechanical properties of the acrylic film and the poly(ethylene terephthalate) are seriously affected by exposure to solar radiation.

The acrylic film disintegrated on the minicollectors after 18-24 months weathering. The poly(ethylene terephthalate) became brittle and lost flexibility after only one to two years exposure in Arizona. This led to failure of the material when a hailstorm occurred.

8. The solar transmittance losses of polycarbonate and poly(methyl methacrylate) were generally about the same, with polycarbonate losses being about one to two percent higher than those for poly(methyl methacrylate). Polycarbonate had losses of five to seven percent at Florida and Maryland and about two to four percent at Arizona. The materials from Florida and Maryland exposures had some deposits on the surface which contributed to the higher transmittance losses.

9. The fiber reinforced plastic materials suffered significant solar transmittance losses after exposure on the minicollectors. Transmittance losses appeared to be due to a combination of weathering factors, i.e., sunlight, heat, moisture, and other weathering. The outer and single covers of the 1 mm FRP had transmittance losses of 10-25 percent while the 1.5 mm FRP transmittance losses were 15-30 percent. Inner cover losses reached 10 percent and 20 percent, for the 1 mm and 1.5 mm FRP materials, respectively.

## 5. FUTURE RESEARCH NEEDS

Additional research is needed 1) to develop improved polymeric glazing materials and 2) to develop improved methods for reliably predicting the service life of potential polymeric glazing materials.

### 5.1 MATERIALS DEVELOPMENT

As shown the data presented in this report, polymeric materials are frequently susceptible to degradation stemming from the environmental factors accompanying solar collector applications. Because of the degradation of many currently available materials, research is needed to develop improved polymeric glazings. In particular, glazing materials are needed which are more resistant to degradation processes, such as photodegradation, thermal degradation and oxidation, than currently available materials.

### 5.2 SERVICE LIFE PREDICTION

Service life data are essential in the effective selection of materials for specific solar collector applications. While methods have been developed to aid in screening potential glazing materials, methods are not available to reliably predict their service lives.

Research is needed to develop improved methods of predicting service life prior to the use of materials in collector glazing applications.

Inherent in the research to develop improved predictive test methods are the following specific needs:

1. Characterization of the mechanisms of degradation of polymeric glazing materials. Knowledge of the degradation mechanisms is essential to ensure that accelerated tests induce the same degradation processes as those which occur in actual use.

2. Characterization of microstructural changes and identification of the relationship between microstructural changes and engineering properties. This would permit the use of microstructural changes in predicting impending changes in engineering properties with the advantage that microstructural changes can be detected at much earlier stages of degradation than engineering properties.

3. Mathematical models to aid extrapolation of short-term test data to long-term performance. In particular, models are needed to account for the synergistic actions of multiple degradative factors, such as ultraviolet radiation, heat, moisture and air contaminants. The use of probabilistic models offers promise for meeting these needs.

# 6. ACKNOWLEDGMENT

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# APPENDIX - SOLAR ENERGY TRANSMITTANCE DATA OF COVER PLATE MATERIALS AFTER NATURAL WEATHERING

Table A1. Solar Energy Transmittance of Cover Plate Materials After Exposure as Single Covers to Natural Weathering in Gaithersburg, Maryland

| Months Exposure | 0 | 3 | 6 | 12[a] | 12[a] | 18 | 24 | 36[a] | 36[a] | 48 |
|---|---|---|---|---|---|---|---|---|---|---|
| Material / Solar Radiation (GJ/m$^2$) | 0 | 1.176 | 2.251 | 5.429 | 5.477 | 7.680 | 10.720 | 16.402 | 16.693 | 22.076 |
| Glass (0.01% iron oxide) | 90.7 | 89.1 | 90.3 | 91.3 | 90.2 | 91.1 | 88.5 | 90.0 | 81.2 | 90.2 |
| Glass (0.10% iron oxide) | 87.4 | 88.2 | 86.8 | 87.5 | 88.8 | 86.7 | 85.9 | 87.0 | 80.4 | 85.5 |
| Fluorinated (ethylene propylene) copolymer | 96.0 | 96.3 | 95.2 | 95.6 | 96.0 | 93.4 | 93.6 | 94.0 | 95.5 | 93.4 |
| Poly(vinyl fluoride) | 92.5 | 90.7 | 89.5 | 87.3 | 91.9 | 89.2 | 87.6 | 83.4 | 82.0 | 80.6 |
| Poly(ethylene terephthalate) | 86.3 | 85.2 | 83.1 | 83.8 | 85.7 | 84.6 | 76.6 | [b] | 85.1 | [b] |
| Acrylic | 90.7 | 90.1 | 87.3 | 86.0 | 87.3 | 89.0 | 87.8 | [b] | [b] | [b] |
| Poly(methyl methacrylate) | 91.0 | 89.5 | 89.1 | 89.2 | 89.3 | 88.1 | 85.8 | 86.3 | 81.3 | 86.8 |
| Polycarbonate | 88.1 | 88.2 | -- | 87.0 | 87.2 | 85.6 | 81.6 | 84.2 | 84.3 | 83.0 |
| Fiber reinforced plastic (1.0 mm) | 86.3 | 85.7 | 84.2 | 84.5 | 84.4 | 82.5 | 80.3 | 77.7 | 68.5 | [b] |
| Fiber reinforced plastic (1.5 mm) | 78.5 | 75.0 | 72.3 | 76.6 | 69.5 | 74.5 | 65.6 | 57.7 | 59.4 | 49.1 |

Transmittance was measured after the test specimens were washed. The solar energy transmittance was calculated for air mass 2. Each transmittance value represents a separate test specimen. Transmittance is expressed in percentage.

[a] Two sets of minicollectors were exposed for the same length of time but different dates.

[b] Material failed prior to this time.

Table A2. Solar Energy Transmittance of Cover Plate Materials After Exposure as Double Covers to Natural Weathering in Gaithersburg, Maryland

| | Outer Cover | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Months Exposure | 0 | 3 | 6 | 12[a] | 12[a] | 18 | 24 | 36[a] | 36[a] | 48 |
| Material / Solar Radiation ($GJ/m^2$) | 0 | 1.176 | 2.251 | 5.429 | 5.477 | 7.680 | 10.720 | 16.402 | 16.693 | 22.076 |
| Glass (0.01% iron oxide) | 90.7 | 89.3 | 87.8 | 91.0 | 91.8 | 90.3 | 90.1 | 90.3 | 89.4 | 89.8 |
| Glass (0.10% iron oxide) | 87.4 | 88.3 | 86.9 | 87.2 | 88.9 | 87.0 | 88.1 | 87.0 | 86.2 | 87.4 |
| Fluorinated (ethylene propylene) copolymer | 96.0 | 95.9 | 95.6 | 95.8 | 96.0 | 95.9 | 96.5 | 95.4 | 95.8 | 95.2 |
| Poly(vinyl fluoride) | 92.5 | 91.4 | 90.7 | 91.7 | 91.8 | 92.8 | 92.0 | 92.1 | 91.6 | 88.7 |
| Poly(ethylene terephthalate) | 86.3 | 86.0 | 84.9 | 85.6 | 85.9 | 85.7 | 86.0 | 86.0 | 84.2 | [b] |
| Acrylic | 90.7 | 90.3 | 90.0 | 89.5 | 90.3 | 89.9 | [b] | [b] | [b] | [b] |
| Poly(methyl methacrylate) | 91.0 | 90.9 | 89.8 | 91.0 | 90.7 | 90.8 | — | 90.4 | 91.3 | 90.4 |
| Polycarbonate | 88.1 | 87.9 | 87.1 | 88.3 | 87.9 | 88.3 | 87.9 | 84.1 | 88.3 | 87.9 |
| Fiber reinforced plastic (1.0 mm) | 86.3 | 84.6 | 85.2 | 81.6 | 83.1 | 84.0 | 82.7 | 77.9 | 80.0 | 79.3 |
| Fiber reinforced plastic (1.5 mm) | 78.3 | 74.7 | 67.6 | 67.1 | 68.1 | 65.8 | 61.7 | — | 72.7 | 68.1 |

| | Inner Cover | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Months Exposure | 0 | 3 | 6 | 12[a] | 12[a] | 18 | 24 | 36[a] | 36[a] | 48 |
| Material / Solar Radiation ($GJ/m^2$) | 0 | 1.176 | 2.251 | 5.429 | 5.477 | 7.680 | 10.720 | 16.402 | 16.693 | 22.076 |
| Glass (0.01% iron oxide) | 90.7 | 89.3 | 87.8 | 91.0 | 91.8 | 90.3 | 90.1 | 90.3 | 89.4 | 89.8 |
| Glass (0.10% iron oxide) | 87.4 | 88.3 | 86.9 | 87.2 | 88.9 | 87.0 | 88.1 | 87.0 | 86.2 | 87.4 |
| Fluorinated (ethylene propylene) copolymer | 96.0 | 95.9 | 95.6 | 95.8 | 96.0 | 95.9 | 96.5 | 95.4 | 95.8 | 95.2 |
| Poly(vinyl fluoride) | 92.5 | 91.4 | 90.7 | 91.7 | 91.8 | 92.8 | 92.0 | 92.1 | 91.6 | 88.7 |
| Poly(ethylene terephthalate) | 86.3 | 86.0 | 84.9 | 85.6 | 85.9 | 85.7 | 86.0 | 86.0 | 84.2 | [b] |
| Acrylic | 90.7 | 90.3 | 90.0 | 89.5 | 90.3 | 89.9 | [b] | [b] | [b] | [b] |
| Poly(methyl methacrylate) | 91.0 | 90.9 | 89.8 | 91.0 | 90.7 | 90.8 | — | 90.4 | 91.3 | 90.4 |
| Polycarbonate | 88.1 | 87.9 | 87.1 | 88.3 | 87.9 | 88.3 | 87.9 | 84.1 | 88.3 | 87.9 |
| Fiber reinforced plastic (1.0 mm) | 86.3 | 84.6 | 85.2 | 81.6 | 83.1 | 84.0 | 82.7 | 77.9 | 80.0 | 79.3 |
| Fiber reinforced plastic (1.5 mm) | 78.3 | 74.7 | 67.6 | 67.1 | 68.1 | 65.8 | 61.7 | — | 72.7 | 68.1 |

Transmittance was measured after the test specimens were washed. The solar energy transmittance was calculated for air mass 2. Each transmittance value represents a separate test specimen. Transmittance is expressed in percentage.

[a] Two sets of minicollectors were exposed for the same length of time but different dates.

[b] Material failed prior to this time.

Table A3. Solar Energy Transmittance Loss of Cover Plate Materials After Exposure as Single Covers to Natural Weathering in Gaithersburg, Maryland

| Material / Months Exposure | 3 | 6 | 12[a] | 12[a] | 18 | 24 | 36[a] | 36[a] | 48 |
|---|---|---|---|---|---|---|---|---|---|
| Solar Radiation (GJ/m$^2$) | 1.176 | 2.251 | 5.429 | 5.477 | 7.680 | 10.720 | 16.402 | 16.693 | 22.076 |
| Glass (0.01% iron oxide) | 1.6 | 0.4 | -0.6 | 0.5 | -0.4 | 2.2 | 0.7 | 9.5 | 0.5 |
| Glass (0.10% iron oxide) | -0.8 | 0.6 | -0.1 | -1.4 | 0.7 | 1.5 | 0.4 | 7.0 | 1.9 |
| Fluorinated (ethylene propylene) copolymer | -0.3 | 0.8 | 0.4 | 0 | 2.6 | 2.4 | 2.0 | 0.5 | 2.6 |
| Poly(vinyl fluoride) | 1.0 | 3.0 | 5.2 | 0.6 | 3.3 | 4.9 | 9.1 | 10.5 | 11.9 |
| Poly(ethylene terephthalate) | 1.1 | 3.2 | 3.5 | 0.6 | 1.7 | 9.7 | [b] | 1.2 | [b] |
| Acrylic | 0.6 | 3.4 | 4.7 | 3.4 | 1.7 | 1.9 | [b] | [b] | [b] |
| Poly(methyl methacrylate) | 1.5 | 1.9 | 1.8 | 1.7 | 2.9 | 5.2 | 4.7 | 9.7 | 4.2 |
| Polycarbonate | -0.1 | - | 1.1 | 0.9 | 2.5 | 6.5 | 3.9 | 3.8 | 5.1 |
| Fiber reinforced plastic (1.0 mm) | 0.6 | 2.1 | 1.8 | 1.9 | 3.8 | 6.0 | 8.6 | 17.8 | - |
| Fiber reinforced plastic (1.5 mm) | 3.5 | 6.2 | 1.9 | 9.0 | 4.0 | 12.9 | 20.8 | 19.1 | 29.4 |

The transmittance is expressed in percentage. This solar energy transmittance loss is the difference between the average for the control test specimens and the values obtained after the test specimen was washed (table A1). Negative values represent a gain in comparison with the average for the controls. This solar energy transmittance loss does not include the loss due to dirt on the surface. Losses due to dirt are tabulated in table A5.

[a] Two sets of minicollectors were exposed for the same length of time but different dates.

[b] Material failed prior to this time.

Table A4. Solar Energy Transmittance Loss of Cover Plate Materials After Exposure as Double Covers to Natural Weathering in Gaithersburg, Maryland

| | Outer Cover | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Months Exposure | 3 | 6 | 12[a] | 12[a] | 18 | 24 | 36[a] | 36[a] | 48 |
| Material / Solar Radiation (GJ/m$^2$) | 1.176 | 2.251 | 5.429 | 5.477 | 7.680 | 10.720 | 16.402 | 16.693 | 22.076 |
| Glass (0.01% iron oxide) | 1.1 | 0.6 | 0.0 | -0.8 | -0.4 | 1.5 | 1.7 | 6.8 | 0.1 |
| Glass (0.10% iron oxide) | -0.5 | 0.2 | 0.0 | -1.6 | -0.5 | -0.5 | 3.6 | 4.7 | 1.2 |
| Fluorinated (ethylene propylene) copolymer | 0.2 | 0.7 | 0.2 | 0.5 | 2.9 | 4.3 | 6.9 | 6.8 | 6.9 |
| Poly(vinyl fluoride) | 2.0 | 3.2 | 4.8 | -0.3 | 0.3 | 5.9 | 7.4 | 8.8 | [b] |
| Poly(ethylene terephthalate) | 0.7 | 1.7 | 2.8 | 0.6 | 1.0 | 5.0 | 4.2 | -0.8 | [b] |
| Acrylic | 1.6 | 3.1 | 2.9 | 2.9 | 3.0 | [b] | [b] | [b] | [b] |
| Poly(methyl methacrylate) | 0.4 | 2.0 | 1.2 | 1.4 | 2.3 | - | 5.1 | 6.3 | 3.1 |
| Polycarbonate | -0.8 | 1.5 | 0.4 | 1.1 | 1.7 | 6.9 | 5.8 | 3.8 | 6.9 |
| Fiber reinforced plastic (1.0 mm) | 1.1 | 2.4 | 3.0 | 2.8 | 5.8 | 8.2 | 10.3 | 14.3 | 15.9 |
| Fiber reinforced plastic (1.5 mm) | 5.2 | 0.9 | 1.7 | 5.6 | 9.7 | 9.8 | 14.3 | 27.9 | 23.6 |

| | Inner Cover | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Months Exposure | 3 | 6 | 12[a] | 12[a] | 18 | 24 | 36[a] | 36[a] | 48 |
| Material / Solar Radiation (GJ/m$^2$) | 1.176 | 2.251 | 5.429 | 5.477 | 7.680 | 10.720 | 16.402 | 16.693 | 22.076 |
| Glass (0.01% iron oxide) | 1.4 | 2.9 | -0.3 | -1.1 | 0.4 | 0.6 | 0.4 | 1.3 | 0.9 |
| Glass (0.10% iron oxide) | -0.9 | 0.5 | 0.2 | -1.5 | 0.4 | -0.7 | 0.4 | 1.2 | 0.0 |
| Fluorinated (ethylene propylene) copolymer | 0.1 | 0.4 | 0.2 | 0.0 | 0.1 | -0.5 | 0.6 | 0.2 | 0.8 |
| Poly(vinyl fluoride) | 1.1 | 1.8 | 0.8 | 0.7 | -0.3 | 0.5 | 0.4 | 0.9 | 3.8 |
| Poly(ethylene terephthalate) | 0.3 | 1.4 | 0.7 | 0.4 | 0.6 | 0.3 | 0.3 | 2.1 | [b] |
| Acrylic | 0.4 | 0.7 | 1.2 | 0.4 | 0.8 | [b] | [b] | [b] | [b] |
| Poly(methyl methacrylate) | 0.1 | 1.2 | 0.0 | 0.3 | 0.2 | - | 0.6 | -0.3 | 0.6 |
| Polycarbonate | 0.2 | 1.0 | -0.2 | 0.2 | -0.2 | 0.2 | 4.0 | -0.2 | 0.2 |
| Fiber reinforced plastic (1.0 mm) | 1.7 | 1.1 | 4.7 | 3.2 | 2.3 | 3.6 | 8.4 | 6.3 | 7.0 |
| Fiber reinforced plastic (1.5 mm) | 3.8 | 10.9 | 11.4 | 10.4 | 12.7 | 16.8 | - | 5.8 | 10.4 |

The transmittance is expressed in percentage. This solar energy transmittance loss is the difference between the average for the control test specimens and the values obtained after the test specimen was washed (table A2). Negative values represent a gain in comparison with the average for the controls. This solar energy transmittance loss does not include the loss due to dirt on the surface. Losses due to dirt are tabulated in table A6.

[a] Two sets of minicollectors were exposed for the same length of time but different dates.

[b] Material failed prior to this time.

Table A5. Solar Energy Transmittance Loss Due to Surface Dirt on Cover Plate Materials After Exposure as Single Covers in Gaithersburg, Maryland

| Months Exposure | 3 | 6 | 12[a] | 12[a] | 18 | 24 | 36[a] | 36[a] | 48 |
|---|---|---|---|---|---|---|---|---|---|
| Material / Solar Radiation (GJ/m$^2$) | 1.176 | 2.251 | 5.429 | 7.477 | 7.680 | 10.720 | 16.402 | 16.693 | 22.076 |
| Glass (0.01% iron oxide) | -1.3 | -0.2 | 3.6 | 4.7 | 4.9 | 4.1 | 1.8 | 1.6 | 1.1 |
| Glass (0.10% iron oxide) | 2.1 | 1.5 | 5.9 | 5.9 | 2.3 | 4.7 | 1.8 | 6.8 | 1.8 |
| Fluorinated (ethylene propylene) copolymer | 4.3 | 1.4 | 12.3 | 1.2 | 9.4 | 7.6 | 15.8 | 10.0 | 11.0 |
| Poly(vinyl fluoride) | 1.2 | 2.6 | 6.5 | 5.8 | 1.9 | 1.8 | 5.7 | 10.3 | 5.0 |
| Poly(ethylene terephthalate) | 0.5 | 0.4 | 8.0 | 4.8 | 4.2 | 1.3 | b/ | 7.2 | 6.0 |
| Acrylic | 2.4 | 1.6 | 7.0 | 4.1 | 8.6 | 3.7 | b/ | b/ | b/ |
| Poly(methyl methacrylate) | 1.4 | 2.6 | 8.8 | 3.9 | 3.2 | 3.9 | 2.2 | 4.9 | 6.2 |
| Polycarbonate | 0.9 | - | 8.7 | 4.2 | 5.3 | 3.1 | 1.3 | 4.8 | 5.3 |
| Fiber reinforced plastic (1.0 mm) | 0.6 | 1.9 | 9.8 | 4.4 | 2.5 | 2.9 | 0.3 | 3.7 | - |
| Fiber reinforced plastic (1.5 mm) | 0.0 | 2.4 | 10.4 | 4.6 | 3.9 | 4.3 | 3.3 | 6.3 | 1.3 |

The solar energy transmittance loss due to dirt is the difference between values obtained before and after washing the test specimen. Negative values represent a loss in transmittance after washing. Transmittance is expressed in percentage.

[a] Two sets of minicollectors were exposed for the same length of time but different dates.

[b] Material failed prior to this time.

Table A6. Solar Energy Transmittance Loss Due to Surface Dirt on Cover Plate Materials After Exposure as Double Covers in Gaithersburg, Maryland

| | Outer Cover | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Months Exposure | 3 | 6 | 12[a] | 12[a] | 18 | 24 | 36[a] | 36[a] | 48 |
| Material / Solar Radiation (GJ/m$^2$) | 1.176 | 2.251 | 5.429 | 5.477 | 7.680 | 10.720 | 16.402 | 16.693 | 22.076 |
| Glass (0.01% iron oxide) | 0.3 | 1.8 | 8.4 | 2.7 | 3.2 | 4.0 | 0.7 | 5.2 | 3.5 |
| Glass (0.10% iron oxide) | 1.2 | 1.8 | 8.2 | 4.8 | 1.8 | 4.8 | 2.2 | 3.5 | 7.0 |
| Fluorinated (ethylene propylene) copolymer | 1.3 | 2.9 | 3.5 | 8.8 | 6.2 | 7.0 | 4.8 | 8.0 | 6.9 |
| Poly(vinyl fluoride) | 0.9 | 6.0 | 5.5 | 6.8 | 3.5 | 3.0 | 1.6 | 10.6 | - |
| Poly(ethylene terephthalate) | 0.8 | 4.5 | 3.8 | 4.3 | 3.3 | 7.2 | 4.5 | 9.3 | [b] |
| Acrylic | 1.0 | 3.4 | 4.9 | 3.3 | 4.2 | [b] | [b] | [b] | [b] |
| Poly(methyl methacrylate) | 2.0 | 2.7 | 7.9 | 3.3 | 2.7 | - | 2.9 | 4.5 | 6.6 |
| Polycarbonate | 2.3 | 1.6 | 6.6 | 5.0 | 5.1 | 4.1 | 0.8 | 5.4 | 3.4 |
| Fiber reinforced plastic (1.0 mm) | 0.8 | 2.3 | 6.7 | 2.6 | 1.5 | 0.3 | 2.5 | 2.7 | 4.9 |
| Fiber reinforced plastic (1.5 mm) | 1.8 | 1.0 | 5.7 | 1.0 | 3.3 | 1.4 | 5.3 | 7.8 | 0.1 |

| | Inner Cover | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Months Exposure | 3 | 6 | 12[a] | 12[a] | 18 | 24 | 36[a] | 36[a] | 48 |
| Material / Solar Radiation (GJ/m$^2$) | 1.176 | 2.251 | 5.429 | 7.477 | 7.680 | 10.720 | 16.402 | 16.693 | 22.076 |
| Glass (0.01% iron oxide) | 0.0 | - | 1.7 | 0.0 | 0.2 | 0.3 | 1.9 | 0.8 | 0.4 |
| Glass (0.10% iron oxide) | 1.3 | - | 0.7 | 2.6 | 0.2 | 2.4 | 0.7 | 0.1 | 0.4 |
| Fluorinated (ethylene propylene) copolymer | 0.4 | 0.7 | 0.6 | 0.5 | 0.8 | 2.9 | 5.1 | 4.7 | 0.9 |
| Poly(vinyl fluoride) | 0.8 | 1.0 | 0.2 | 0.3 | 0.9 | 0.3 | 0.9 | -0.2 | [b] |
| Poly(ethylene terephthalate) | 0.3 | -0.6 | 1.0 | 0.6 | 0.6 | 0.5 | 0.0 | 1.2 | [b] |
| Acrylic | 0.3 | 0.8 | -0.1 | 0.4 | 0.3 | [b] | [b] | [b] | [b] |
| Poly(methyl methacrylate) | 0.8 | 0.2 | 0.9 | 0.9 | -0.3 | - | 0.2 | 1.4 | 0.4 |
| Polycarbonate | -0.1 | 0.2 | 1.2 | 0.5 | 0.7 | 0.6 | 0.5 | 1.2 | 0.9 |
| Fiber reinforced plastic (1.0 mm) | -1.4 | 0.5 | 0.6 | 0.3 | -0.8 | -1.8 | -0.4 | 1.2 | 1.5 |
| Fiber reinforced plastic (1.5 mm) | -0.3 | -0.2 | 0.1 | -2.3 | 0.3 | -1.1 | - | 3.9 | 2.0 |

The solar energy transmittance loss due to dirt is the difference between values obtained before and after washing the test specimen. Negative values represent a loss in transmittance after washing. Transmittance is expressed in percentage.

[a] Two sets of minicollectors were exposed for the same length of time but different dates.

[b] Material failed prior to this time.

Table A7. Solar Energy Transmittance of Cover Plate Materials After Exposure as Single Covers to Natural Weathering in Miami, Florida

| Months Exposure | 0 | 3 | 6 | 12[a] | 12[a] | 18 | 24 | 36[a] | 36[a] | 48 |
|---|---|---|---|---|---|---|---|---|---|---|
| Material Solar Radiation (GJ/m$^2$) | 0 | 1.455 | 2.864 | 6.344 | 6.523 | 9.333 | 13.398 | 19.398 | 19.859 | 26.333 |
| Glass (0.01% iron oxide) | 90.7 | 90.1 | 90.0 | 88.8 | 90.5 | 89.1 | 90.4 | 88.2 | 90.1 | 90.1 |
| Glass (0.10% iron oxide) | 87.4 | 88.0 | 87.0 | 88.6 | 87.0 | 85.9 | 87.3 | 86.9 | 85.9 | 87.0 |
| Fluorinated (ethylene propylene) copolymer | 96.0 | 95.7 | 95.3 | 95.2 | 94.9 | 92.4 | 91.7 | 95.6 | 90.0 | 95.0 |
| Poly(vinyl fluoride) | 92.5 | 91.9 | 91.4 | 88.5 | 91.7 | 87.3 | 87.9 | --- | 89.0 | 89.1 |
| Poly(ethylene terephthalate) | 86.3 | 86.3 | 86.1 | 81.4 | 78.6 | 81.5 | 81.5 | 85.5 | --- | 79.6 |
| Acrylic | 90.7 | 88.8 | 89.7 | 87.5 | 88.7 | 87.3 | [b] | [b] | [b] | [b] |
| Poly(methyl methacrylate) | 91.0 | 90.3 | 89.1 | 88.8 | 87.7 | 86.9 | 86.1 | 87.8 | 86.5 | 86.5 |
| Polycarbonate | 88.1 | 88.4 | 88.0 | 85.6 | 84.6 | 83.5 | 80.2 | 84.2 | --- | 84.5 |
| Fiber reinforced plastic (1.0 mm) | 86.3 | 84.9 | 85.0 | 82.2 | 84.4 | 77.2 | 75.5 | 65.0 | 67.2 | 64.2 |
| Fiber reinforced plastic (1.5 mm) | 78.5 | 72.9 | 71.5 | 70.0 | 70.6 | 58.9 | 63.0 | 62.2 | 61.6 | 51.0 |

Transmittance was measured after the test specimens were washed. The solar energy transmittance was calculated for air mass 2. Each transmittance value represents a separate test specimen. Transmittance is expressed in percentage.

[a] Two sets of minicollectors were exposed for the same length of time but different dates.

[b] Material failed prior to this time.

Table A8. Solar Energy Transmittance of Cover Plate Materials After Exposure as Double Covers to Natural Weathering in Miami, Florida

| | Outer Cover | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Months Exposure | 0 | 3 | 6 | 12[a] | 12[a] | 18 | 24 | 36[a] | 36[a] | 48 |
| Material / Solar Radiation (GJ/$m^2$) | 0 | 1.455 | 2.864 | 6.344 | 6.523 | 9.333 | 13.125 | 19.398 | 19.859 | 26.333 |
| Glass (0.01% iron oxide) | 90.7 | 91.0 | 90.3 | 92.4 | 90.1 | 89.3 | 89.2 | 89.0 | 89.3 | 90.5 |
| Glass (0.10% iron oxide) | 87.4 | 87.7 | 87.4 | 86.6 | 86.8 | 86.5 | 86.6 | 86.9 | 86.4 | 86.3 |
| Fluorinated (ethylene propylene) copolymer | 96.0 | 96.5 | 96.0 | 94.7 | 95.9 | 91.5 | 89.4 | 94.5 | -- | 95.4 |
| Poly(vinyl fluoride) | 92.5 | 91.6 | 91.1 | 89.5 | 91.5 | 92.5 | 88.1 | 89.6 | 89.1 | [b] |
| Poly(ethylene terephthalate) | 86.3 | 86.7 | 85.4 | 78.6 | 81.1 | 81.1 | 82.4 | [b] | 81.5 | [b] |
| Acrylic | 90.7 | 87.5 | 88.1 | 88.6 | 88.0 | [b] | [b] | [b] | [b] | [b] |
| Poly(methyl methacrylate) | 91.0 | 90.0 | 89.2 | 88.2 | 89.0 | 87.7 | 87.9 | 88.2 | 85.7 | 85.8 |
| Polycarbonate | 88.1 | 88.2 | 87.3 | 85.7 | 85.6 | 83.1 | 83.0 | 81.5 | 82.3 | -- |
| Fiber reinforced plastic (1.0 mm) | 86.3 | 88.5 | 85.5 | 79.0 | 77.2 | 77.8 | 71.3 | 68.8 | 61.8 | 64.2 |
| Fiber reinforced plastic (1.5 mm) | 78.5 | 80.9 | 78.2 | 58.8 | 67.9 | 54.2 | 53.7 | 56.4 | 44.6 | 57.3 |

| | Inner Cover | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Months Exposure | 0 | 3 | 6 | 12[a] | 12[a] | 18 | 24 | 36[a] | 36[a] | 48 |
| Material / Solar Radiation (GJ/$m^2$) | 0 | 1.455 | 2.864 | 6.344 | 6.523 | 9.333 | 13.125 | 19.398 | 19.859 | 26.333 |
| Glass (0.01% iron oxide) | 90.7 | 90.9 | 90.7 | 92.3 | 90.6 | 90.2 | 91.6 | 89.6 | 91.7 | 90.2 |
| Glass (0.10% iron oxide) | 87.4 | 87.7 | 87.2 | 88.0 | 86.9 | 87.3 | 88.4 | 87.2 | 87.9 | 87.4 |
| Fluorinated (ethylene propylene) copolymer | 96.0 | 96.4 | 96.1 | 95.3 | 95.7 | 95.8 | 96.1 | 95.9 | -- | 95.2 |
| Poly(vinyl fluoride) | 92.5 | 92.1 | 92.4 | 91.8 | 91.7 | 91.8 | 91.7 | [b] | 90.8 | [b] |
| Poly(ethylene terephthalate) | 86.3 | 86.4 | 85.7 | 85.0 | 85.8 | 85.5 | 86.2 | 80.0 | 85.7 | 82.5 |
| Acrylic | 90.7 | 89.7 | 91.1 | 89.7 | 90.3 | 90.0 | [b] | [b] | [b] | [b] |
| Poly(methyl methacrylate) | 91.0 | 91.4 | 91.5 | 91.5 | 90.4 | 90.4 | 91.3 | 90.0 | 90.2 | 90.7 |
| Polycarbonate | 88.1 | 88.3 | 88.4 | 89.0 | 87.5 | 87.3 | 88.2 | 85.9 | 87.3 | 84.2 |
| Fiber reinforced plastic (1.0 mm) | 86.3 | 87.9 | 86.1 | 83.0 | 79.4 | 74.8 | 74.8 | 76.2 | 76.2 | 77.3 |
| Fiber reinforced plastic (1.5 mm) | 78.5 | 67.0 | 72.1 | 58.7 | 68.6 | 66.4 | 56.6 | 56.6 | 68.9 | 61.0 |

Transmittance was measured after the test specimens were washed. The solar energy transmittance was calculated for air mass 2. Each transmittance value represents a separate test specimen. Transmittance is expressed in percentage.

[a] Two sets of minicollectors were exposed for the same length of time but different dates.

[b] Material failed prior to this time.

Table A9. Solar Energy Transmittance Loss of Cover Plate Materials After Exposure as Single Covers to Natural Weathering in Miami, Florida

| Months Exposure | 3 | 6 | 12[a] | 12[a] | 18 | 24 | 36[a] | 36[a] | 48 |
|---|---|---|---|---|---|---|---|---|---|
| Material / Solar Radiation ($GJ/m^2$) | 1.455 | 2.864 | 6.344 | 6.523 | 9.333 | 13.125 | 19.398 | 19.859 | 26.333 |
| Glass (0.01% iron oxide) | 0.6 | 0.7 | 0.9 | 0.2 | 1.6 | 0.3 | 2.5 | 0.6 | 0.6 |
| Glass (0.10% iron oxide) | -0.6 | 0.4 | -1.2 | 0.4 | 1.5 | 0.1 | 0.5 | 1.5 | 0.4 |
| Fluorinated (ethylene propylene) copolymer | 0.3 | 0.7 | 0.8 | 1.1 | 3.6 | 4.3 | 0.4 | 6.0 | 1.0 |
| Poly(vinyl fluoride) | 0.6 | 1.1 | 4.0 | 0.8 | 5.2 | 4.6 | - | 3.5 | 3.4 |
| Poly(ethylene terephthalate) | 0.0 | 0.2 | 4.9 | 7.7 | 4.8 | 4.8 | 0.8 | [b] | 6.7 |
| Acrylic | 1.9 | 1.0 | 3.2 | 2.0 | 3.4 | [b] | [b] | [b] | [b] |
| Poly(methyl methacrylate) | 0.7 | 1.9 | 2.2 | 2.3 | 4.1 | 4.9 | 3.2 | 4.5 | 4.5 |
| Polycarbonate | -0.3 | 0.1 | 2.5 | 3.5 | 4.6 | 7.9 | 3.9 | - | 3.6 |
| Fiber reinforced plastic (1.0 mm) | 1.4 | 1.3 | 4.1 | 1.9 | 9.1 | 0.9 | 21.3 | 19.1 | 22.1 |
| Fiber reinforced plastic (1.5 mm) | 5.4 | 7.0 | 8.5 | 7.9 | 19.6 | 15.9 | 16.1 | 16.9 | 27.5 |

Transmittance is expressed in percentage. This solar energy transmittance loss is the difference between the average for the control test specimens and the values obtained after the test specimen was washed (table A7). Negative values represent a gain in comparison with the average for the controls. This solar energy transmittance loss does not inclued loss due to dirt on the surface. Losses due to dirt are tabulated in table A11.

[a] Two sets of minicollectors were exposed for the same length of time but different dates.

[b] Material failed prior to this time.

Table A10. Solar Energy Transmittance Loss of Cover Plate Materials After Exposure as Double Covers to Natural Weathering in Miami, Florida

| | Outer Cover | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Months Exposure | 3 | 6 | 12[a] | 12[a] | 18 | 24 | 36[a] | 36[a] | 48 |
| Material / Solar Radiation (GJ/m$^2$) | 1.455 | 2.864 | 6.344 | 6.523 | 9.333 | 13.125 | 19.398 | 19.859 | 26.333 |
| Glass (0.01% iron oxide) | -0.3 | 0.4 | -1.7 | 0.6 | 1.4 | 1.5 | 1.7 | 1.4 | 0.2 |
| Glass (0.10% iron oxide) | 0.3 | 0.0 | 0.8 | 0.6 | 0.9 | 0.9 | 0.5 | 1.0 | 1.1 |
| Fluorinated (ethylene propylene) copolymer | -0.5 | 0.0 | 1.3 | 0.1 | 4.5 | 1.4 | 1.5 | - | 0.6 |
| Poly(vinyl fluoride) | 0.9 | 1.4 | 3.0 | 1.0 | 0.0 | 4.4 | 2.6 | 3.4 | [b] |
| Poly(ethylene terephthalate) | -0.4 | 0.9 | 7.7 | 5.2 | 5.2 | 3.9 | [b] | 4.8 | [b] |
| Acrylic | 3.2 | 2.6 | 2.1 | 2.7 | [b] | [b] | [b] | [b] | [b] |
| Poly(methyl methacrylate) | 1.0 | 1.8 | 2.8 | 2.0 | 3.3 | 3.1 | 2.8 | 5.3 | 5.2 |
| Polycarbonate | -0.1 | 0.8 | 2.4 | 2.5 | 5.0 | 5.1 | 6.6 | 5.8 | - |
| Fiber reinforced plastic (1.0 mm) | -2.2 | 0.8 | 7.3 | 9.1 | 8.5 | 15.0 | 17.5 | 24.5 | 22.1 |
| Fiber reinforced plastic (1.5 mm) | -2.4 | 0.3 | 19.7 | 10.4 | 24.1 | 24.8 | 21.9 | 33.9 | 21.2 |

| | Inner Cover | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Months Exposure | 3 | 6 | 12[a] | 12[a] | 18 | 24 | 36[a] | 36[a] | 48 |
| Material / Solar Radiation (GJ/m$^2$) | 1.455 | 2.864 | 6.344 | 6.523 | 9.333 | 13.125 | 19.398 | 19.859 | 26.333 |
| Glass (0.01% iron oxide) | -0.2 | 0.0 | -0.6 | 0.1 | 0.5 | -0.9 | 1.1 | -1.0 | 0.5 |
| Glass (0.10% iron oxide) | -0.3 | 0.2 | -0.6 | 0.5 | 0.1 | -1.0 | 0.2 | -0.5 | 0.0 |
| Fluorinated (ethylene propylene) copolymer | -0.4 | -0.1 | 0.7 | 0.3 | 0.2 | -0.1 | 0.1 | - | 0.8 |
| Poly(vinyl fluoride) | 0.4 | 0.1 | 0.7 | 0.8 | 0.7 | 0.8 | [b] | 1.7 | [b] |
| Poly(ethylene terephthalate) | -0.1 | 0.6 | 1.3 | 0.5 | 0.8 | 0.1 | 6.3 | 0.6 | 3.8 |
| Acrylic | 1.0 | -0.4 | 1.0 | 0.4 | 0.7 | [b] | [b] | [b] | [b] |
| Poly(methyl methacrylate) | -0.4 | -0.5 | 0.0 | 0.6 | 0.6 | -0.3 | 1.0 | 0.8 | 0.3 |
| Polycarbonate | -0.2 | -0.3 | 0.9 | 0.6 | 0.8 | -0.1 | 2.2 | 0.8 | 3.9 |
| Fiber reinforced plastic (1.0 mm) | -1.6 | 0.2 | 1.9 | 3.3 | 6.9 | 1.5 | 10.1 | 10.1 | 9.0 |
| Fiber reinforced plastic (1.5 mm) | 11.5 | 6.4 | 19.8 | 9.9 | 10.1 | 12.5 | 21.7 | 9.6 | 17.5 |

Transmittance is expressed in percentage. This solar energy transmittance loss is the difference between the average for the control test specimens and the values obtained after the test specimen was washed (table A8). Negative values represent a gain in comparison with the average for the controls. This solar energy transmittance loss does not inclued loss due to dirt on the surface. Losses due to dirt are tabulated in table A12.

[a] Two sets of minicollectors were exposed for the same length of time but different dates.

[b] Material failed prior to this time.

Table A11. Solar Energy Transmittance Loss Due to Surface Dirt on Cover Plate Materials After Exposure as Single Covers in Miami, Florida

| Months Exposure | 3 | 6 | 12[a] | 12[a] | 18 | 24 | 36[a] | 36[a] | 48 |
|---|---|---|---|---|---|---|---|---|---|
| Material / Solar Radiation (GJ/m$^2$) | 1.455 | 2.864 | 6.344 | 6.523 | 9.333 | 13.125 | 19.398 | 19.859 | 26.333 |
| Glass (0.01% iron oxide) | 3.1 | 2.2 | 2.6 | 3.3 | 4.1 | 5.5 | 3.9 | 2.7 | 3.5 |
| Glass (0.10% iron oxide) | 1.6 | 1.9 | 3.5 | 3.8 | 4.0 | 4.4 | 6.7 | 4.9 | 0.8 |
| Fluorinated (ethylene propylene) copolymer | 2.5 | 7.1 | 6.2 | 8.5 | 5.9 | 7.7 | 12.4 | 2.9 | 7.4 |
| Poly(vinyl fluoride) | 2.4 | 1.8 | 1.8 | 7.1 | 2.9 | 2.2 | [b] | 2.9 | 3.4 |
| Poly(ethylene terephthalate) | 2.5 | 3.6 | 3.4 | 7.1 | 10.2 | 5.7 | 8.1 | [b] | 3.2 |
| Acrylic | 1.6 | 4.8 | 3.0 | 3.9 | 1.9 | [b] | [b] | [b] | [b] |
| Poly(methyl methacrylate) | 1.7 | 2.2 | 1.5 | 4.2 | 5.2 | 2.6 | 3.7 | 2.6 | 1.7 |
| Polycarbonate | 2.5 | 2.9 | 3.9 | 6.4 | 5.9 | 4.8 | 4.7 | - | 1.7 |
| Fiber reinforced plastic (1.0 mm) | 2.3 | 2.6 | 3.4 | 6.7 | 2.9 | -1.1 | 4.5 | 2.9 | 8.8 |
| Fiber reinforced plastic (1.5 mm) | 3.7 | 0.5 | 6.2 | 4.3 | 5.9 | 6.5 | 6.7 | 6.6 | 17.0 |

The solar energy transmittance loss due to dirt is the difference between the value obtained before and after washing the test specimen. Negative values represent a loss in transmittance after washing. Transmittance is expressed in percentage.

[a] Two sets of minicollectors were exposed for the same length of time but different dates.

[b] Material failed prior to this time.

Table A12. Solar Energy Transmittance Loss Due to Surface Dirt on Cover Plate Materials After Exposure as Double Covers in Miami, Florida

| | Outer Cover | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Months Exposure | 3 | 6 | 12[a] | 12[a] | 18 | 24 | 36[a] | 36[a] | 48 |
| Material / Solar Radiation (GJ/m$^2$) | 1.455 | 2.864 | 6.344 | 6.523 | 9.333 | 13.125 | 19.398 | 19.859 | 26.333 |
| Glass (0.01% iron oxide) | 3.4 | 1.0 | 3.3 | 1.1 | 5.7 | 2.2 | 2.7 | 2.3 | 3.3 |
| Glass (0.10% iron oxide) | 1.7 | 2.1 | 1.8 | 5.7 | 3.9 | 2.1 | 4.7 | 3.1 | 16.1 |
| Fluorinated (ethylene propylene) copolymer | 6.2 | 5.8 | 6.2 | 7.4 | 2.9 | 0.9 | 11.4 | - | 10.6 |
| Poly(vinyl fluoride) | 2.0 | 0.5 | 1.4 | 7.2 | 6.6 | 1.7 | 2.6 | 2.0 | [b] |
| Poly(ethylene terephthalate) | 2.3 | 1.9 | 1.0 | 10.9 | 10.9 | 4.5 | [b] | 4.4 | [b] |
| Acrylic | 0.1 | 0.7 | 2.5 | 2.7 | [b] | [b] | [b] | [b] | [b] |
| Poly(methyl methacrylate) | -1.1 | 2.2 | 1.0 | 5.0 | 3.7 | 3.4 | 6.6 | 2.5 | 4.7 |
| Polycarbonate | -0.5 | 2.1 | 5.8 | 6.3 | 6.1 | 5.1 | 4.6 | 1.6 | - |
| Fiber reinforced plastic (1.0 mm) | 2.6 | 2.5 | 2.1 | 6.7 | 4.4 | 2.2 | 2.5 | 0.9 | 8.6 |
| Fiber reinforced plastic (1.5 mm) | 4.7 | 1.6 | 6.3 | 4.6 | 4.0 | 6.1 | 3.9 | 4.5 | 5.6 |

| | Inner Cover | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Months Exposure | 3 | 6 | 12[a] | 12[a] | 18 | 24 | 36[a] | 36[a] | 48 |
| Material / Solar Radiation (GJ/m$^2$) | 1.455 | 2.864 | 6.344 | 6.523 | 9.333 | 13.125 | 19.398 | 19.859 | 26.333 |
| Glass (0.01% iron oxide) | 3.0 | 1.6 | 3.2 | 2.4 | 8.1 | 3.1 | 2.8 | 0.8 | 11.1 |
| Glass (0.10% iron oxide) | 0.6 | 1.4 | 1.9 | 0.7 | 4.3 | 15.3 | 1.8 | 0.8 | 3.4 |
| Fluorinated (ethylene propylene) copolymer | 1.0 | 0.9 | -0.6 | 0.3 | 0.9 | 2.7 | 0.7 | - | 10.4 |
| Poly(vinyl fluoride) | 1.5 | 1.1 | 2.3 | 0.6 | 2.7 | 2.6 | - | 0.0 | - |
| Poly(ethylene terephthalate) | 0.8 | 0.2 | -0.3 | 0.4 | 0.1 | 1.2 | 0.2 | 2.7 | 22.2 |
| Acrylic | -0.3 | 1.5 | 0.1 | 0.8 | 3.2 | [b] | [b] | [b] | [b] |
| Poly(methyl methacrylate) | -1.6 | 1.7 | 3.1 | 0.4 | 9.2 | 1.8 | 3.5 | -0.3 | 11.3 |
| Polycarbonate | -1.6 | 1.0 | 7.2 | 0.3 | 5.6 | 6.2 | 2.7 | -1.0 | 2.9 |
| Fiber reinforced plastic (1.0 mm) | 2.8 | 1.1 | 0.0 | 1.2 | 1.7 | 3.6 | 7.7 | 1.5 | 17.5 |
| Fiber reinforced plastic (1.5 mm) | 2.2 | 2.2 | -0.1 | 1.3 | 3.9 | 2.3 | 5.2 | -0.6 | 2.9 |

The solar energy transmittance loss due to dirt is the difference between the value obtained before and after washing the test specimen. Negative values represent a loss in transmittance after washing. Transmittance is expressed in percentage.

[a] Two sets of minicollectors were exposed for the same length of time but different dates.

[b] Material failed prior to this time.

Table A13. Solar Energy Transmittance of Cover Plate Materials After Exposure as Single Covers to Natural Weathering in New River, Arizona

| Months Exposure | 0 | 3[a] | 3[a] | 6[a] | 6[a] | 12[a] | 12[a] | 18 | 24 | 36 | 48 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Material / Solar Radiation ($GJ/m^2$) | 0 | 1.422 | 2.012 | 3.487 | 5.123 | 8.006 | 8.259 | 11.642 | 16.370 | 24.414 | 33.038 |
| Glass (0.01% iron oxide) | 90.7 | 90.8 | 89.1 | 89.7 | 92.4 | 91.5 | 90.0 | 89.8 | 90.0 | 89.8 | 90.0 |
| Glass (0.10% iron oxide) | 87.4 | 86.9 | 87.4 | 87.1 | 89.3 | 87.2 | 87.1 | 88.0 | 87.2 | 89.4 | 86.6 |
| Fluorinated (ethylene propylene) copolymer | 96.0 | 95.8 | 95.3 | 95.3 | 95.6 | 94.7 | 95.2 | 95.4 | 95.5 | 95.2 | 95.3 |
| Poly(vinyl fluoride) | 92.5 | 91.4 | 90.7 | 91.0 | 91.3 | 90.5 | 91.3 | 90.7 | 91.4 | 88.9 | 90.7 |
| Poly(ethylene terephthalate) | 86.3 | 84.9 | 85.3 | 85.9 | 84.9 | 86.8 | 83.1 | 79.7 | [b] | [b] | [b] |
| Acrylic | 90.7 | 89.1 | 89.8 | 90.4 | 90.5 | 89.7 | 86.8 | [b] | [b] | [b] | [b] |
| Poly(methyl methacrylate) | 91.0 | 89.5 | 89.4 | 88.8 | 91.3 | 89.2 | 87.8 | 88.5 | 89.4 | 90.8 | 89.2 |
| Polycarbonate | 88.1 | 87.9 | 87.3 | 87.6 | 86.4 | — | 84.9 | 85.0 | 86.3 | 84.7 | 83.6 |
| Fiber reinforced plastic (1.0 mm) | 86.3 | 85.3 | 84.4 | 84.5 | 83.6 | 82.6 | 80.2 | 81.6 | 84.4 | 73.2 | 72.9 |
| Fiber reinforced plastic (1.5 mm) | 78.5 | 73.9 | 74.3 | 69.9 | 66.0 | 65.8 | 76.6 | 68.2 | 69.2 | 65.4 | 62.2 |

The solar energy transmittance loss due to dirt is the difference between the value obtained before and after washing the test specimen. Negative values represent a loss in transmittance after washing. Transmittance is expressed in percentage.

[a] Two sets of minicollectors were exposed for the same length of time but different dates.

[b] Material failed prior to this time.

Table A14. Solar Energy Transmittance of Cover Plate Materials After Exposure as Double Covers to Natural Weathering in New River, Arizona

| | Outer Cover | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Months Exposure | 0 | 3[a] | 3[a] | 6[a] | 6[a] | 12[a] | 12[a] | 18 | 24 | 36 | 48 |
| Material / Solar Radiation (GJ/m$^2$) | 0 | 1.422 | 2.012 | 3.487 | 5.123 | 8.006 | 8.259 | 11.642 | 16.370 | 24.414 | 33.038 |
| Glass (0.01% iron oxide) | 90.7 | 90.6 | 89.8 | 91.1 | 92.1 | 91.0 | 90.2 | 90.2 | 91.2 | 91.9 | 90.1 |
| Glass (0.10% iron oxide) | 87.4 | 87.1 | 86.6 | 87.1 | 89.4 | 88.9 | 87.1 | 87.1 | 87.9 | 88.8 | 87.5 |
| Fluorinated (ethylene propylene) copolymer | 96.0 | 95.6 | 95.3 | 95.7 | 95.6 | 95.9 | 95.8 | 94.9 | 95.5 | 95.8 | 95.3 |
| Poly(vinyl fluoride) | 92.5 | 91.8 | 90.4 | 89.7 | 91.7 | 90.7 | 91.3 | [b] | 89.5 | 90.4 | [b] |
| Poly(ethylene terephthalate) | 86.3 | 85.7 | 85.5 | 86.0 | 85.0 | 85.2 | [b] | 84.8 | [b] | [b] | [b] |
| Acrylic | 90.7 | 89.8 | 90.0 | 90.8 | 90.7 | 89.2 | [b] | [b] | [b] | [b] | [b] |
| Poly(methyl methacrylate) | 91.0 | 89.3 | 89.4 | 89.3 | 91.5 | 90.0 | 88.3 | 89.0 | 89.3 | 88.2 | 88.3 |
| Polycarbonate | 88.1 | 87.6 | 87.9 | 87.8 | 86.5 | 85.9 | 85.8 | 86.0 | 85.1 | 84.4 | 83.8 |
| Fiber reinforced plastic (1.0 mm) | 86.3 | 86.5 | 84.5 | 84.5 | 84.2 | 84.0 | 83.1 | 83.0 | 82.8 | 75.1 | 60.7 |
| Fiber reinforced plastic (1.5 mm) | 78.5 | 78.3 | 77.5 | 77.8 | 72.0 | 72.1 | 75.7 | 72.0 | 70.9 | 65.8 | 65.6 |

| | Inner Cover | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Months Exposure | 0 | 3[a] | 3[a] | 6[a] | 6[a] | 12[a] | 12[a] | 18 | 24 | 36 | 48 |
| Material / Solar Radiation (GJ/m$^2$) | 0 | 1.422 | 2.012 | 3.487 | 5.123 | 8.006 | 8.259 | 11.642 | 16.370 | 24.414 | 33.038 |
| Glass (0.01% iron oxide) | 90.7 | 90.6 | 88.3 | 90.1 | 92.3 | 90.3 | 90.4 | 90.1 | 89.7 | 90.0 | 90.0 |
| Glass (0.10% iron oxide) | 87.4 | 87.5 | 87.4 | 86.5 | 89.4 | 89.9 | 87.0 | 87.1 | 86.5 | 86.9 | 86.9 |
| Fluorinated (ethylene propylene) copolymer | 96.0 | 95.7 | 95.7 | 95.8 | 95.6 | 96.3 | 96.0 | 95.8 | 95.9 | 95.3 | 95.4 |
| Poly(vinyl fluoride) | 92.5 | 91.8 | 91.1 | 91.7 | 91.4 | 92.1 | 91.8 | [b] | [b] | [b] | [b] |
| Poly(ethylene terephthalate) | 86.3 | 85.7 | 85.5 | 84.5 | 84.9 | 85.7 | [b] | 85.1 | [b] | [b] | [b] |
| Acrylic | 90.7 | 90.7 | 90.1 | 90.5 | 90.3 | 90.8 | [b] | 91.0 | [b] | [b] | [b] |
| Poly(methyl methacrylate) | 91.0 | 89.9 | 90.7 | 90.6 | 91.3 | 90.7 | 90.6 | 90.4 | 90.8 | 90.1 | 90.1 |
| Polycarbonate | 88.1 | 87.4 | 87.8 | 87.8 | 88.1 | 87.6 | 87.6 | 87.5 | 87.2 | — | 87.4 |
| Fiber reinforced plastic (1.0 mm) | 86.3 | 84.2 | 83.0 | 84.5 | 82.7 | 80.7 | 82.4 | 77.8 | 80.1 | 78.8 | 76.3 |
| Fiber reinforced plastic (1.5 mm) | 78.5 | 70.7 | 67.9 | 69.5 | 64.0 | 70.7 | 65.8 | 59.1 | 68.4 | 64.7 | — |

Transmittance was measured after the test specimens were washed. The solar energy transmittance was calculated for air mass 2. Each transmittance value represents a separate test specimen. Transmittance is expressed in percentage.

[a] Two sets of minicollectors were exposed for the same length of time but different dates.

[b] Material failed prior to this time.

Table A15. Solar Energy Transmittance Loss of Cover Plate Materials After Exposure as Single Covers to Natural Weathering in New River, Arizona

| Months Exposure | 3[a] | 3[a] | 6[a] | 6[a] | 12[a] | 12[a] | 18[a] | 24 | 36 | 48 |
|---|---|---|---|---|---|---|---|---|---|---|
| Material / Solar Radiation (GJ/m$^2$) | 1.422 | 2.012 | 3.487 | 5.123 | 8.006 | 8.259 | 11.642 | 16.370 | 24.414 | 33.038 |
| Glass (0.01% iron oxide) | -0.1 | 1.6 | 1.0 | -1.7 | -0.8 | 0.7 | 0.9 | 0.7 | 0.9 | 0.7 |
| Glass (0.10% iron oxide) | 0.5 | 0.0 | 0.3 | -1.9 | 0.2 | 0.3 | -0.6 | 0.2 | -2.0 | 0.8 |
| Fluorinated (ethylene propylene) copolymer | 0.2 | 0.7 | 0.7 | 0.4 | 1.3 | 0.8 | 0.6 | 0.5 | 0.8 | 0.7 |
| Poly(vinyl fluoride) | 1.1 | 1.8 | 1.5 | 1.2 | 2.0 | 1.2 | 1.8 | 1.1 | 3.4 | 1.8 |
| Poly(ethylene terephthalate) | 1.4 | 1.0 | 0.4 | 1.4 | -0.5 | 3.2 | 6.6 | [b] | [b] | [b] |
| Acrylic | 1.6 | 0.9 | 0.3 | 0.2 | 1.0 | 3.9 | [b] | [b] | [b] | [b] |
| Poly(methyl methacrylate) | 1.5 | 1.6 | 2.2 | -0.3 | 1.8 | 3.2 | 2.5 | 1.6 | 0.2 | 1.8 |
| Polycarbonate | 0.2 | 0.8 | 0.5 | 1.7 | - | 3.2 | 3.1 | 1.8 | 3.4 | 4.5 |
| Fiber reinforced plastic (1.0 mm) | 1.0 | 1.9 | 1.8 | 2.7 | 3.7 | 6.1 | 4.7 | 1.9 | 13.1 | 13.4 |
| Fiber reinforced plastic (1.5 mm) | 4.6 | 4.2 | 8.6 | 12.5 | 12.5 | 1.9 | 10.3 | 13.1 | 16.3 | 16.3 |

Transmittance is expressed in percentage. This solar energy transmittance loss is the difference between the average for the control test specimens and the value obtained after the test specimen was washed (table A13). Negative values represent a gain in comparison with the average of controls. This solar energy transmittance loss does not include loss due to dirt on the surface. Losses due to dirt are tabulated in table A17.

[a] Two sets of minicollectors were exposed for the same length of time but different dates.

[b] Material failed prior to this time.

Table A16. Solar Energy Transmittance Loss of Cover Plate Materials After Exposure as Double Covers to Natural Weathering in New River, Arizona

| | Outer Cover | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Months Exposure | 3[a] | 3[a] | 6[a] | 6[a] | 12[a] | 12[a] | 18 | 24 | 36 | 48 |
| Material / Solar Radiation (GJ/m$^2$) | 1.422 | 2.012 | 3.487 | 5.123 | 8.006 | 8.259 | 11.642 | 16.370 | 24.414 | 33.038 |
| Glass (0.01% iron oxide) | 0.1 | 0.9 | -0.4 | -1.4 | -0.3 | 0.5 | 0.5 | -0.5 | -1.2 | 0.6 |
| Glass (0.10% iron oxide) | 0.3 | 0.8 | 0.3 | -2.0 | -1.5 | 0.3 | 0.3 | -0.5 | -1.4 | -0.1 |
| Fluorinated (ethylene propylene) copolymer | 0.4 | 0.7 | 0.3 | 0.4 | 0.1 | 0.2 | 1.1 | 0.5 | 0.2 | 0.9 |
| Poly(vinyl fluoride) | 0.7 | 2.1 | 2.8 | 0.8 | 1.8 | 1.2 | [b] | 3.0 | 2.1 | [b] |
| Poly(ethylene terephthalate) | 0.6 | 0.8 | 0.3 | 1.3 | 1.1 | [b] | 1.5 | [b] | [b] | [b] |
| Acrylic | 0.9 | 0.7 | -0.1 | 0.0 | 1.5 | [b] | [b] | [b] | [b] | [b] |
| Poly(methyl methacrylate) | 1.7 | 1.6 | 1.7 | -0.5 | 1.0 | 2.7 | 2.0 | 1.7 | 2.8 | 2.7 |
| Polycarbonate | 0.5 | 0.2 | 0.3 | 1.6 | 2.2 | 2.3 | 2.1 | 3.0 | 3.7 | 4.3 |
| Fiber reinforced plastic (1.0 mm) | -0.2 | 1.8 | 1.8 | 2.1 | 2.3 | 3.2 | 3.3 | 3.5 | 11.2 | 25.6 |
| Fiber reinforced plastic (1.5 mm) | 0.2 | 1.0 | 0.7 | 6.5 | 6.4 | 2.8 | 6.5 | 7.6 | 12.7 | 12.9 |

| | Inner Cover | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Months Exposure | 3[a] | 3[a] | 6[a] | 6[a] | 12[a] | 12[a] | 18 | 24 | 36 | 48 |
| Material / Solar Radiation (GJ/m$^2$) | 1.422 | 2.012 | 3.487 | 5.123 | 8.006 | 8.259 | 11.642 | 16.370 | 24.414 | 33.038 |
| Glass (0.01% iron oxide) | 0.1 | 2.4 | 0.6 | -1.6 | 0.4 | 0.3 | 0.6 | 1.0 | 0.7 | 0.7 |
| Glass (0.10% iron oxide) | -0.1 | 0.0 | 0.9 | -2.0 | -2.5 | 0.4 | 0.3 | 0.9 | 0.5 | 0.5 |
| Fluorinated (ethylene propylene) copolymer | 0.3 | 0.3 | 0.2 | 0.4 | -0.3 | 0.0 | 0.2 | 0.1 | 0.7 | 0.6 |
| Poly(vinyl fluoride) | 0.7 | 1.4 | 0.8 | 1.1 | 0.4 | 0.7 | [b] | [b] | [b] | [b] |
| Poly(ethylene terephthalate) | 0.6 | 0.8 | 1.8 | 1.4 | 0.6 | [b] | 1.2 | [b] | [b] | [b] |
| Acrylic | 0.0 | 0.6 | 0.2 | 0.4 | -0.1 | [b] | -0.3 | [b] | [b] | [b] |
| Poly(methyl methacrylate) | 1.1 | 0.3 | 0.4 | -0.3 | 0.3 | 0.4 | 0.6 | 0.2 | 0.9 | 0.9 |
| Polycarbonate | 0.7 | 0.3 | 0.3 | 0.0 | 0.5 | 0.5 | 0.6 | 0.9 | – | 0.7 |
| Fiber reinforced plastic (1.0 mm) | 2.1 | 3.3 | 1.8 | 3.6 | 5.6 | 3.9 | 8.5 | 6.2 | 7.5 | 10.0 |
| Fiber reinforced plastic (1.5 mm) | 7.8 | 10.6 | 9.0 | 14.5 | 7.8 | 12.7 | 19.4 | 10.1 | 13.8 | [b] |

Transmittance is expressed in percentage. This solar energy transmittance loss is the difference between the average for the control test specimens and the value obtained after the test specimen was washed (table A14). Negative values represent a gain in comparison with the average of controls. This solar energy transmittance loss does not include loss due to dirt on the surface. Losses due to dirt are tabulated in table A18.

[a] Two sets of minicollectors were exposed for the same length of time but different dates.

[b] Material failed prior to this time.

Table A17. Solar Energy Transmittance Loss Due to Surface Dirt on Cover Plate Materials After Exposure as Single Covers in New River, Arizona

| Months Exposure | 3a/ | 3a/ | 6a/ | 6a/ | 12a/ | 12a/ | 18 | 24 | 36 | 48 |
|---|---|---|---|---|---|---|---|---|---|---|
| Material / Solar Radiation ($GJ/m^2$) | 1.422 | 2.012 | 3.487 | 5.123 | 8.006 | 8.259 | 11.642 | 16.370 | 24.414 | 33.038 |
| Glass (0.01% iron oxide) | 1.4 | -0.4 | 1.2 | 4.9 | 1.9 | 4.5 | 2.3 | 3.2 | -1.2 | 3.0 |
| Glass (0.10% iron oxide) | 0.4 | -0.2 | 1.7 | 3.6 | 0.6 | 1.2 | 4.0 | 4.6 | 2.1 | 3.6 |
| Fluorinated (ethylene propylene) copolymer | 2.5 | 1.8 | 2.4 | 1.1 | 3.1 | 4.3 | 3.8 | 5.4 | 5.8 | 6.3 |
| Poly(vinyl fluoride) | 0.4 | 1.3 | 0.8 | 0.7 | 0.9 | 4.6 | 3.0 | 3.9 | -1.4 | 4.9 |
| Poly(ethylene terephthalate) | 0.3 | 2.1 | 2.0 | 1.0 | 4.3 | 12.1 | 2.9 | b/ | b/ | b/ |
| Acrylic | 0.0 | 1.9 | 1.6 | 1.7 | 1.6 | 7.8 | b/ | b/ | b/ | b/ |
| Poly(methyl methacrylate) | 0.8 | 0.8 | 1.7 | 4.5 | 2.4 | 2.7 | 3.8 | 5.5 | 1.9 | 3.7 |
| Polycarbonate | 0.7 | 1.2 | 1.7 | 2.2 | - | 0.8 | 4.1 | 2.3 | 1.2 | 3.1 |
| Fiber reinforced plastic (1.0 mm) | 1.8 | 0.1 | 0.7 | 1.3 | 1.7 | 1.0 | 6.6 | 7.2 | 3.8 | 6.3 |
| Fiber reinforced plastic (1.5 mm) | 0.1 | 1.9 | 1.4 | -0.7 | 0.2 | 13.6 | 3.5 | 8.4 | 4.5 | 2.7 |

The solar energy transmittance loss due to dirt is the difference between the solar energy transmittance measurements made before and after washing the test specimen. Negative values represent a loss in transmittance after washing. Transmittance is expressed in percentage.

a/ Two sets of minicollectors were exposed for the same length of time but different dates.

b/ Material failed prior to this time.

Table A18. Solar Energy Transmittance Loss Due to Surface Dirt on Cover Plate Materials After Exposure as Double Covers in New River, Arizona

| | Outer Cover | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Months Exposure | 3a/ | 3a/ | 6a/ | 6a/ | 12a/ | 12a/ | 18 | 24 | 36 | 48 |
| Material / Solar Radiation (GJ/m$^2$) | 1.422 | 2.012 | 3.487 | 5.123 | 8.006 | 8.259 | 11.642 | 16.370 | 24.414 | 33.038 |
| Glass (0.01% iron oxide) | 0.2 | 0.1 | 1.9 | 5.8 | 0.3 | 2.1 | 3.0 | 5.4 | 2.5 | 0.5 |
| Glass (0.10% iron oxide) | 0.2 | 0.5 | 1.0 | 4.6 | 1.8 | 3.5 | 2.8 | 4.1 | 1.5 | 3.9 |
| Fluorinated (ethylene propylene) copolymer | 2.5 | 1.7 | 2.2 | 1.2 | 2.8 | 4.0 | 3.4 | 1.1 | 6.9 | 4.8 |
| Poly(vinyl fluoride) | 0.8 | 0.0 | 0.7 | 1.2 | 2.0 | 3.8 | b/ | 2.3 | 3.9 | b/ |
| Poly(ethylene terephthalate) | 0.1 | 0.9 | 1.9 | 1.2 | 1.4 | b/ | 7.6 | b/ | b/ | b/ |
| Acrylic | 1.6 | 1.8 | 1.3 | 2.3 | 0.4 | b/ | b/ | b/ | b/ | b/ |
| Poly(methyl methacrylate) | 0.0 | 2.0 | 1.4 | 4.1 | 3.5 | 2.0 | 2.9 | 4.8 | 1.2 | 3.2 |
| Polycarbonate | 1.1 | 1.7 | 1.4 | 2.0 | 2.0 | 1.0 | 3.4 | 2.6 | 0.0 | 0.9 |
| Fiber reinforced plastic (1.0 mm) | 0.8 | 1.1 | 0.5 | 3.7 | 0.7 | 5.5 | 3.5 | 4.8 | 1.9 | 6.2 |
| Fiber reinforced plastic (1.5 mm) | 0.8 | 0.8 | 3.8 | 2.9 | 2.0 | 3.0 | 3.8 | 9.1 | 8.2 | 7.7 |

| | Inner Cover | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Months Exposure | 3a/ | 3a/ | 6a/ | 6a/ | 12a/ | 12a/ | 18 | 24 | 36 | 48 |
| Material / Solar Radiation (GJ/m$^2$) | 1.422 | 2.012 | 3.487 | 5.123 | 8.006 | 8.259 | 11.642 | 16.370 | 24.414 | 33.038 |
| Glass (0.01% iron oxide) | -0.5 | -1.0 | 0.9 | 3.3 | 3.2 | 0.2 | 0.8 | 1.9 | -0.3 | 4.3 |
| Glass (0.10% iron oxide) | -0.4 | 0.7 | -0.1 | 2.5 | 1.7 | 0.5 | 0.1 | 0.6 | 0.1 | 3.7 |
| Fluorinated (ethylene propylene) copolymer | 0.0 | 0.4 | 0.3 | 0.0 | 2.1 | 0.8 | 0.7 | 2.2 | 0.5 | 0.2 |
| Poly(vinyl fluoride) | 0.3 | 1.0 | 0.6 | 0.0 | 2.3 | 0.4 | b/ | b/ | b/ | b/ |
| Poly(ethylene terephthalate) | 0.1 | 0.2 | -0.5 | -0.1 | 1.7 | b/ | 0.4 | b/ | b/ | b/ |
| Acrylic | 0.9 | 1.2 | 0.8 | 0.2 | 1.9 | b/ | 1.8 | b/ | b/ | b/ |
| Poly(methyl methacrylate) | -0.8 | 1.0 | 0.0 | 1.7 | 1.5 | 0.5 | 1.0 | 2.8 | 0.3 | 1.6 |
| Polycarbonate | 0.2 | 0.6 | 0.4 | 0.7 | 2.1 | 0.4 | 1.7 | 4.1 | - | 2.7 |
| Fiber reinforced plastic (1.0 mm) | 0.0 | -1.2 | 0.3 | 0.0 | 0.8 | 0.0 | 3.7 | 5.9 | 2.7 | 2.8 |
| Fiber reinforced plastic (1.5 mm) | -0.7 | -1.1 | 0.9 | -0.2 | 6.4 | 9.4 | 2.2 | 4.3 | 0.2 | - |

The solar energy transmittance loss due to dirt is the difference between the solar energy transmittance measurements made before and after washing the test specimen. Negative values represent a loss in transmittance after washing. Transmittance is expressed in percentage.

a/ Two sets of minicollectors were exposed for the same length of time but different dates.

b/ Material failed prior to this time.

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10. SUPPLEMENTARY NOTES

☐ 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)*

Weathering studies were performed to obtain data on the performance and durability of cover plate materials for flat plate solar collectors used in solar heating and cooling systems. Ten materials were evaluated to assess their durability after natural weathering and artificial weathering with a xenon arc light. The materials were weathered for four years on small mini-collectors in Arizona, Florida, and Maryland after which the solar energy transmittance and the effect of dirt on the transmittance were measured. The tensile properties of selected film materials were also assessed after weathering. The effects of the natural weathering are compared: (1) for materials exposed as inner and outer cover plates for each weathering site; (2) for the three weathering sites; and (3) with materials artificially weathered with a xenon arc light.

12. KEY WORDS *(Six to twelve entries; alphabetical order: capitalize only proper names; and separate key words by semicolons)*

artificial weathering; cover plate materials; durability; natural weathering; solar collectors; solar energy; solar energy transmittance; tensile properties; weathering of cover plates.

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