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Effects of Air Mass and Integration Methods on Results for Optical Property Measurements of Solar Cover Plate and Absorber Materials

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EFFECTS OF AIR MASS AND INTEGRATION METHODS ON RESULTS FOR OPTICAL PROPERTY MEASUREMENTS OF SOLAR COVER PLATE AND ABSORBER MATERIALS

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

ABSTRACT

This study was undertaken to compare methods of calculating the transmittance of cover plate materials and the reflectance of absorber materials. The study was limited to evaluation of factors which influence the results with method A of ASTM E 424. Optical data were obtained for both aged and unaged test specimens using an integrating sphere spectrophotometer. The data were integrated using: (1) the weighted and selected ordinate methods in ASTM E 424, Method A, at air mass 2.0, and (2) the selected ordinate method at air mass 1.5 and 1.0. The solar reflectance and solar transmittance values calculated using the various methods are presented in this report along with discussions of the impact of the data in terms of possible revisions to ASTM E 424.

Keywords: air mass; ASTM E 424; integrating sphere spectrophotometer; reflectance; selected ordinate; solar absorber materials; solar cover plates; transmittance; weighted ordinate.

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ACKNOWLEDGMENT

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1. INTRODUCTION

1.1 BACKGROUND

Solar transmittance and reflectance are the key attributes required, respectively, of cover plate and absorber coating materials for solar collectors. Transmittance and reflectance values are used by collector manufacturers, architects, and researchers in choosing materials, in calculating expected thermal efficiency of collectors and in measuring short-term and long-term performance of collectors and materials. ASTM E 424-71, Standard Methods of Test for Solar Energy Transmittance and Reflectance (Terrestrial) of Sheet Materials [1][1/] is currently being revised by the American Society for Testing and Materials Committee E44 on Solar Energy Conversion. This study was undertaken to develop data to assess the effect of several variables in ASTM E 424-71 to determine if revision of these parts is necessary. ASTM E 424 is the most commonly used standard method for determining solar transmittance and reflectance.

ASTM E 424 contains two methods of measurement. Method A is performed using an integrating sphere spectrophotometer in a laboratory and is applicable for both transmittance and reflectance. Method B is performed outdoors using a pyranometer in an enclosure as the detector and the sun as the energy source. It is applicable only for transmittance. For method A, the value of the solar energy transmitted or reflected is obtained by measuring the spectral transmittance or reflectance with a spectrophotometer and then integrating the spectral data over a standard solar energy distribution curve for air mass 2.0. Two methods of integration, weighted ordinates and selected ordinates, are provided in ASTM E 424. Since the user of method A may arbitrarily choose either method of integration, it is essential to determine if the two methods of integration provide the same results for all materials.

It is also important to determine the effect of air mass on the solar optical properties of solar collector materials. ASTM E 424 states that both method A and method B produce essentially equivalent results. However, method A requires that the solar energy spectral distribution for air mass 2.0 be used, while no similar limitation is placed on measurements made using method B. Transmittance values determined outdoors with method B are seldom measured under conditions which relate to air mass 2.0. They are more likely to be measured when the air mass is lower than 2.0.

Most materials used in solar energy systems have distinctly different spectral transmittance and reflectance curves. For some materials the curve is essentially flat over the entire spectral range of solar energy, while for other materials the curve is not flat. As a consequence, no single intervals spectral characteristics can be considered typical of all materials used in solar collectors.

[1/] Numbers in brackets refer to references in section 7.

Clearly, two factors have a potential to influence the transmittance and reflectance values obtained using method A of E 424. These factors are method of integration, and solar energy spectral distribution (air mass). The importance of each factor depends on the material. The effect of each variable was examined in this study.

1.2 OBJECTIVES

The objectives of this study were: (1) to determine if the selected and weighted ordinate methods of integration produce equal transmittance and reflectance values for typical materials; (2) to determine if the solar energy spectral distribution (air mass) used in the calculations affects the transmittance and reflectance values for typical materials; and (3) to develop recommendations for revisions to E 424, method A, if necessary.

1.3 APPROACH

To accomplish these objectives, spectral transmittance and reflectance data generated in two previous studies [2, 3] were used. The data included both weathered and unweathered cover plate and absorber materials. The approach was: a) to develop computer programs to integrate spectral data using the air mass 2, weighted and selected ordinate methods of E 424, b) to calculate and compare the transmittance and reflectance using the weighted and selected ordinate integration methods for selected materials, c) to develop programs to integrate the spectral data using the solar energy distributions for air mass 1.0 and 1.5, and d) to calculate and compare transmittance and reflectance for the selected materials at air masses of 2.0, 1.5 and 1.0.

2. FACTORS INFLUENCING METHOD A CALCULATIONS

2.1 RELATIONSHIP OF SOLAR ENERGY DISTRIBUTION TO AIR MASS

The solar energy radiation received at the earth's surface is dependent upon geographic location, day of year, and time of day. The spectral distribution of the emitted solar energy is fixed and corresponds closely to the spectrum of a 5762°K black body source. The spectral distribution of the energy received at the earth's surface differs from that of the emitted energy because of scattering and absorption processes in the atmosphere. The degree to which these processes modify the spectral distribution depends on the path length traversed through the atmosphere. For all but very high solar zenith angles (i.e., $\theta_z \leq 70°$) this path length is directly proportional to the air mass parameter, m, defined as

$$m = \frac{1}{\cos \theta_z}$$

where m = air mass, and

θ_z = angle subtended by the zenith and the line of sight to the sun.

The air mass is equal to one when the sun is directly overhead and is greater than one as the line of sight to the sun deviates from the zenith. For example, when the sun reaches an angle of 60° between the zenith and the line of sight, the distance through which the beam travels before it reaches the earth has doubled, and the air mass is equal to 2.

By convention, the air mass is taken to be equal to zero outside the earth's atmosphere.

The solar energy spectral distributions for air masses 1.0, 1.5, and 2.0 are illustrated in figure 1. These air mass values correspond to solar zenith angles of 0°, 48°, and 60°, respectively. Conditions corresponding to air mass 1.0 never occur in the continental United States. The authors of ASTM E 424 chose air mass 2.0, zenith angle 60°, as representative, but most solar collectors that are in service are exposed to more hours of radiation that approximates air mass 1.5 (θ_z = 48.19°). The most important differences between the distributions occur in the ultraviolet and visible regions.

2.2 SPECTRAL PROPERTIES OF THE MATERIAL

The spectral reflectance and transmittance properties of absorber and cover plate materials vary depending upon the type of material. Absorber materials can be categorized as either selective or nonselective. The spectral reflectance of a nonselective absorber is a relatively flat line over the range of solar energy (figure 2), while the spectral reflectance of a selective absorber changes over the range of solar energy (figure 3), with its reflectance generally increasing above 1000 nm.

Other than vertical shifts, the differences in the spectral transmittance curves of cover plate materials occur primarily in two regions: (1) the ultraviolet region (below 400 nm), and (2) the near infrared region above 1100 nm (figures 4 and 5). The absorption bands in these regions are dependent upon the material composition. Vertical shifts in the flat parts of the transmittance curves are dependent upon both material composition and thickness.

2.3 INTEGRATION METHODS

2.3.1 Weighted Ordinate

In the weighted ordinate method of integration the solar spectrum is divided into a finite number of equal intervals, e.g., 50 nm. Each interval is integrated to determine the energy, then these energies are summed to obtain the total energy under the curve. The relative energy for each interval is then calculated and is represented as a percentage of the total energy. The wavelength at the midpoint of the interval (e.g., 450 nm represents 425 to 475 nm) is then used as the wavelength for the weighted ordinate. The total solar energy transmittance is obtained by integrating over the standard solar energy distribution as follows,

$$T_{se} = \sum_{\lambda_1}^{\lambda_2} T_\lambda \cdot E_\lambda$$

where T_{se} = total solar energy transmittance in percent
λ = wavelength of weighted ordinate
T_λ = transmittance at wavelength λ
E_λ = fraction of the total energy in the interval centered at the wavelength λ

Reflectance is obtained using a similar equation.

ASTM E 424 contains the weighted ordinates for air mass 2 at 50 mm intervals.

2.3.2 Selected Ordinates

In the selected ordinate method the solar spectrum is divided into a finite number of intervals. However, instead of equal intervals, as used in the weighted ordinate method, the spectrum is divided into intervals that represent equal increments of solar energy. The spectral transmittance or reflectance of the material is thus weighted equally in each such interval and no further weighting is necessary [5]. The wavelength at the midpoint of the interval is the selected ordinate. The total solar energy transmittance or reflectance is determined by summing the transmittance values for each of the selected ordinates and dividing this value by the number of selected ordinates. E 424 uses twenty selected ordinates for air mass 2. Other numbers (50 and 100) of selected ordinates have also been used when greater accuracy was desired.

3. DESCRIPTION OF DATA AND CALCULATIONS

3.1 MEASUREMENT OF OPTICAL PROPERTIES

The spectral transmittance and reflectance of materials were measured as described in ASTM E 424, method A over the spectral range from 300 to 2150 nm utilizing a spectrophotometer with a 76 mm (3 in) diameter integrating sphere. The illumination and viewing mode was normal diffuse for transmittance and diffuse for reflectance. The transmittance and reflectance measurements were made by placing the test specimens in direct contact with the sphere aperture so that the incident monochromatic radiation was normal to the plane of the specimen for transmittance specimens and within 7 degrees of perpendicularity to the plane of the reflectance specimens. The spectral reflectance and transmittance data were digitized and sent directly to a computer where they were stored for future manipulation.

3.2 DESCRIPTION OF MATERIALS

The spectral transmittance and reflectance data analyzed in this study were obtained from previous studies on absorber materials [3] and cover plate materials [2]. These studies investigated the performance of materials before and after artificial weathering and natural weathering. Data sets representing typical materials and exposures were selected for analysis in this study. Four absorbers, two selective and two nonselective, were chosen. The materials are listed in table 1. The reflectance data (from absorber materials) used in this study were for: (1) control specimens (no natural or artificial weathering), (2) specimens exposed to oven aging, and (3) specimens exposed to humidity at elevated temperatures. The spectra reflectance curves for the control specimens are shown in figures 2 and 3. The five cover plate materials used in this study illustrate the range of cover materials used in solar collectors. They include glass, plastic film and plastic sheet, and are also listed in (table 1). The transmittance data (for cover plate materials) used in this study were from: (1) control specimens, and (2) specimens exposed to oven aging. The spectral transmittance curves for the control specimens are given in figures 4 and 5.

3.3 CALCULATION OF OPTICAL PROPERTIES

The two integration methods were compared using air mass 2 data from E 424-71. The selected and weighted ordinate values used in the calculations are given in tables 2 and 3.

Three air masses, i.e., 2.0, 1.5, and 1.0, were chosen to determine the effect of different air masses on the calculation of reflectance and transmittance. These represent zenith angles of 60°, 48.19°, and 0°. The selected ordinate integration method was used for these comparisons. For air mass 2 the twenty selected ordinates in E 424 were used, while the data for air masses 1.5 and 1.0 were taken from "the sensitivity of solar transmittance, reflectance and absorptance of selected averaging procedures and solar irradiance," [6] and "solar spectral irradiance at ground level" [7]. Fifty selected ordinates were produced for air masses 1.5 and 1.0. These are given in (tables 4 and 5), respectively. Note that for both air mass 1.5 and air mass 1.0, the last ordinate is beyond the range of the spectrophotometer (300-2150 nm). The approach used in this study to calculate the out-of-limit ordinate was: (1) to sum each of the first 49 ordinates; (2) to the above value, add the value of the 49th ordinate a second time to give a total of 50 ordinates; and (3) to divide the total by 50 to give the solar transmittance or reflectance value for air mass 1.5 and air mass 1.0. This procedure was considered to be less biased than the alternatives of (1) taking the 50th ordinate to be either zero or 1, or (2) averaging only the first 49 ordinates.

4. RESULTS AND DISCUSSION

In comparing the reflectance and transmittance data calculated using different integration methods and air masses, the authors considered a difference of 0.5 percent and greater to be significant.

4.1 REFLECTANCE OF ABSORBER SPECIMENS

4.1.1 Control (Unweathered) Specimens

Reflectance data obtained for the control (unweathered) specimens of the four absorber materials are presented at the top of table 6. Data are presented for: 1) air mass 2.0 using both the weighted and selected ordinate calculation methods; and 2) air mass 1.5 and 1.0 using the selected ordinate method.

For the control specimens, comparison of reflectance obtained by both the weighted and selected ordinate methods using ASTM E 424 at air mass 2.0 show the two methods of calculation to yield comparable results. Differences of 0.1 percent occurred for each material, but this is considered insignificant. For black chrome on steel, the reflectance was 4.9 percent using both weighted and selected ordinates calculation methods; for black chrome on copper, the reflectance was 4.8 and 4.9 percent, respectively.

Comparisons of reflectance for air masses 2.0, 1.5 and 1.0 for control black chrome absorber materials show that higher reflectance values are obtained at air masses 1.5 and 1.0 than at 2.0. At air mass 1.5, both black chrome specimens had a reflectance of 6.2 percent while, at air mass 1.0, the reflectance was 6.0 percent for both specimens.

For the control specimens of nonselective absorber materials (urethane and porcelain enamel), little or no effect was observed on reflectance by the method of calculation or by the air mass.

4.1.2 Weathered Specimens

Table 6 also contains reflectance data for weathered absorber materials including data for: 1) air mass 2.0 using both the weighted and selected ordinate calculation methods; and 2) air mass 1.5 and 1.0 using the selected ordinate method.

When calculated at air mass 2 using selected and weighted ordinates the reflectance of black chrome on steel after exposure to moisture is essentially identical. This is illustrated in figure 6. After weathering reflectance values of black chrome on steel and copper were higher at air masses 1.5 and 1.0 than those at air mass 2.0 by up to 1.6 percent. The effect of air mass and method of calculation on reflectance of black chrome are further illustrated in (figures 7, 8 and 9).

For weathered nonselective absorber materials (urethane and porcelain enamel), little or no effect was observed on reflectance by the method of calculation or by the air mass used. The effect of air mass is illustrated in figure 10 for urethane on steel.

4.1.3 Effect of Method of Calculation at Air Mass 2.0

The data in table 6 show that there was little if any effect on reflectance of absorber materials from the method of calculation at air mass 2.0; hence, both the weighted or selected ordinate methods from ASTM E 424 would be expected to yield comparable reflectance values.

4.1.4 Effect of Air Mass on Reflectance

For the selected ordinate method, reflectance values for unweathered black chrome absorbers (selective) when calculated using mass 1.5 and air mass 1.0 were from 1.1 to 1.2 percent higher than those for at air mass 2.0. For weathered black chrome, the reflectance values at air mass 1.5 and 1.0 were from 0.8 to 1.2 percent higher than those at air mass 2.0. The higher solar reflectance values at air mass 1.5 and 1.0 are due to the shape of the reflectance curves in the near-infrared region of the spectrum (see figure 3).

The reflectance values of the nonselective absorbers (urethane and porcelain enamel) were comparable at all three air masses. The reason for this is that the spectral curves of these materials are almost flat line over the entire spectrum from 300 to 2150 nm (figure 2).

The data indicate that the use of different air mass values could lead to discrepancies in values of reflectance for selective absorber materials.

4.2 TRANSMITTANCE OF COVER PLATE MATERIALS

Transmittance data for weathered and control (unweathered) cover plate materials are tabulated in table 7. Data are presented for: 1) air mass 2.0 using both the weighted and selected ordinate calculation methods; and 2) air mass 1.5 and 1.0 using the selected ordinate method.

4.2.1 Effect of Method of Calculation at Air Mass 2.0

4.2.1.1 Control (Unweathered) Specimens

Comparison of transmittance data at air mass 2.0 for unweathered materials using the weighted and selected ordinate methods from ASTM E 424 shows that: (1) for glass, fluorinated (ethylene propylene) copolymer, and poly(vinyl fluoride), the transmittance differed by no more than 0.2 percent; and (2) for polycarbonate and fiber reinforced plastic the transmittance was less using the selected ordinate method than that obtained using the weighted ordinate method. For example, the transmittance of the fiber reinforced plastic was 78.2 and 76.8 percent for the weighted and selected ordinate methods, respectively.

4.2.1.2 Weathered Specimens

Transmittance values, obtained by the weighted and selected ordinate methods, were comparable for glass and fluorinated (ethylene propylene) copolymer in that the maximum differences were 0.2 percent. For poly(vinyl fluoride), polycarbonate and fiber reinforced plastic, however, the transmittance values obtained with the weighted ordinate method were consistently higher than those obtained with the selected ordinate method. For example, polycarbonate transmittance values were from 0.8 to 1.1 percent higher using the weighted ordinate method. This effect is illustrated in figures 11 and 12 for poly(vinyl fluoride) and polycarbonate, respectively.

4.2.1.3 Summary

The data show that comparable transmittance values are obtained using the weighted and selected ordinate methods for glass and fluorinated (ethylene propylene) copolymer. The data show that discrepancies arise between the two methods of calculation for poly(vinyl fluoride), polycarbonate and fiber reinforced plastic. The discrepancies result from absorption bands for these materials in the near-infrared region (e.g., polycarbonate and fiber reinforced plastic) or from a shift in the absorption on the ultraviolet region of aged materials of the spectra. For poly(vinyl fluoride), polycarbonate and fiber reinforced plastic, the weighted ordinate method yields consistently higher transmittance values than the selected ordinate method. The data indicate that the method of calculation (weighted versus selected ordinates) can lead to significant differences in transmittance for some cover plate materials.

4.2.2 Effect of Air Mass

4.2.2.1 Control Specimens at Air Mass 2.0, 1.5 and 1.0

Transmittance data of unweathered materials, calculated using the selected ordinate method at air mass 2.0, 1.5, and 1.0, show that for fluorinated (ethylene propylene) copolymer the difference in transmittance values is small, i.e., 0.3 percent or less, between air mass 2.0 and air mass 1.0. For glass the difference between air mass 2.0 and air mass 1.0 is 0.5 percent, although it is only 0.2 percent between air mass 2.0 and air mass 1.5. For poly(vinyl fluoride), polycarbonate and fiber reinforced plastic, however, the difference in transmittance values between air mass 2.0 and air mass 1.0 is greater. For example, the percent transmittance of polycarbonate varies from 87.3 at air mass 2.0 to 82.7 at air mass 1.0. For fiber reinforced plastic, the difference in transmittance was 2.1 percent between air mass 2.0 and 1.5 and 1.9 percent between air mass 1.5 and 1.0. For unweathered cover plate materials, the transmittance usually decreased as the air mass decreased.

For unweathered materials, the decreasing values in solar transmittance with decreasing air mass values are primarily caused by two factors: (1) absorption bands in the infrared region of the spectra; and (2) increasing energy at the ends of the solar spectral band as the air mass decreases. The increasing energy mentioned above causes a slight shift in the equal energy distribution points to the ends of the spectra. The spectral transmittance curves of many of the cover plate materials fall off rapidly in the ultraviolet region, thus causing losses in the integrated value as the air mass decreases. As shown in the data, this change can be as much as 4.6 percent for some unaged materials between air mass 2.0 and air mass 1.0.

4.2.2.2 Weathered Specimens at Air Mass 2.0, 1.5 and 1.0

Transmittance data of heat aged cover plate materials, calculated using the selected ordinate method at air masses 2.0, 1.5 and 1.0 show that air mass has little effect on the calculated transmittance for fluorinated(ethylene propylene) copolymer. For glass the difference between air mass 2.0 and air mass 1.0 was about 0.6 percent while it was less comparing air mass 2.0 and 1.5. Figures 13 and 14 illustrate the effect of air mass on fluorinated(ethylene propylene) copolymer and glass respectively, with increased time of heat aging.

As was observed with control specimens, however, the transmittance of weathered poly(vinyl fluoride), polycarbonate plastic decreased as air mass decreased. For poly(vinyl fluoride) and fiber reinforced plastic, the transmittance differences calculated using air mass 2.0 and 1.0 values were about 4.5-5 percent, while the differences between air mass 2 and 1.5 were 2.5-3 percent. Figures 15 and 16 illustrate the effect of air mass on the transmittance of polycarbonate and fiber reinforced plastic, respectively. Poly(vinyl fluoride) transmittance values showed a further trend of interest in that, as the time of exposure to heat aging increased, the difference between the transmittance calculated using various air masses tended to increase. This is illustrated in figure 17.

For weathered materials, decreases in transmittance with decreasing air mass values are primarily due to the ultraviolet region of the spectra. The transmittance spectra of many plastic cover plate materials falls off sharply at 350 nm or above (see figures 4 and 5). As these materials age, the wavelength at which they stop transmitting energy becomes longer. This is illustrated in figure 18, which contains the spectral transmittance of aged poly(vinyl fluoride). With increased aging, the absorption band at the left of graph moves toward the right to the longer wavelengths. When solar transmittance is calculated, the resultant value is lower as the air mass decreases, due to increasing solar energy at the lower wavelengths of the solar spectrum.

4.2.2.3 Summary

The data show that comparable values of transmittances are obtained using the selected ordinate method at air mass 2.0, 1.5 and 1.0 for fluorinated(ethylene propylene) copolymer. For glass the differences are about 0.5 percent between air mass 2.0 and 1.0 while for poly(vinyl fluoride), polycarbonate and fiber reinforced plastic differences of several percent may occur. The data further show (figure 12) that the discrepancies tend to increase for poly(vinyl fluoride) with increased time of heat aging.

5. CONCLUSIONS

Since method A of E 424 is the preferred method, it is expected that the reflectance and transmittance data produced by its use should be equivalent. The variations permitted in the calculations should not result in different values of reflectance and transmittance. The following conclusions relate to calculations of solar energy transmittance and reflectance using ASTM E 424, method A.

5.1 ABSORBER COATING MATERIALS

1. At air mass 2 both the weighted and selected ordinates calculation methods yield comparable reflectance values.

2. A change in air mass has no observable effect on the reflectance values calculated for nonselective absorbers.

3. Air mass values used in calculating reflectance can lead to discrepancies for selective absorbers. Black chrome reflectance values changed by up to 1.2 percent when the air mass changed from 2.0 to 1.0.

5.2 COVER PLATE MATERIALS

1. The selected and weighted ordinate methods do not produce identical solar transmittance values. Transmittance can vary by up to one percent for some materials depending on which method is used in the calculations. The differences occur with cover plate materials which have absorption bands in their near infrared (NIR) region of their spectra. When differences occur the weighted ordinates method gives higher results.

2. Air mass values used in calculations have a considerable effect on the transmittance values obtained. Changing the air mass values used in calculating transmittance can lead to differences of 3 to 4 percent for some materials. The differences may increase as degradation of the material increases. The materials most affected by the air mass change are those which transmit the least energy in the ultraviolet region (below 390 nm).

6. RECOMMENDATIONS

1. One integration method should be specified for the calculation of transmittance and reflectance using ASTM E 424, method A. The selected and weighted ordinate methods of integration do not produce identical results for material having absorption bands in the near infrared region of the spectra. Since optical properties are heavily used in technical evaluation of competing products, it is necessary to assure that data for various materials can be compared. Thus a single calculation method is required.

2. It is suggested that the solar energy distribution used in ASTM E 424, method A, be changed to air mass 1.5. The reason for this recommendation is that most collectors that are in service are exposed to more hours of radiation that approximate air mass 1.5 or 48.19° than air mass 2.0 or 60° zenith angle.

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Table 1. Absorber and Cover Plate Materials Used in This Study

Absorber Materials	Substrate
Black chrome	Steel
Black chrome	Copper
Urethane paint	Steel
Porcelain enamel	Steel

Cover Plate Materials	Nominal Thickness mm	(in)
Glass (0.10% iron oxide)	3.2	(1/8)
Fluorinated (ethylene propylene) copolymer	0.025	(0.001)
Poly(vinyl fluoride)	0.10	(0.004)
Polycarbonate	1.02	(0.04)
Fiber reinforced plastic	1.05	(0.06)

Table 2. Relative Energies of Weighted Ordinates for Calculation of Solar Energy Transmittance or Reflectance at Air Mass 2.0

Wavelength nm	Relative Energy	Wavelength nm	Relative Energy	Wavelength nm	Relative Energy
350	1.27	950	3.29	1550	1.49
400	3.18	1000	4.25	1600	1.36
450	6.79	1050	3.72	1650	1.17
500	8.20	1100	1.70	1700	0.89
550	8.03	1150	1.46	1750	0.54
600	7.88	1200	2.52	1800	0.01
650	7.92	1250	2.21	1850	0.00
700	7.48	1300	1.78	1900	0.00
750	5.85	1350	0.12	1950	0.12
800	5.79	1400	0.00	2000	0.02
850	5.66	1450	0.16	2050	0.26
900	3.24	1500	1.06	2100	0.58
				TOTAL	100.00

Table 3. Twenty Selected Ordinates for Calculation of Solar Transmittance or Reflectance at Air Mass 2.0

Ordinate Number	Wavelength nm	Ordinate Number	Wavelength nm
1	390	11	745
2	444	12	786
3	481	13	831
4	511	14	877
5	543	15	959
6	574	16	1026
7	606	17	1105
8	639	18	1228
9	669	19	1497
10	705	20	1722

Table 4. Fifty Selected Ordinates for Calculation of Solar Transmittance or Reflectance at Air Mass 1.5

Ordinate Number	Wavelength nm	Ordinate Number	Wavelength nm
1	342	26	717
2	375	27	736
3	400	28	753
4	418	29	773
5	434	30	792
6	449	31	812
7	461	32	834
8	472	33	855
9	482	34	876
10	494	35	901
11	505	36	933
12	517	37	975
13	529	38	1003
14	541	39	1029
15	553	40	1057
16	567	41	1091
17	581	42	1169
18	595	43	1215
19	610	44	1261
20	624	45	1317
21	638	46	1528
22	653	47	1606
23	668	48	1693
24	684	49	2023
25	700	50	2276

Table 5. Fifty Selected Ordinates for Calculation of Solar Transmittance or Reflectance at Air Mass 1.0

Ordinate Number	Wavelength nm	Ordinate Number	Wavelength nm
1	331	26	689
2	356	27	713
3	380	28	731
4	401	29	752
5	415	30	770
6	429	31	785
7	443	32	814
8	455	33	834
9	465	34	849
10	477	35	871
11	488	36	902
12	500	37	938
13	512	38	975
14	524	39	987
15	537	40	1025
16	545	41	1056
17	558	42	1117
18	572	43	1173
19	587	44	1221
20	601	45	1287
21	615	46	1495
22	629	47	1587
23	644	48	1703
24	659	49	2055
25	675	50	2298

Table 6. Tabulation of Reflectance Data for Absorber Materials

Material	Exposure[1/] Test; Length	Percent Reflectance Weighted Ordinate at Air Mass 2.0	Selected at Air Mass 2.0	Selected at Air Mass 1.5	Selected at Air Mass 1.0
Black chrome on steel	Control	4.9	4.9	6.2	6.0
Black chrome on copper	Control	4.8	4.9	6.2	6.0
Urethane paint on steel	Control	2.9	2.8	2.8	2.8
Porcelain on steel	Control	6.6	6.5	6.6	6.6
Black chrome on steel	Moisture Test[2/] 2 weeks	4.5	4.5	5.5	5.4
Black chrome on steel	Moisture Test[2/] 6 weeks	4.2	4.2	5.3	5.2
Black chrome on steel	Moisture Test[2/] 12 weeks	3.7	3.8	4.8	4.7
Black chrome on steel	Heat Age 200°C 12 weeks	3.7	3.7	4.7	4.6
Black chrome on copper	Heat Age 200°C 12 weeks	7.0	7.4	8.6	8.2
Urethane on steel	Moisture Test[2/] 2 weeks	3.0	2.8	3.0	2.9
Urethane on steel	Moisture Test[2/] 6 weeks	4.5	4.3	4.2	4.2
Urethane on steel	Moisture Test[2/] 12 weeks	4.8	4.6	4.6	4.6
Porcelain on steel	Heat Age 250°C 6 weeks	4.3	4.3	4.2	4.2

1/ Denotes the weathering test carried out prior to obtaining optical measurements.

2/ Moisture test was conducted at 92°C and 97 percent relative humidity.

Table 7. Tabulation of Transmittance Data for Cover Plate Materials

Material	Exposure Test	Time of Exposure	Weighted Ordinate at Air Mass 2.0	Selected Ordinate at Air Mass 2.0	Selected Ordinate at Air Mass 1.5	Selected Ordinate at Air Mass 1.0
Glass	Control	0	87.4	87.6	87.4	87.1
Fluorinated (ethylene propylene) copolymer	Control	0	96.4	96.5	96.3	96.4
Poly(vinyl fluoride)	Control	0	92.2	92.4	91.7	91.3
Polycarbonate[1]	Control	0	88.2	87.3	84.5	82.7
Fiber reinforced plastic	Control	0	78.2	76.8	74.7	72.8
Glass	Heat Age 150°C	10	87.1	87.1	87.2	86.7
		100	87.4	87.6	87.3	87.0
		225	87.1	87.2	87.1	86.5
		500	87.1	87.3	86.9	86.6
		750	87.2	87.3	87.1	86.8
		1000	86.9	87.1	86.9	86.5
		1250	86.6	86.7	86.6	86.1
		1500	87.5	87.6	87.3	87.0
		1825	87.3	87.4	87.2	86.9
Fluorinated (ethylene propylene) copolymer	Heat Age 150°C	10	95.4	95.3	95.3	95.2
		100	95.4	95.4	95.3	95.4
		225	95.5	95.5	95.4	95.3
		500	95.6	95.6	95.6	95.4
		750	95.3	95.4	95.3	95.3
		1000	95.4	95.5	95.5	95.5
		1250	95.6	95.5	95.3	95.4
		1500	95.6	95.5	95.3	95.4
		1825	95.2	95.2	95.0	95.1
Poly(vinyl fluoride)	Heat Age 150°C	10	91.2	91.1	90.5	90.2
		100	87.5	87.3	85.4	84.2
		225	88.3	88.0	86.6	85.4
		500	86.7	86.4	84.6	83.1
		750	82.3	81.8	79.4	77.3
		1000	80.4	80.0	77.2	75.0
		1250	74.9	74.5	71.2	68.7
		1500	71.6	71.2	67.7	65.1
		1825	72.1	71.7	68.2	65.8
Polycarbonate	Heat Age 150°C	10	86.9	86.1	83.4	81.5
		225	87.1	86.2	83.4	81.7
		500	86.7	85.6	82.9	81.0
		750	86.3	85.4	82.6	80.8
		1000	86.5	85.6	82.7	80.9
		1250	86.1	85.3	82.4	80.5
		1500	86.3	85.3	82.5	80.6
		1825	85.6	84.8	81.9	80.0
Fiber reinforced plastic	Heat Age 150°C	10	70.9	69.7	67.2	65.2
		100	60.6	59.8	56.6	54.4
		225	54.3	53.5	50.2	48.0
		500	52.4	51.7	48.4	46.3
		750	43.9	43.3	40.4	38.4
		1000	40.0	39.5	36.7	35.0
		1250	40.0	39.4	36.7	34.9
		1500	44.8	44.2	41.0	39.1
		1825	39.7	39.1	36.5	34.7

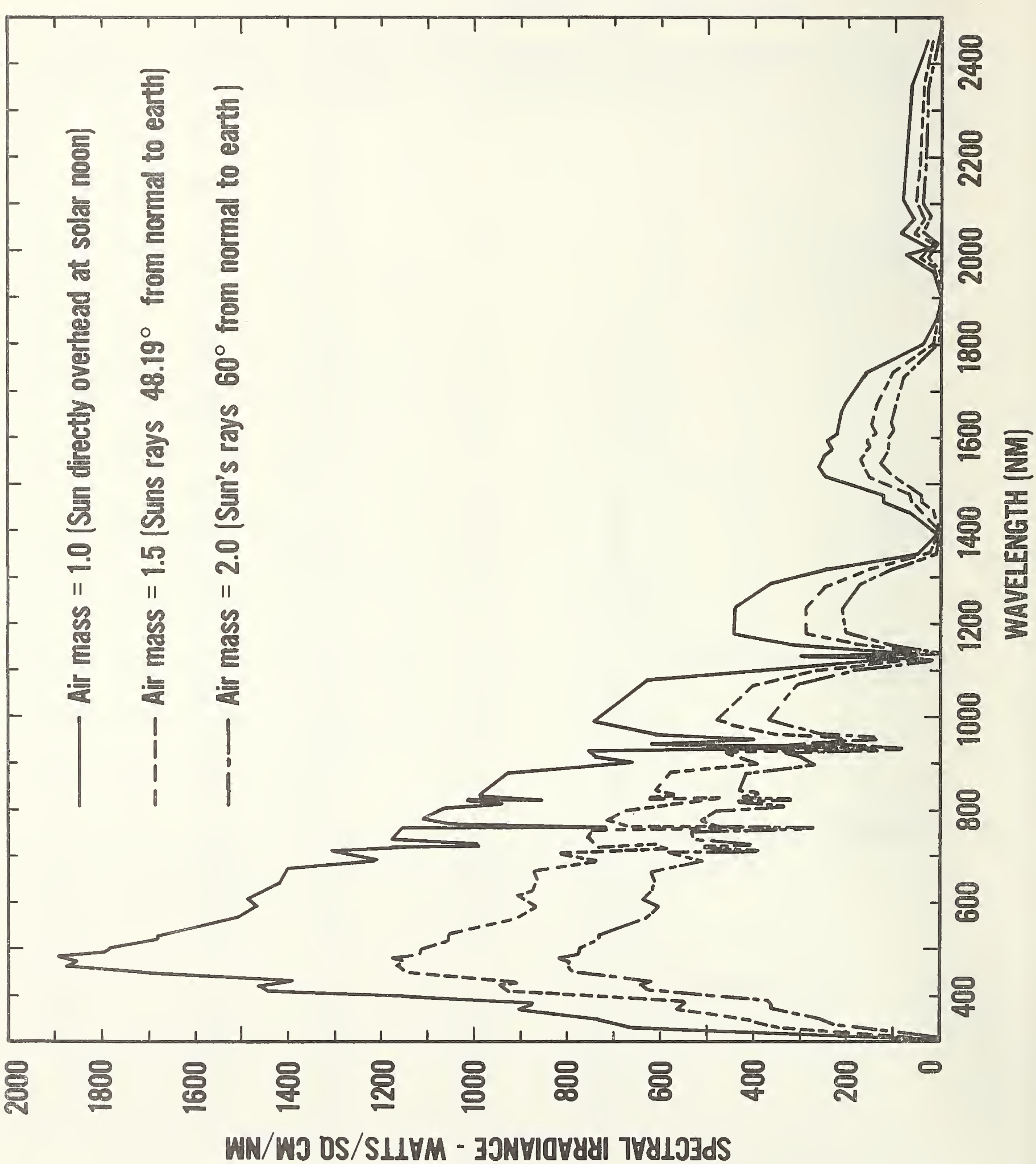

Figure 1. Spectral distribution of sunlight at air masses 1, 1.5 and 2.0

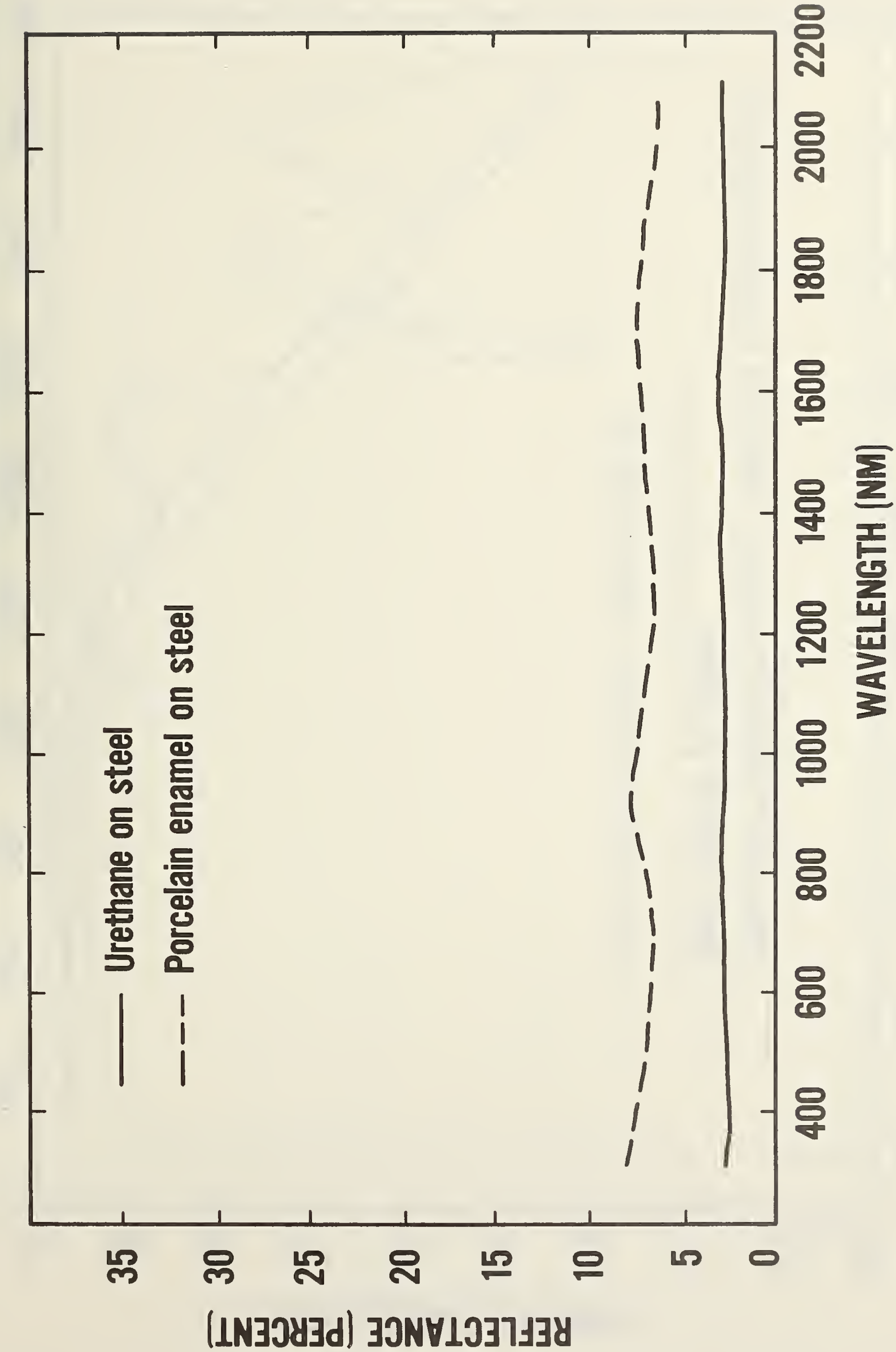

Figure 2. Spectral reflectance of nonselective absorber materials, urethane on steel and porcelain enamel on steel

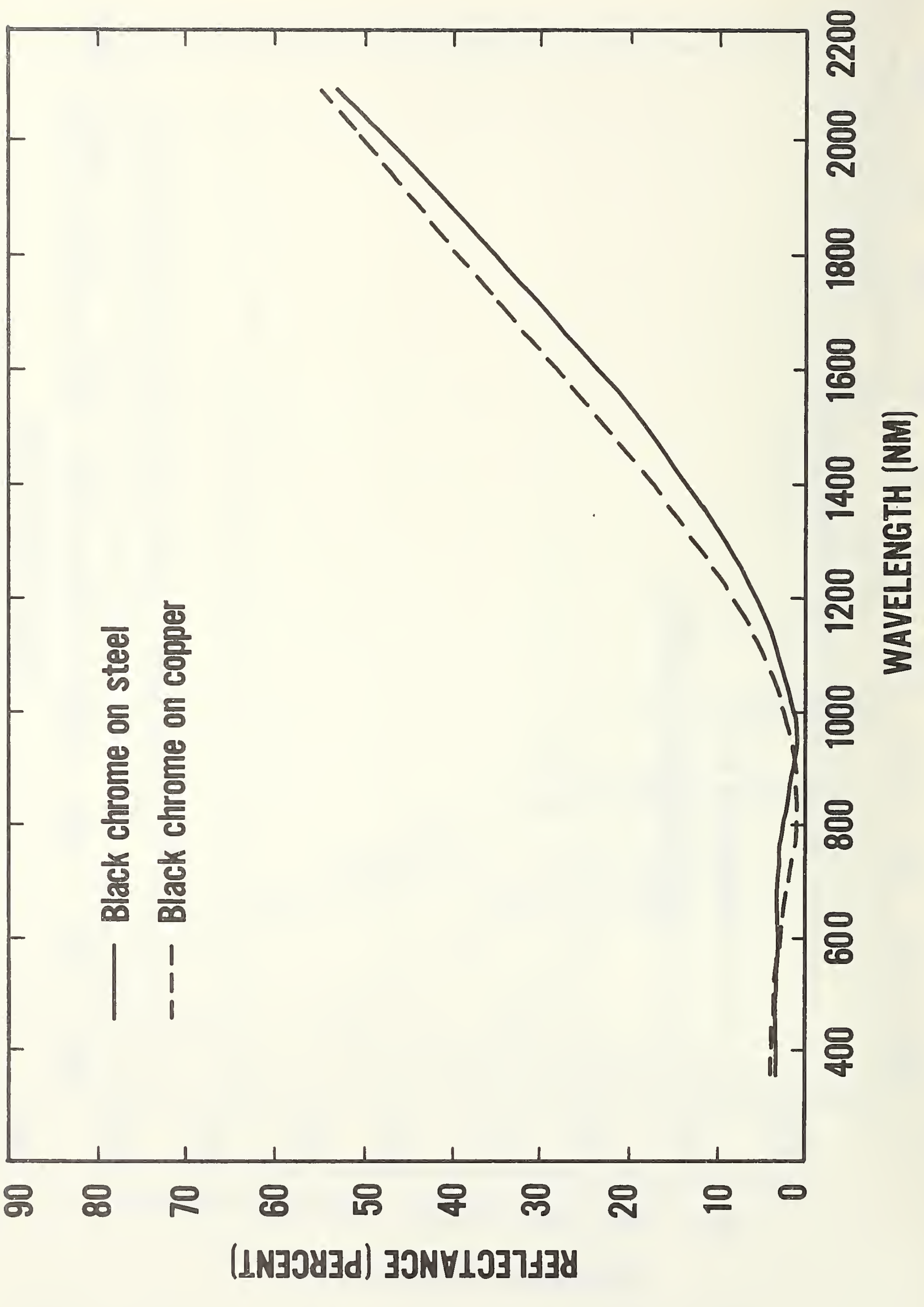

Figure 3. Spectral reflectance of selective absorber materials, black chrome on steel and black chrome on copper

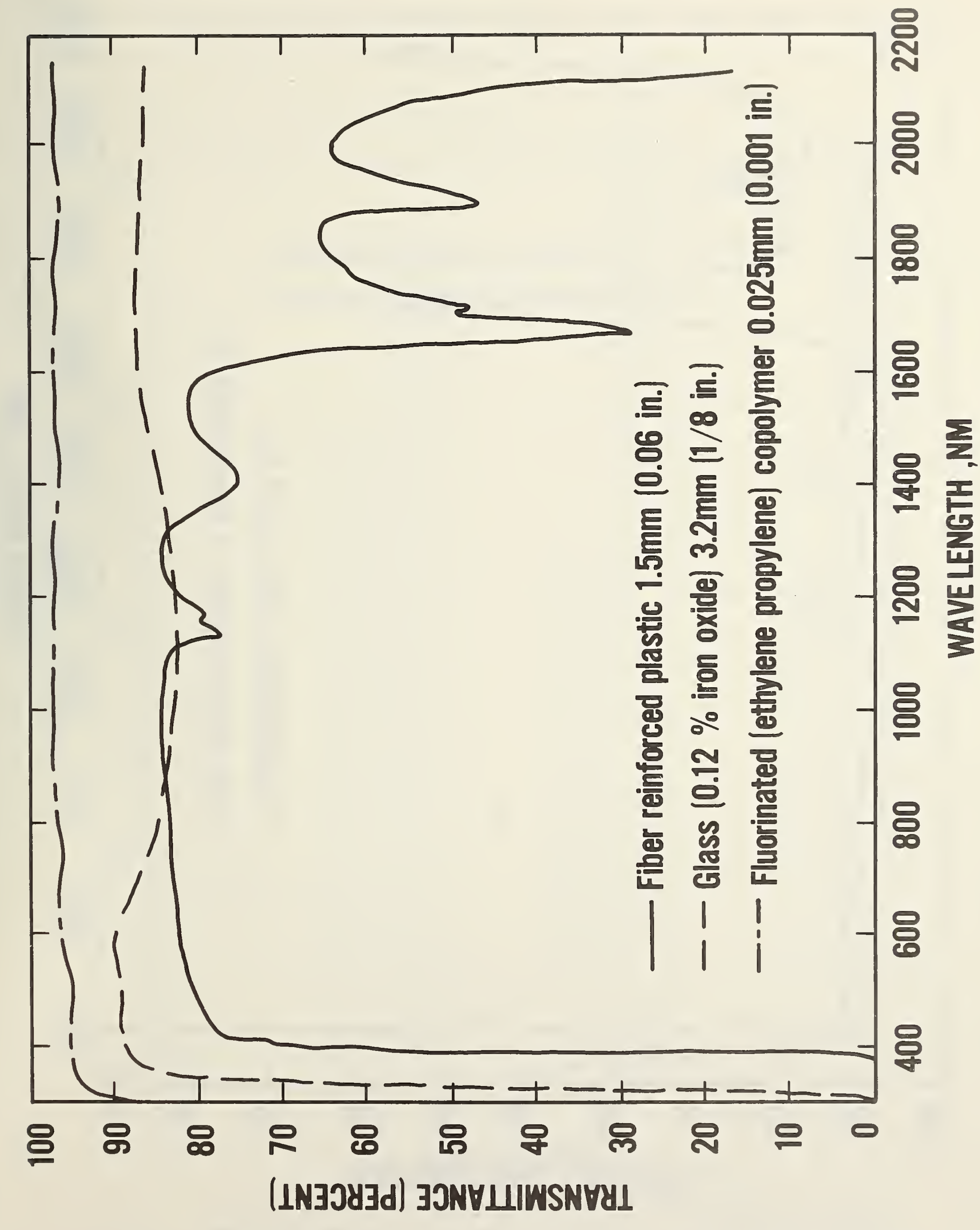

Figure 4. Spectral transmittance of three cover plate materials, fiber reinforced plastic fluorinated (ethylene propylene) copolymer and glass

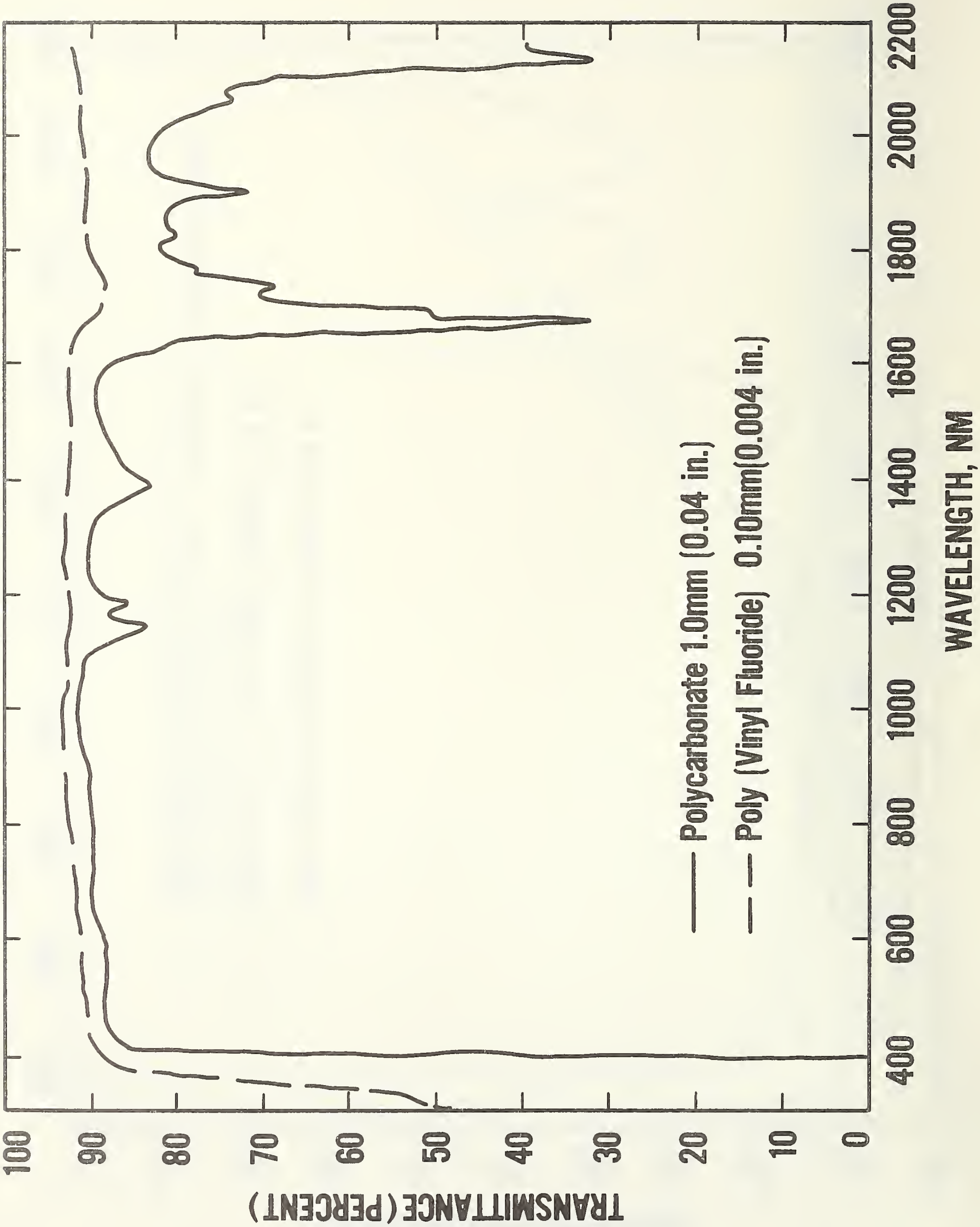

Figure 5. Spectral transmittance of two cover plate materials, polycarbonate and poly(vinyl fluoride)

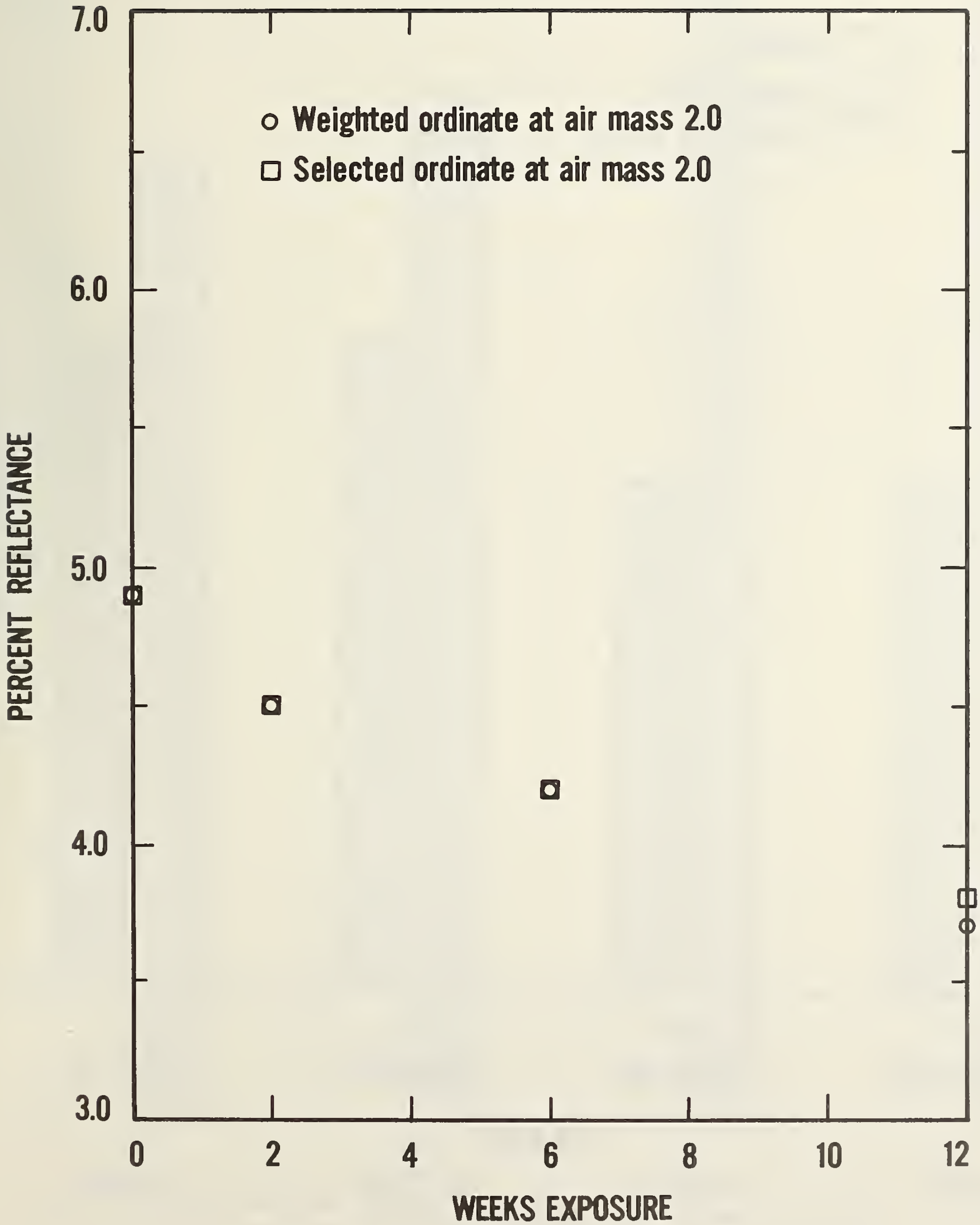

Figure 6. Comparison of reflectance of weathered black chrome on steel using the weighted and selected ordinate calculation methods at air mass 2.0; weathering environment was 92°C and 97 percent relative humidity

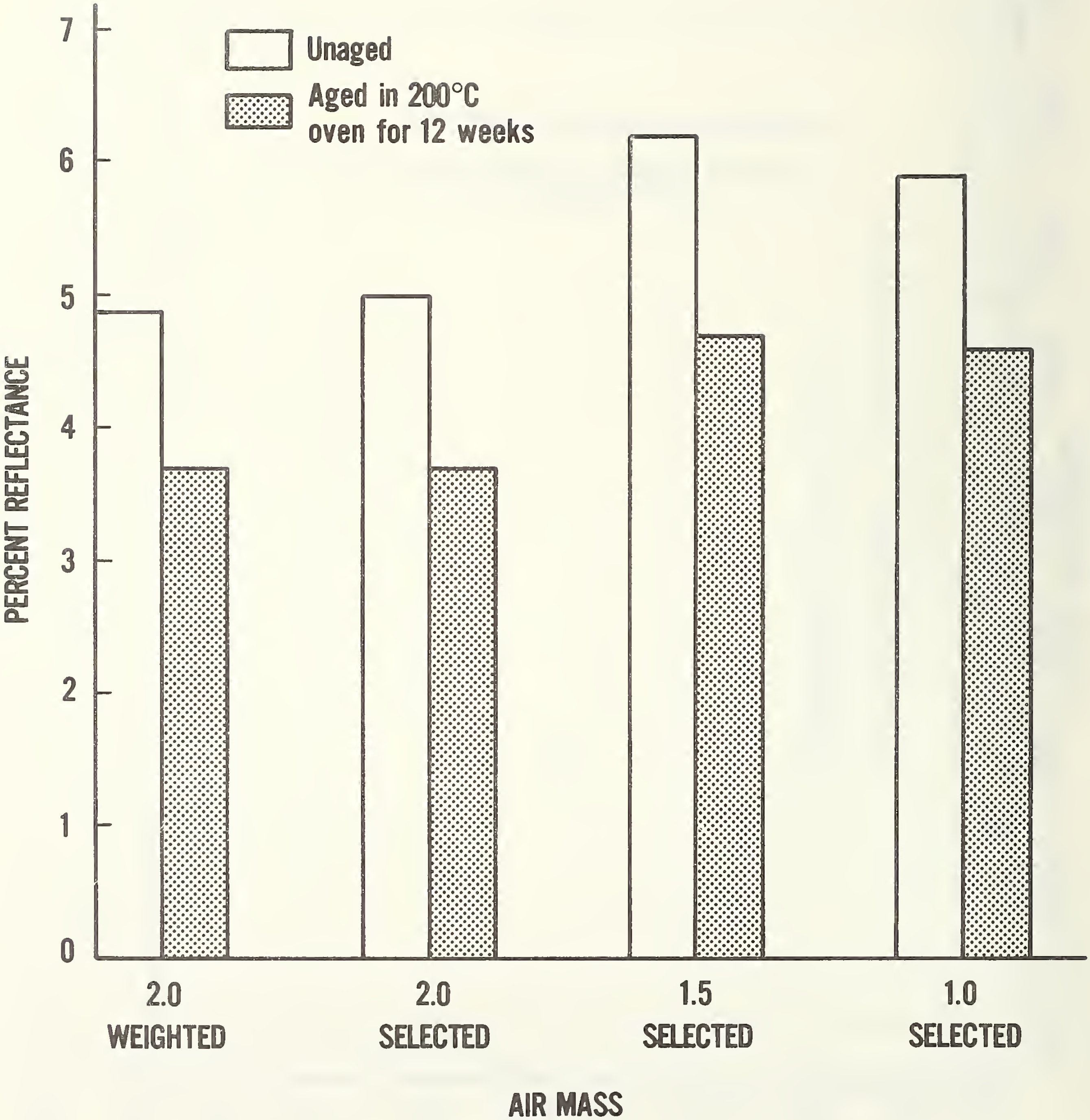

Figure 7. Effect of method of calculation and air mass on reflectance of weathered and unweathered black chrome on steel

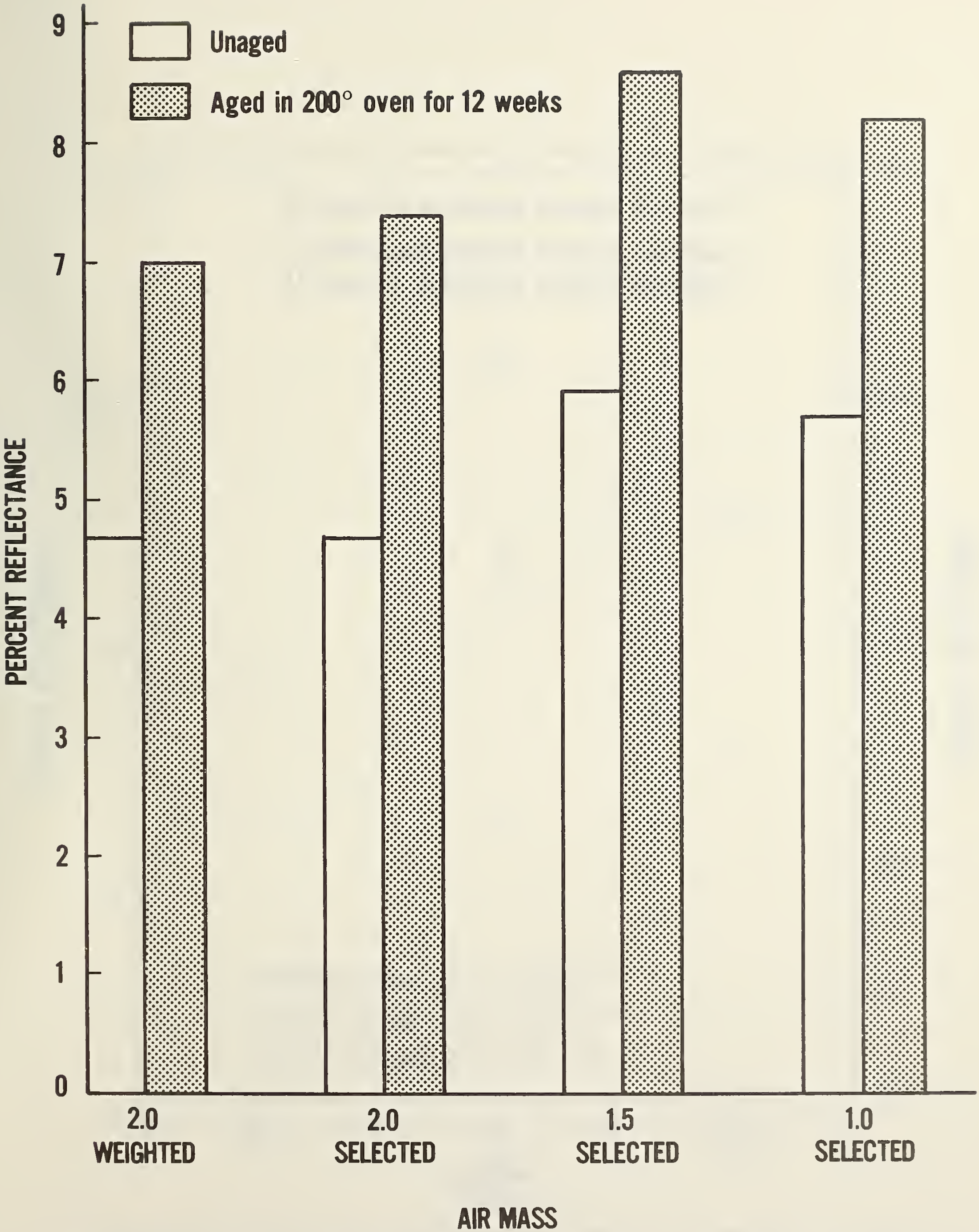

Figure 8. Effect of method of calculation and air mass on reflectance of weathered and unweathered black chrome on copper

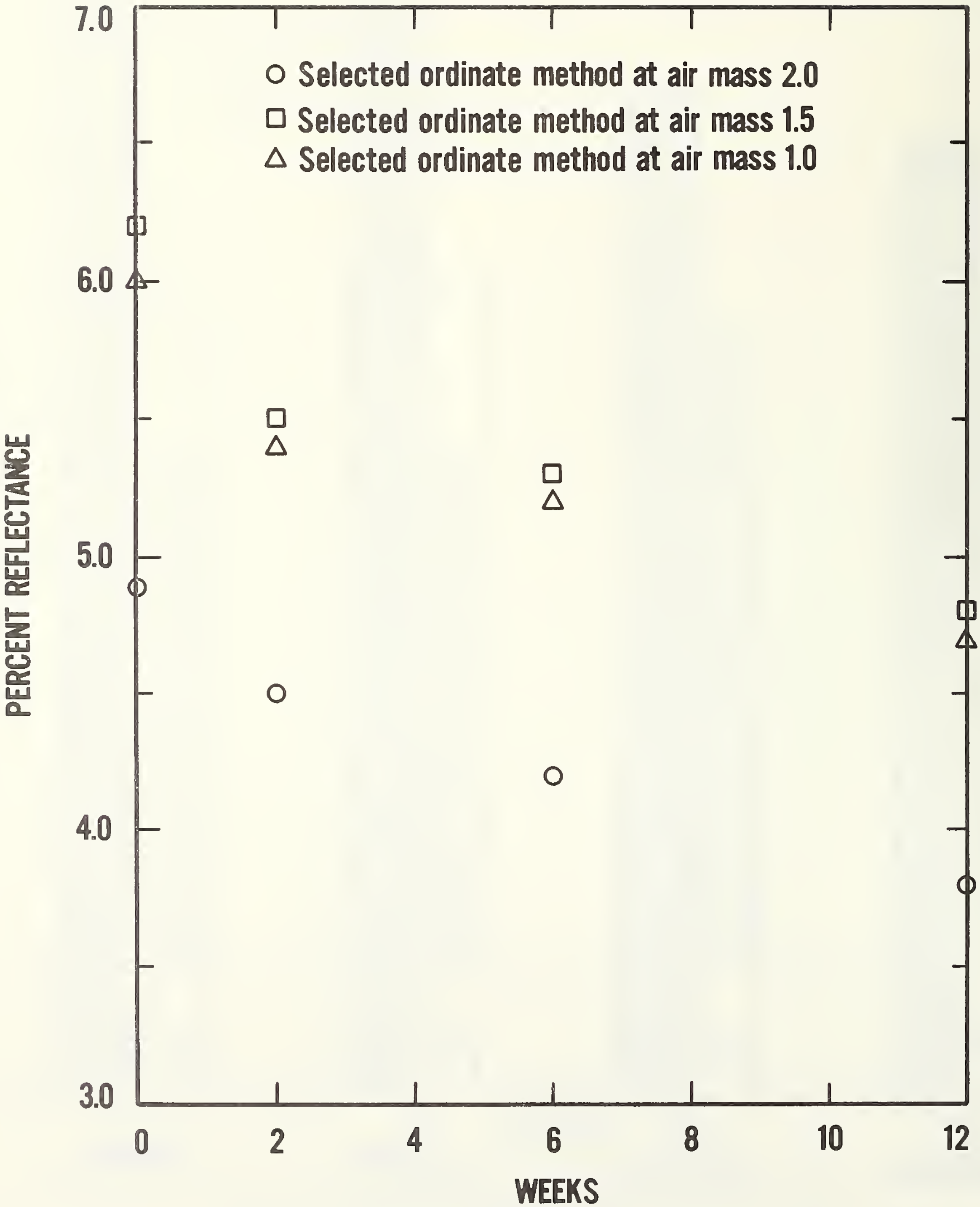

Figure 9. Effect of air mass on the reflectance of black chrome on steel following exposure at 92°C and 97 percent relative humidity

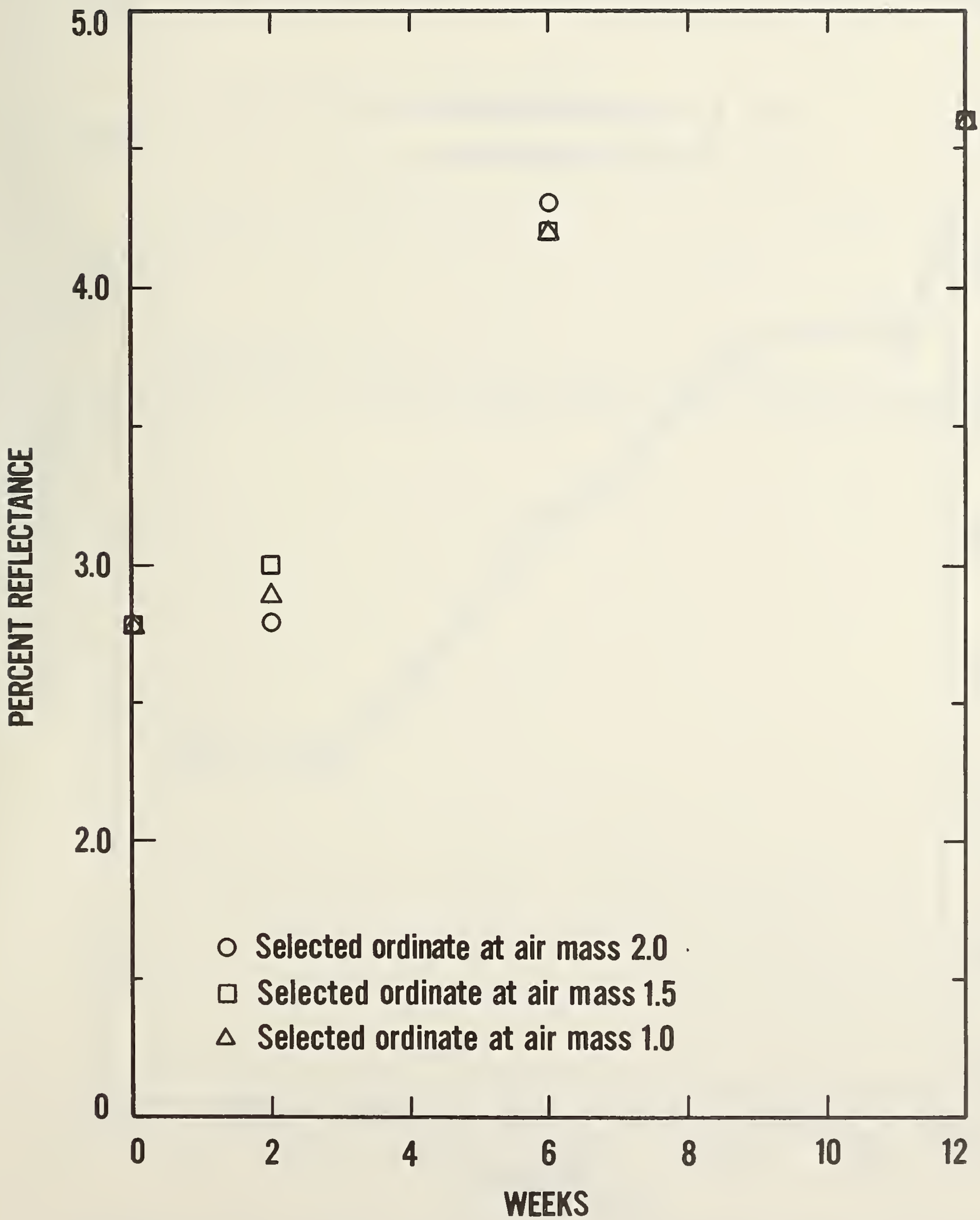

Figure 10. Effect of air mass on the reflectance of urethane on steel following exposure at 92°C and 97 percent relative humidity

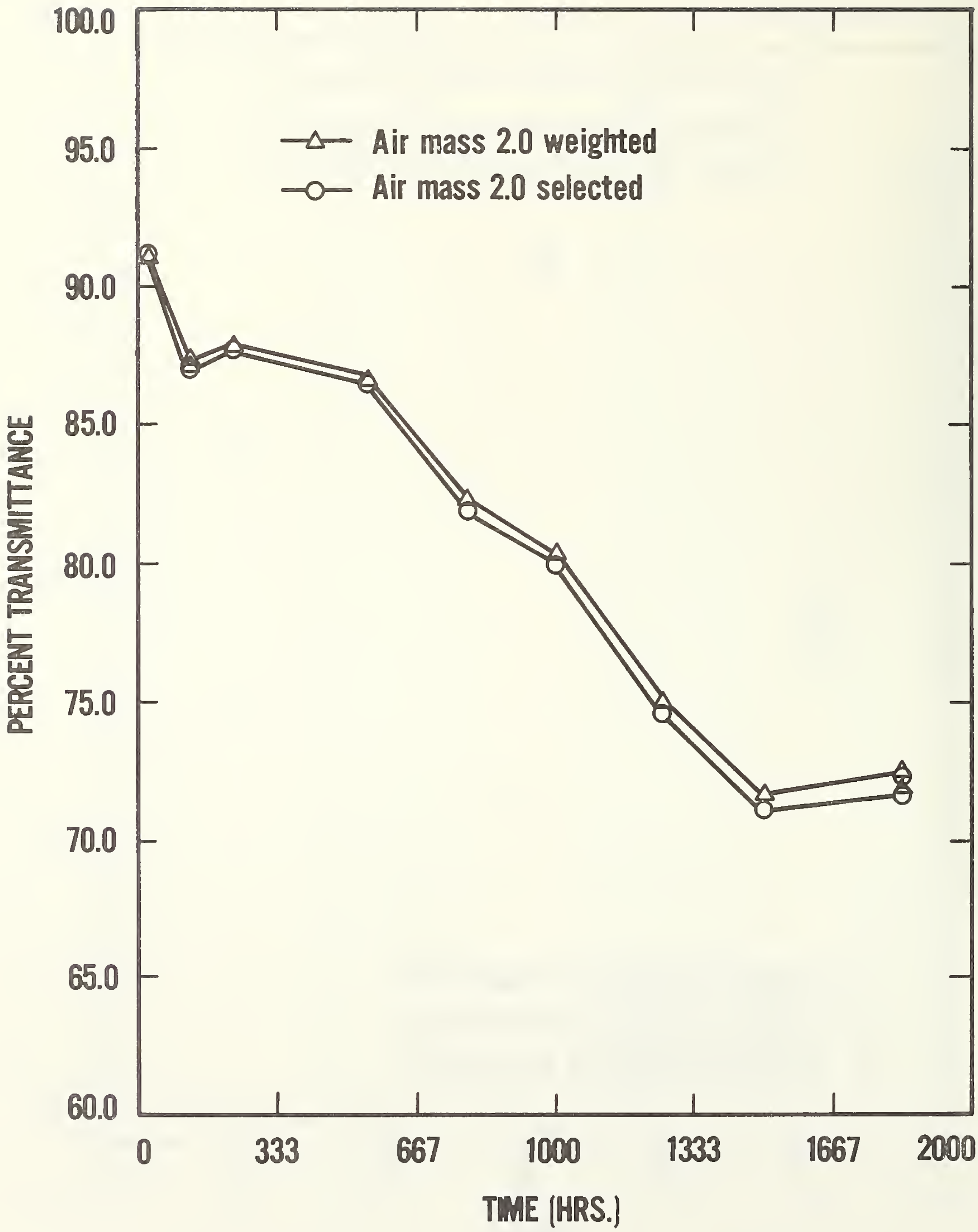

Figure 11. Effect of method of calculation at air mass 2.0 on transmittance of poly(vinyl fluoride) weathered by heat aging at 150°C

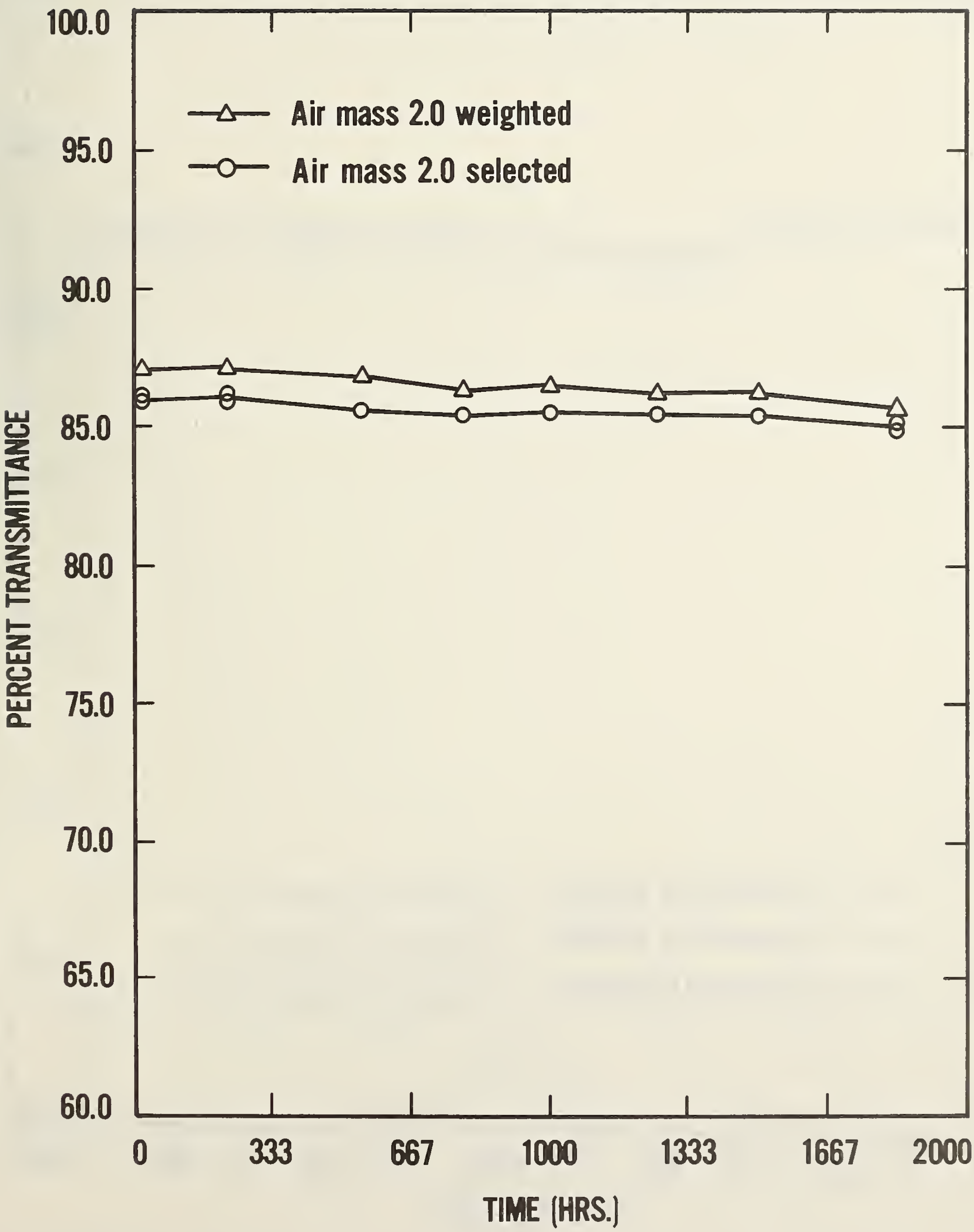

Figure 12. Effect of method of calculation at air mass 2.0 on transmittance of polycarbonate weathered by heat aging at 150°C

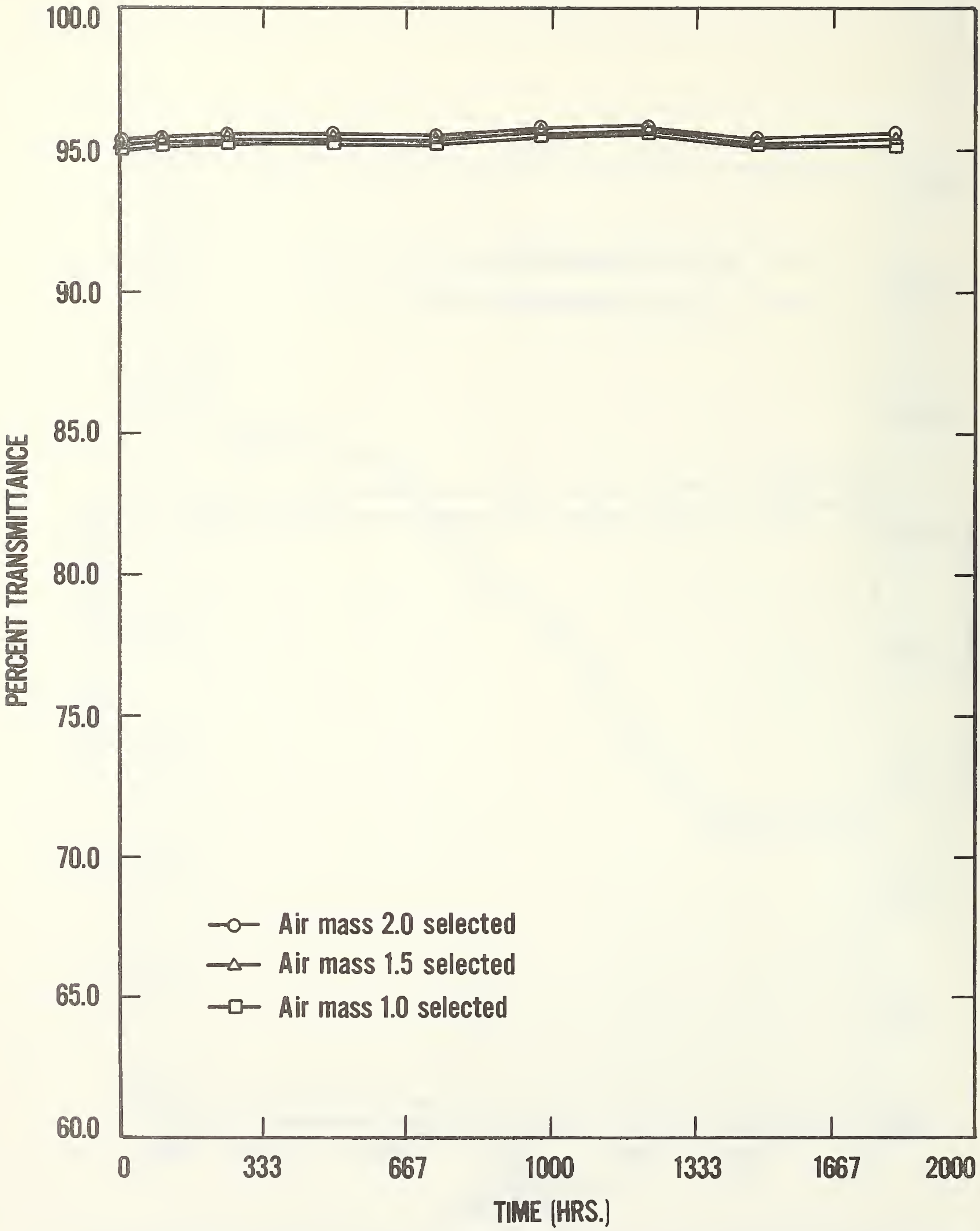

Figure 13. Effect of air mass on transmittance of fluorinated ethylene propylene) copolymer weathered by heat aging at 150°C

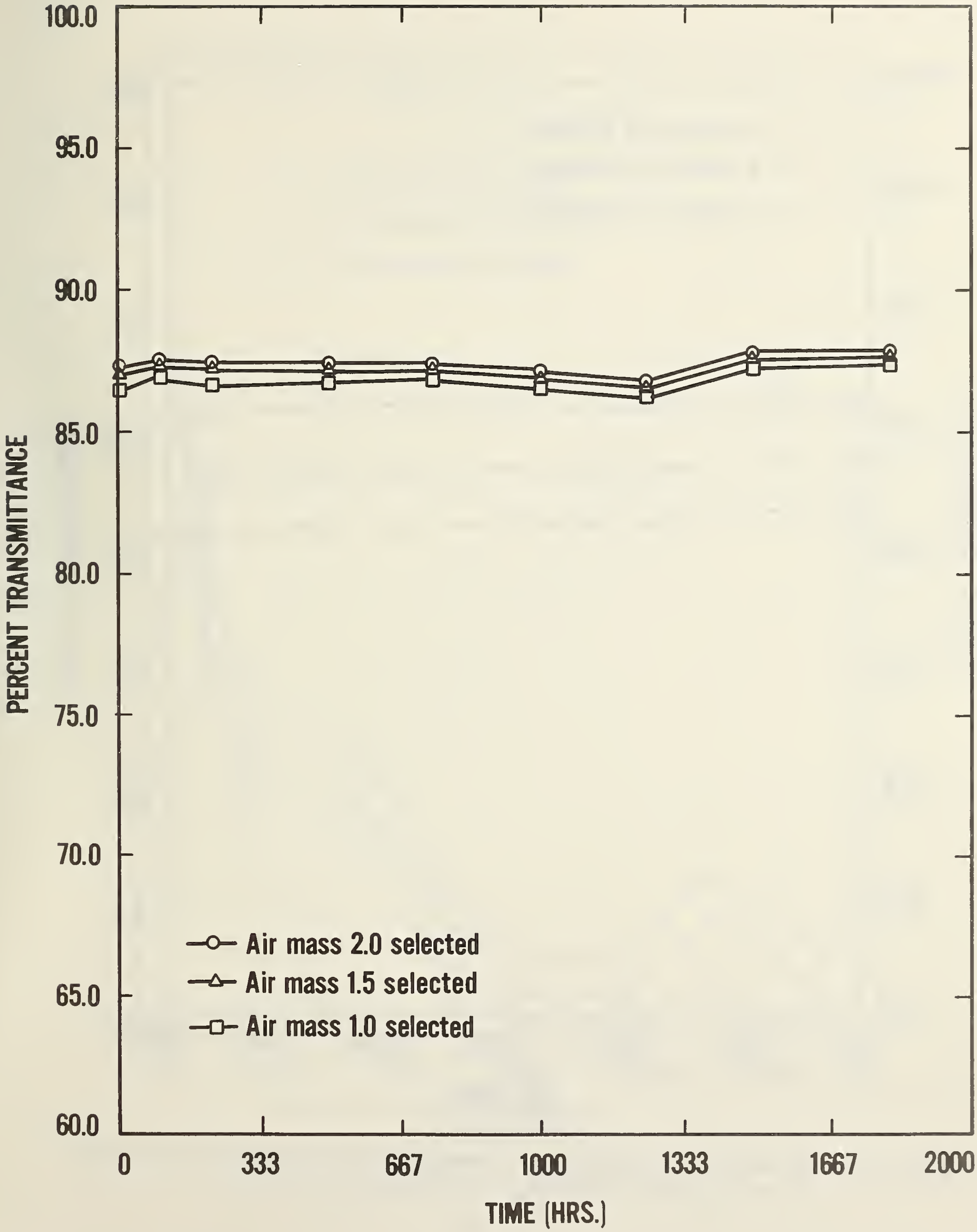

Figure 14. Effect of air mass on transmittance of glass weathered by heat aging at 150°C

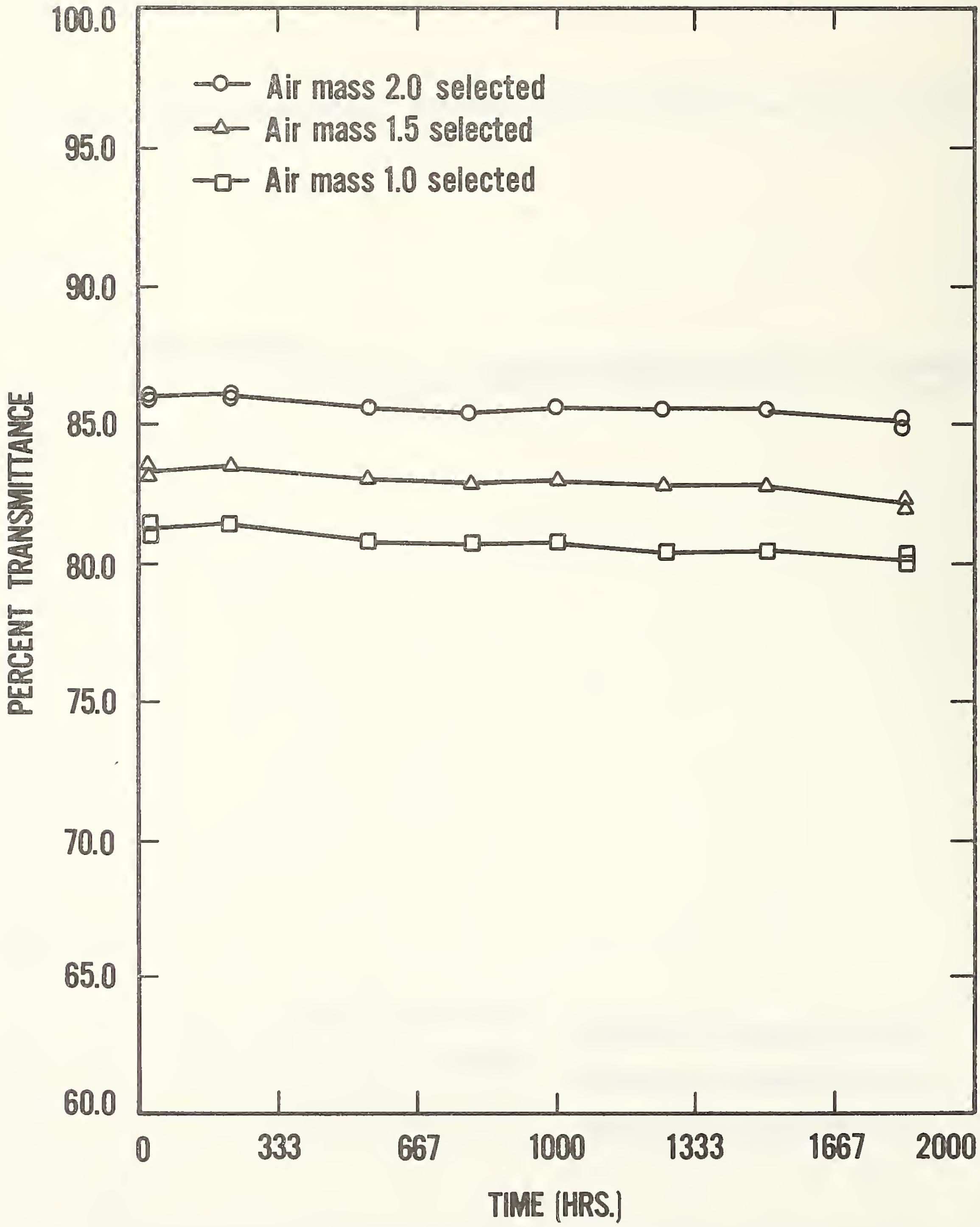

Figure 15. Effect of air mass on the transmittance of polycarbonate weathered by heat aging at 150°C

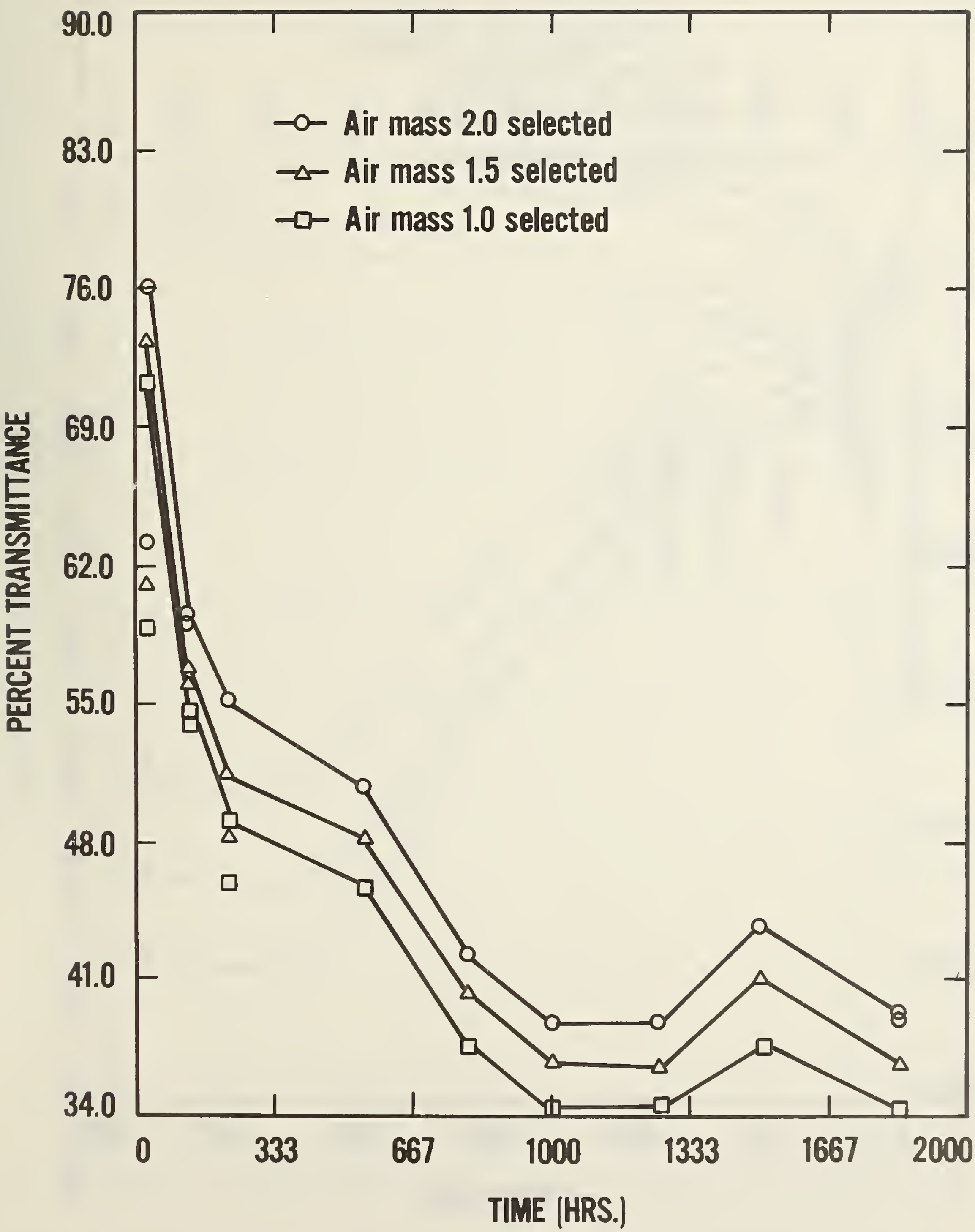

Figure 16. Effect of air mass on the transmittance of fiber reinforced plastic weathered by heat aging at 150°C

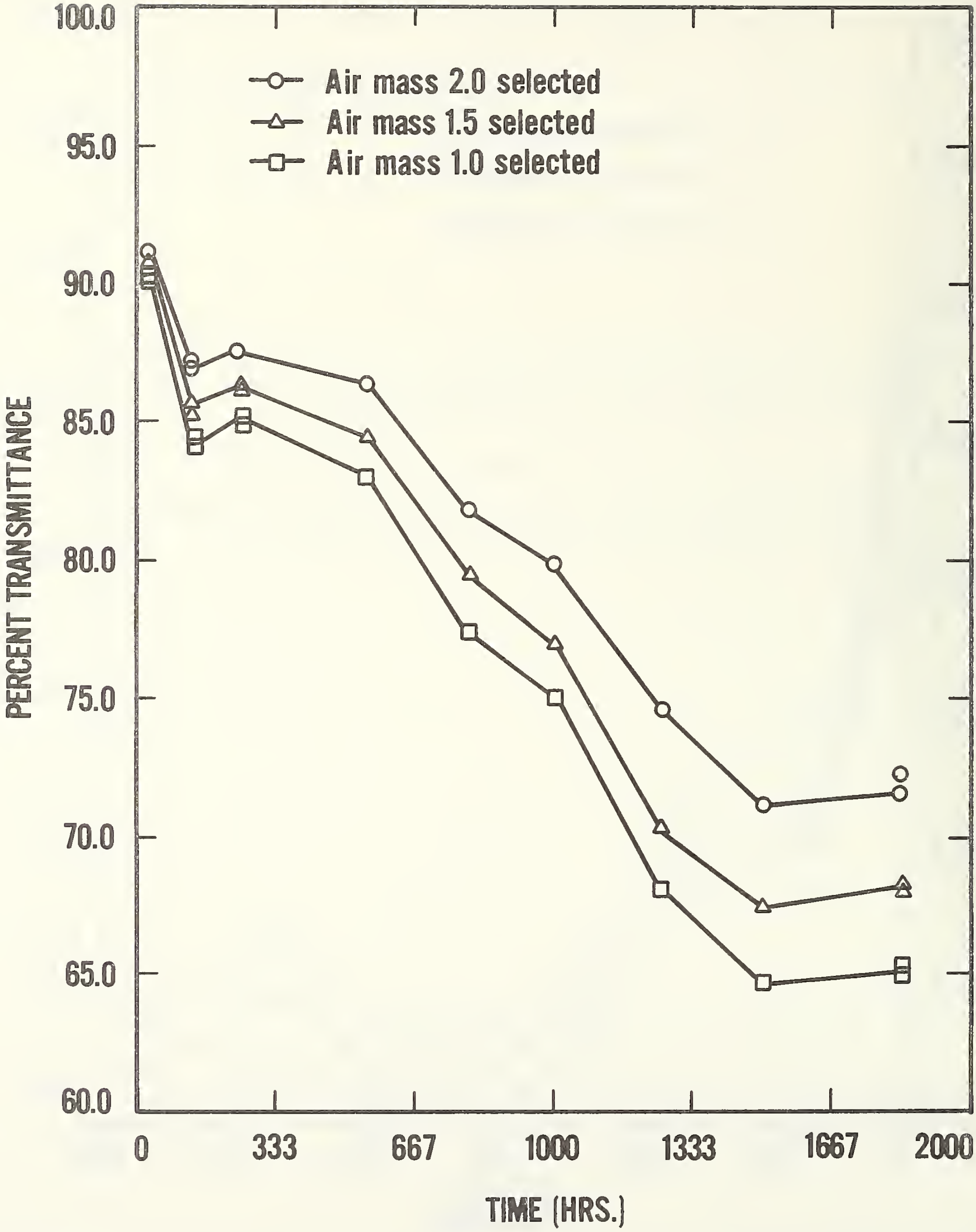

Figure 17. Effect of air mass and increased time of heat age on the transmittance of poly(vinyl fluoride)

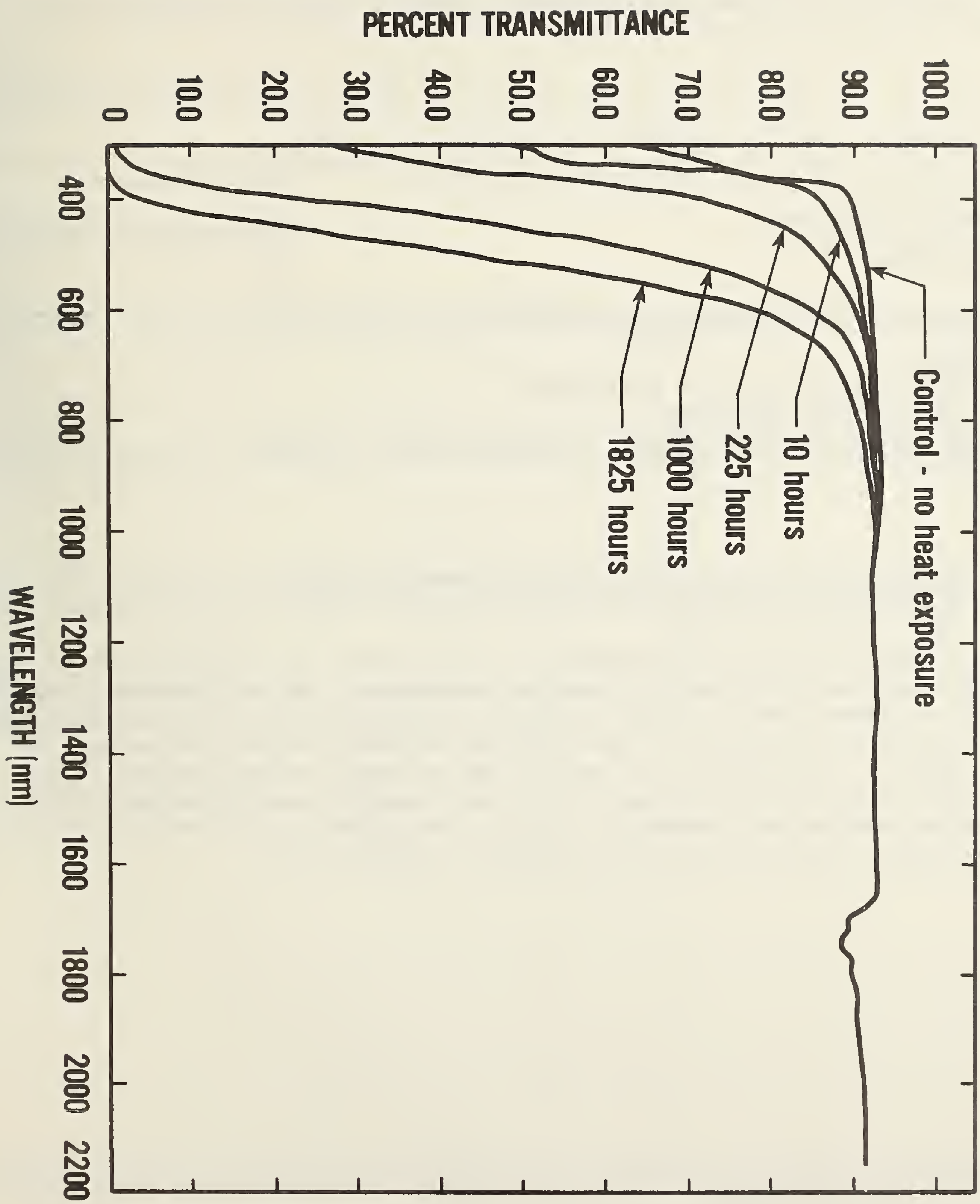

Figure 18. Spectral transmittance of poly(vinyl fluoride) exposed to 150°C for four time periods

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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)

This study was undertaken to compare methods of calculating the transmittance of cover plate materials and the reflectance of absorber materials. Optical data were obtained for both aged and unaged test specimens using an integrating sphere spectrophotometer. The data were integrated using: (1) the weighted and selected ordinate methods in ASTM E 424, Method A, at air mass 2.0, and (2) the selected ordinate method at air mass 1.5 and 1.0. The Solar reflectance and solar transmittance values calculated using the various methods are presented in this report along with discussions of the impact of the data in terms of possible revisions to ASTM E 424.

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

air mass; ASTM E 424; integrating sphere spectrophotometer; reflectance; selected ordinate; solar absorber materials; solar cover plates; transmittance; weighted ordinate.

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