NBS TECHNICAL NOTE 1174

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

Energy and Cost Evaluation of Solar Window Film Use in an Office Building

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ABSTRACT

The impact of solar window film utilization on building HVAC system loads, energy consumption and costs, is examined for a typical office building. The evaluation includes characterization and measurement of important film properties, performance of single-glazing window systems with and without film, simulation of annual building energy performance using the DOE-2 computer program, and a life-cycle cost analysis. Six window film options are compared to clear glass performance for seven climatic regions throughout the United States.

Guidelines are developed for effective solar film utilization in office buildings, in terms of energy performance and cost-effectiveness. Results indicate that solar films can be effective in reducing building energy requirements and costs in areas with high cooling loads, with less savings expected in areas with lower cooling loads and higher heating loads, and no savings in regions with high heating loads.

Key words: building energy analysis; cooling loads; heating loads; solar film; solar heat gain; window management.

PREFACE

A. AUTHORITY

This study has been executed pursuant to a GSA/NBS agreement, through the National Capital Region Design and Construction Division.

B. PURPOSE

The objective of this study is to evaluate the effects of solar window film utilization on building HVAC system loads and energy requirements, and to determine the cost-effectiveness of solar film use for an office building for seven climatic regions of the United States. Guidelines are developed and presented to enable effective utilization of solar window films in office building applications.

C. DISCLAIMER OF APPLICATION

The results and analysis are intended to be used only for the purpose described herein, and may not be applicable to other cases. Neither GSA nor NBS are responsible for any other use or application of the data, results or conclusions contained in this report.

The user is cautioned to evaluate the local weather conditions, building design and type of construction, location, height, usage and other relevant factors prior to any application of the data, results or conclusions contained in this report. Each building must be considered on an individual basis.

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W. S. Fleming & Associates were consulted to develop the initial building simulation file for the DOE-2 computer procedure.

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EXECUTIVE SUMMARY

A. PROBLEM STATEMENT

This report focuses on the evaluation of the impact of solar films on the annual building energy requirements for a typical office building with single glazing amounting to 54 percent of the exterior building envelope. This type of evaluation is complex due to the many factors influencing window performance, including the solar and thermal properties and environmental conditions. The heat transfer through the window must be determined with and without the solar films for a wide variety of climatic conditions. Then the change in the annual heating and cooling requirements of the building and the corresponding changes in energy usage must be determined for each film type evaluated. Lastly, the cost of heating and cooling energy must be determined, along with the material and installation costs and the expected useful lifetime, so that the cost effectiveness of solar film use can be determined on a life-cycle cost basis.

The results of this evaluation are presented in terms of guidelines for effective solar film utilization for seven climatic regions of the United States.

B. EVALUATION PROCEDURE

Six different solar films on clear glass were compared to clear glass without film. The evaluation procedure consisted of three phases, namely:

1. Characterization and measurement of the important solar film properties and the solar/thermal performance of a typical window system with each of the solar films. (Phase 1)

2. Computer simulation of building annual heating and cooling loads and energy requirements using the DOE-2 analysis program and a typical GSA office building, for seven regions of the United States. (Phase 2)

3. Economic analysis of the cost effectiveness of solar film utilization, including net savings, savings-to-investment ratio and payback period.

The solar film characteristics determined in phase one were used as input data for the computer simulation in phase two. Calculated building energy requirements for the Washington, D.C. location (the actual location of the building) were compared to the actual metered energy consumption, to validate the building model and simulation procedure. The calculated energy requirements were analyzed to determine the associated energy costs, using regional energy cost information provided by GSA, and including the effect of escalating energy prices. The energy costs were used to perform a life-cycle cost analysis for each film option at each location. The cost information was compared to determine the most effective film type for each location, and to determine if a net annual savings would occur.

C. GENERAL RECOMMENDATIONS AND COST-EFFECTIVENESS

The general recommendations are most easily explained through the use of tables due to the large number of options. These tables are found in section 5. Briefly, as would be expected, a net energy savings is realized in locations with high ratios of cooling loads to heating loads. This would be the case in the south and southwest areas of the country in particular. The life-cycle cost savings is dependent upon the energy savings together with initial cost and expected life of the film. Most films are warranted for five years, but the expected life could be much longer if the films are properly installed and maintained. Several installations have lasted through 15 years, but it is difficult to predict expected life for all situations.

Since the life expectancy is difficult to determine, calculations were performed using a ten year life and a fifteen year life, so a range of expected cost effectiveness could be determined. The results of this analysis indicate that solar films are likely to be cost effective in the southern half of the United States. The cost effectiveness calculations are strongly dependent upon energy costs, and each combination of heating and cooling energy costs would give different results.

D. MAJOR CONCERNS AND LIMITATIONS

The use of solar films in special situations requires special consideration. Since solar films can absorb a significant amount of solar radiation, the window glass may experience a temperature rise leading to thermal stresses and possible cracking in the glass and at the glass-frame interface. In most instances the temperature rise should cause no problem, as long as the glass is able to dissipate heat to the surroundings through convection and radiation. Thus, solar film should not be installed on the inner surface of a double-pane window if the glass is rigidly restrained on all sides preventing thermal expansion, nor on a heat absorbing glass. Suitability of a window for installation of solar film can be determined by examining the framing for flexibility and thermal expansion capability, and by consulting the window manufacturer.

If good visibility from inside to outside at night is required a highly reflective solar film may cause problems. This is because the film appears to be reflective when viewed from the bright side, meaning that the building occupants can see out during the day, but outsiders can see in at night. In most cases this would be only of minor concern.

One drawback to solar film use is that films are usually installed permanently. Thus, the beneficial summer film performance is counteracted by the undesirable winter performance. Some other window management systems are variable, either manually or automatically, and allow for adjustment to suit the weather conditions. Removable/reuseable solar films are available, but are not practical in many cases due to inaccessibility and labor costs. One should consider alternatives to solar films, such as shades, blinds, or louvers, if variable window management is required.

Solar films can have other impacts in buildings including glare reduction, shaving of peak cooling loads, reduced cooling plant capacity requirements and safety considerations.

1. INTRODUCTION

Window heat transfer has a significant impact on building energy requirements for heating and cooling [1,2]. Various systems are available for controlling window heat transfer [3,4,5], including shades, screens, drapes, special glasses, louvers and films. While evaluations have been conducted to assess the performance of these types of window management systems under different environmental conditions [6,7], very little information is available concerning the net annual energy performance of such systems. That is, it is obvious that reducing solar heat gain in summer results in a savings in cooling energy, but it is possible that an increase in the heating energy requirement in winter might offset the summer savings.

This report focuses on the evaluation of the impact of solar films on the annual building energy requirements for a typical office building with single glazing amounting to 54 percent of the exterior building envelope. This type of evaluation is complex due to the many factors influencing window performance, including the solar and thermal properties and environmental conditions. The heat transfer through the window must be determined with and without the solar films for a wide variety of climatic conditions. Then the change in the annual heating and cooling requirements of the building and the corresponding changes in energy usage must be determined for each film typed evaluated. Lastly, the cost of heating and cooling energy must be determined, along with the material and installation costs and the expected useful lifetime, so that the cost effectiveness of solar film use can be determined on a life-cycle cost basis [8].

The results of this evaluation are presented as guidelines for effective solar film utilization for seven climatic regions of the United States.

2. SOLAR FILM BACKGROUND

2.1 GENERAL DESCRIPTION

Solar window films have been utilized in buildings for a variety of reasons. The main impacts of solar film include:

a. Reduction in Peak HVAC System Loads

Solar films reduce the rate of heat transfer through the glazing, by reflecting and absorbing incident solar radiation, and by reducing convection and radiation heat transfer at the inner glazing surface. Peak load reduction is beneficial because it reduces cooling capacity requirements and electricity demand charges.

b. Energy Conservation

The reduction in peak HVAC system loads may reduce annual building energy requirements, if the reduction in cooling energy requirements due to shading offsets the usual increase in heating energy requirements due to reduction in free solar heat in winter.

c. Occupant Comfort

Comfort is a somewhat subjective parameter, but can be quantified to the extent that certain combinations of temperature, air flow, and radiation conditions are acceptable to most people, while other combinations are outside the comfort range.

Since clear glazing transmits large amounts of solar radiation, overheating can occur near the windows due to a combination of the greenhouse effect and insufficient air mixing, a condition which results in a lack of distribution of the solar heat gain to the rest of the building interior. In addition, building occupants are usually not comfortable if working in an area in which the rays of direct solar radiation strike them.

d. Glare Control

This aspect is related to occupant comfort. High levels of solar radiation, either direct or reflected from exterior or interior surfaces, can lead to unacceptable glare conditions due to high luminance ratios between the bright surface(s) and the remainder of the room [9].

e. Safety

Application of window film will significantly reduce to possibility of shattering of the glass due to impact, because of the reinforced/adhesive quality of the plastic film. Upon impact, the glass may break, but in many cases the broken pieces will be held together by the film.

f. Aesthetics

The aesthetic qualities of solar films are largely subjective and are related to the mirror-like reflectance and/or the tinted color. Some privacy is obtained for building occupants when the exterior is brighter than the interior (i.e., daytime), since the films appear to be reflective mainly as viewed from the brighter side. However, this phenomenon reverses at night, when it becomes difficult to view out the window.

g. Reduction in Ultraviolet Radiation Transmission

Ultraviolet radiation can contribute significantly to accelerated material aging and deteriorization, such as fading of drapes and carpets. Some films have a very low ultraviolet transmittance, less than two percent, due to reflection or absorption of most of the radiation in the UV region.

There are some tradeoffs among the previously listed solar film uses, mostly relating to the relationships between window heat transfer, solar heat gain, energy conservation, and comfort. Briefly stated, the application of a solar window film will typically reduce solar heat gain on a year-round basis, resulting in a savings in cooling energy and an increase in heating energy. There will also be a decrease in the amount of daylight available, and thus a possible increase in electric lighting requirements, although that aspect was not considered in this study.

Another trade-off involves comfort versus winter solar heat gain. Consider the case in which the south-facing offices of a building are subjected to overheating on sunny winter days, due to the low sun angle. Application of a solar-control film would reduce overheating and improve comfort. However, since the building is in a heating mode, the solar heat gain is reducing heating energy requirements, so a reduction in solar heat gain would improve comfort at the expense of increasing heating costs. These aspects are considered in more detail in the section on window heat transfer.

2.2 SOLAR FILM CHARACTERISTICS

2.2.1 Physical Properties

Solar window films are constructed of two or more thin plastic layers laminated into a thin sheet. If the film is reflective, one of the film layers is metallized through a vacuum deposition procedure which leaves a controlled density of aluminum sandwiched between two plastic layers. Additional layers of film can be added to obtain a particular tint or color. The base material of the film is usually transparent polyester, and the inner layer is polyester for normal emittance films, and polypropylene for a low emittance films.

A protective release sheet covers the adhesive side of the film, which faces the inner surface of the window glass. Currently, most films have a water-activated, pressure-sensitive adhesive system. Once the release sheet is removed, the adhesive and glass surface are sprayed with water, allowing the film to be positioned on the glass and trimmed. Figure 1 shows several typical variations of film construction.

The other film properties fall under the category of solar/thermal characteristics. These are reflectance (ρ), absorptance (α), transmittance (τ), and emittance (ε). See figure 2.

ρ = reflectance; percentage of incident radiation reflected from the film.

α = absorptance; percentage of incident radiation absorbed by the film.

τ = transmittance; percentage of incident radiation transmitted through the film.

ε = emittance; the ratio of radiation intensity from a surface to that from a black body at the same temperature.

All of these properties are functions of the wavelength of the incident radiation; however, averaged or integrated values are usually determined from measurement and/or calculation. Since the following relation is true,

$$\rho + \alpha + \tau = 1$$

specification of the values of any two of these parameters also determines the third. The reflectance and absorptance are determined by the film materials and construction. The reflectance properties are controlled by the density of the vacuum deposited aluminum layer, with greater densities producing greater reflectances. The highest reflectance films in normal use have a ρ of about 55 percent, to allow some visibility through the film. However, any degree of reflectance can be obtained through use of the proper aluminum density. In contrast, the reflectance of clear glass is less than 10 percent. The absorptance of a film is controlled by the darkness of the tint, and the number and thickness of the tinted layer(s). While clear glass exhibits an absorptance of less than 10 percent, most films have an absorptance of 30 percent or more, and may range over 60 percent. By varying the reflectance and absorptance, the transmittance can be set at any level, but usually ranges from 10 to 50 percent.

The surface emittance of a film determines the ability of the film to reflect infrared radiation. A low emittance film installed on an inner window surface will reduce radiative heat exchange between the window and the room thereby reducing conductive heat loss through the window during heating periods and radiative heat gain to the room interior from the warmer window surface during cooling periods. Typically, the films are available with normal emittance ($\varepsilon \approx 0.80$) and low emittance ($\varepsilon \approx 0.25$). Some films which are considered normal emittance actually exhibit a slightly lower emittence in the range of 0.6 to 0.7. The values of ρ, α, and τ for the six test films are listed in the measurements section (4.2) of this report.

Typical film properties are listed in table 1.

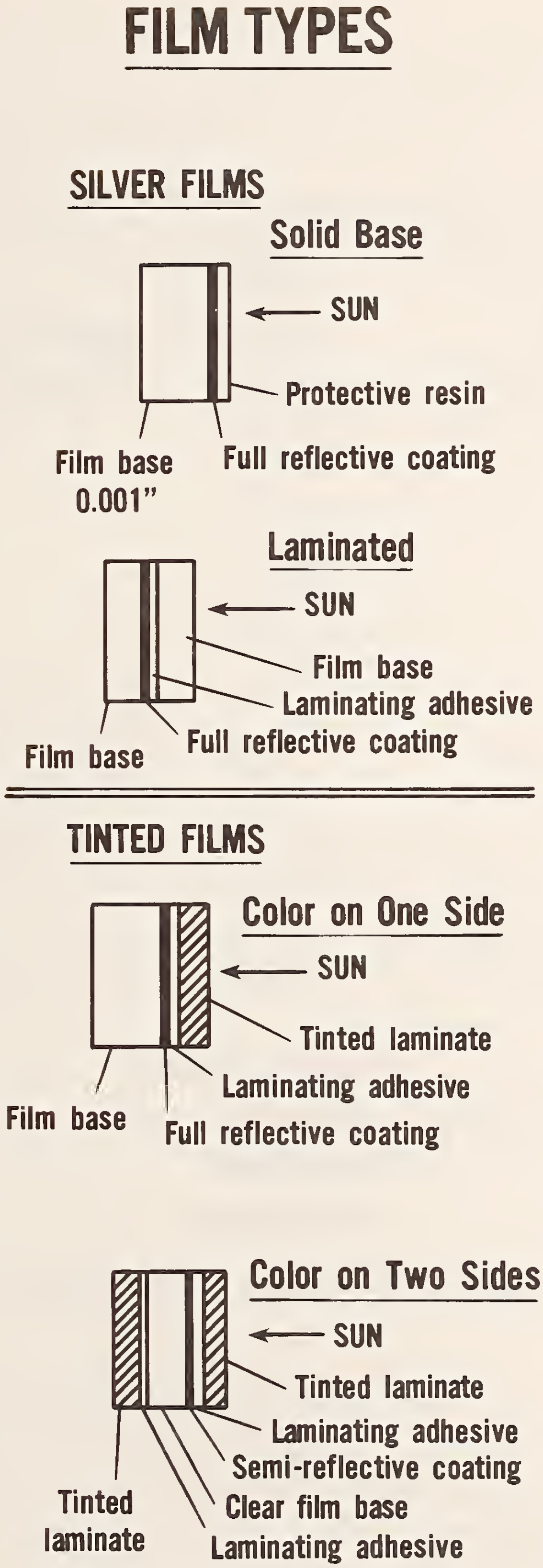
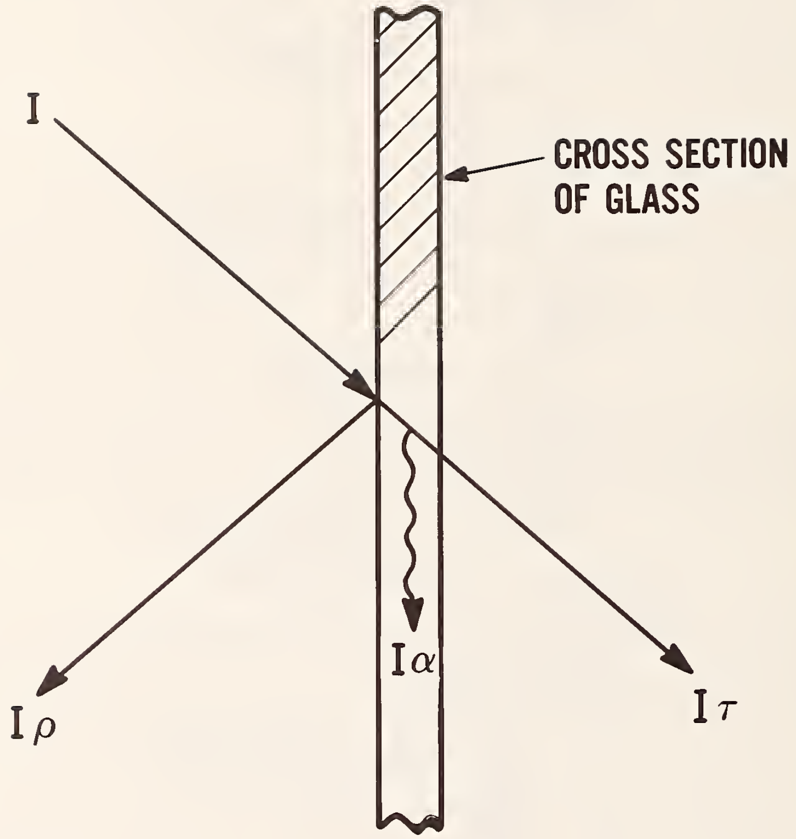


Figure 1 Construction of typical solar window films



I = incident irradiance
ρ = reflectance
α = absorptance
τ = transmittance

Figure 2 Impact of window on incident solar radiation

Table 1.

Title: Typical Physical Properties of Films

Description: This table lists the major film characteristics along with a range of typical values of each parameter.

Parameter	Range
thickness	0.0254-0.0127 m (0.01-0.005 in)
tensile strength	4202-17513 N/m (24-100 lbs/in) of width
maximum elongation to break	100-200%
colors	silver, grey, gold bronze, clear and others
reflectance	0.20-0.55
absorptance	0.30-0.60
transmittance	0.10-0.50
emittance	0.25-0.85
ultraviolet transmittance	1-30%

2.2.2 Application of Solar Films

Solar films are bonded directly to the inner surface of the window glass. Most films are permanently installed, although some are reusable and can be removed and replaced on a periodic basis. These reusable films are not included in this analysis since the labor involved in removing and replacing all of the films in an office building with a large window area would probably cost more than any savings which would be attributed to that procedure. Reusuable films are used mainly for residential or special applications.

Solar film installation is simple in concept, but requires skill and attention to detail to provide for a good, optically clear bonding of the film to the glass. Typical installation instructions are as follows:

Film Installation Instructions

Whether you use professional installers, or "in-house" personnel to install film, satisfactory results require careful attention to:

a. Window cleaning before application.
b. Edge trimming to leave narrow, uniform lines.
c. Squeegee work to avoid creases, marks.
d. Preventing dust and dirt under the film.
e. Eliminating air bubbles and "pools" of liquid.

f. Maintaining smooth, non-distorted, non-grainy exterior appearance.
g. Silicone polishing of film after installation.

Using In-house Installers:

When windows are conventionally sized and positioned, the use of in-house personnel can save money. Results can be as good as professional work if the installers will follow the simple routine for window cleaning, film handling, squeegee work, trimming and cleanup. With proper training and guidance, in-house personnel can install film economically because set-up time is minimal. One man, or a team of two, can use "stand-by" time to complete an installation. Film can be installed on only one window or in one office at a time, unlike other maintenance work which must be completed once it is started. In-house personnel should acquire some experience before tackling large windows that require two pieces of film to be seamed together.

The potential waste factor when installing films on windows that are difficult to reach, or have drop ceilings or are high in the air may make it more economical to use the professional installer. However, when windows have small panes or are in areas where prime appearance is not a factor, the shortcomings of the in-house installer may not be visible or objectionable. Generally on large jobs it may cost less to use professional installers, particularly if the windows are in prime office areas. Also, manufacturers may not offer a full five-year guarantee if work is not done by factory-trained installers.

Care and maintenance of windows with solar film is similar to that of glass, except abrasive cleaners should not be used. Typical care instructions are as follows:

1. Wait three (3) weeks before cleaning the film for the first time after the installation.

2. Use any of the following solutions: mild soap and water; or isopropyl alcohol (1 part) and water (20 parts) - the latter produces sparkling clean windows and no residue to be rubbed away. Ammonia and/or ammonia-based cleaning solutions are <u>not</u> recommended.

3. Spray the film lightly, all over, with the cleaning solution, using a hand sprayer. (You may also apply the cleaning solution with a cloth, if desired, but this method takes longer to apply and clean.)

4. Remove the cleaning solution with a squeegee, applying <u>light</u> pressure (just enough to remove the moisture of the cleaning solution). A soft cloth or soft paper towel or sponge may also be used.

5. Do <u>NOT</u> squeegee dry film - slight scratches may result. Respray if necessary.

6. Dry the edges of the window (and film) thoroughly with a soft cloth or paper towel, so that no moisture remains to seep under the film at the edges.

7. If the film is spliced, exercise caution around the splice. Do NOT pull the squeegee (or cloth, etc.) across the splice. Always pull the squeegee (or cloth, etc.) along the splice, carefully. Be sure that the splice edges are dry afterwards - blot if necessary.

A few cautions should be observed:

1. Do NOT use hard brushes or abrasives in cleaning the film - scratches or tears will result.

2. Do NOT rub or clean the film when condensation is present.

3. Do NOT rub or brush sharp-edged articles such as scrapers, razors, or even jewelry against the film.

4. Do NOT post heavy gummed signs, Christmas spray-on snow, etc., on the film. If signs or decorations are desired, a lightly gummed tape may be used, with caution. If the tape leaves a residue, dampen a soft cloth with lighter fluid and rub that area gently.

2.2.3 Cost

The cost of installing solar film includes both material and labor costs. As with any product, considerable variation in costs exists, depending upon the type of film, size of the job, special installation requirements and other market factors. Recent government installations have cost approximately one to two dollars per square foot of film. It is not possible to predict the future course of film costs, as changes in materials and processing procedures may produce changes in costs. The magnitude of the installation costs depends upon whether the labor is performed by in-house personnel or contractors and on site location, since considerable variation exists in labor costs throughout the country. For the purpose of performing the economic analysis found later in the report, the actual film cost for the study building was used. This cost was approximately one dollar per square foot including installation.

3. WINDOW HEAT TRANSFER

3.1 BACKGROUND

Heat transfer through fenestration systems consists two components, namely solar energy transmitted by the glazing, and energy convected and radiated between the glazing and the building interior. Heat transfer occurs as a result of two major driving forces, incident solar radiation and inside-to-outside air temperature differences. Analyzing and quantifying the solar/thermal performance of fenestration systems is a complex task due to the many factors influencing the two heat transfer components, especially when complicated or variable window systems are considered. However, in the case of single glazing with no auxiliary shading, some simplifications and assumptions lead to procedures for estimating window heat transfer on the basis of a few key parameters.

The thermal and solar properties of window systems have been characterized in terms of two standard parameters:

1) Thermal transmittance (U-factor); the ratio of the heat gain through the window to the temperature difference between the inside and outside air, and

2) Shading coefficient (SC); the ratio of the amount of solar heat gain for the actual window to the solar heat gain for a single pane reference glass.

The value for the solar heat gain for the reference glass must be known or computed to use the shading coefficient to compute heat transfer. A more direct calculation of window heat transfer can be obtained using the shading factor.

3) Shading factor (F); the ratio of solar heat gain through a window to the level of incident solar radiation.

The solar heat gain can be calculated from the product of the incident irradiance and the shading factor.

For window glass with or without solar film, the U-factor, SC, and F are dependent upon the particular combination of the parameters of reflectance, absorptance, transmittance and emittance. The relationships between the factors can be summarized as follows.

The U-factor is essentially dependent upon the emittance of the surface, with lower values of emittance producing lower U-factors. This is due to a reduction of radiant heat transfer from the room to the interior surface. The absorptance can also influence the U-factor by causing an increase in the glazing temperature which can in turn influence heat transfer due to free convection.

The shading coefficient and shading factor are directly related by the constant reference glass shading factor, so both are similarly affected by the U-factor, absorptance and transmittance. Shading factor increases with larger values for either transmittance, absorptance or U-factor, with transmittance usually being the most significant component.

The ASHRAE Handbook of Fundamentals [10] describes the procedures for calculating both solar and total heat gain through fenestration areas. The procedures and parameters involved are summarized below for the case of single glazing. Similar procedures are available for multiple glazing systems. The heat balance between a unit area of sunlit single glazing material and its thermal environment is:

$$I + U(T_O - T_I) = q_R + q_S + q_T + q_{RC_o} + q_{RC_i}\,\text{1/}. \tag{1}$$

where I = incident solar radiation,
U = thermal transmittance of glazing,
T_O = outdoor air temperature,
T_I = indoor air temperature,
q_R = reflected solar radiation,
q_S = stored solar radiation,
q_T = transmitted solar radiation,
q_{RC_o} = radiation and convection to exterior, and
q_{RC_i} = radiation and convection to interior.

The heat storage term, q_S, is usually quite small and can be neglected. The reflected term, q_R, and the radiation and convection to exterior term, q_{RC_o}, represent the heat rejection to the exterior, leaving the transmitted term, q_T and the radiation and convection to interior term, q_{RC_i}, to represent the heat gain.

Equation 1 neglects the effect of transmission of solar radiation through the glazing in an outward direction, which occurs due to reflection of solar radiation from interior surfaces. This effect is usually quite small in relation to the level of incident solar radiation [11], since most of the solar energy would have to undergo multiple reflections before leaving the room through the window. Also, since glass is opaque to longwave infrared radiation beyond 3500 Nm (3.5 microns), any absorbed solar radiation which is subsequently reradiated from room surfaces will be trapped in the room. This is commonly called the "greenhouse effect".

In terms of the driving forces, net window heat transfer at any point in time is given by:

$$Q = I\tau + N_i(\alpha I) + U(T_O - T_I). \tag{2}$$

1/ ASHRAE Handbook of Fundamentals, Chapter 26, Fenestration, ASHRAE, New York, 1977, (equations 1-7).

where Q = net heat transfer,
τ = solar transmittance of glazing,
N_i = inward-flowing fraction of the absorbed solar radiation,
α = solar absorptance of glazing.

Since the first two terms of eq. 2 are related to the solar radiation, they can be combined to produce:

$$Q = IF + U(T_O - T_I). \tag{3}$$

where F = shading factor.

Thus, the shading factor is defined as the ratio of the solar heat gain to the level of incident solar radiation, and includes both the transmitted solar radiation and the fraction of the absorbed solar radiation which is transferred to the interior space. For single glazing, resistance to heat transfer is composed of the interior and exterior air films and the thermal resistance of the glass itself. Very little resistance is provided by the glass, however, due to its small thickness [12].

The thermal transmittance (U-factor), being the inverse of the thermal resistance, is given by:

$$\frac{1}{U} = \frac{1}{h_I} + \frac{1}{h_O} \text{ or } U = \frac{h_I\ h_O}{h_I + h_O} \tag{4}$$

where:

h_I = combined interior surface coefficient,
h_O = combined exterior surface coefficient.

The nature and magnitudes of the surface coefficients are described in a later section of this report. Manipulation of eqs. 2, 3, and 4 leads to the following relations:

$$N_i = \frac{U}{h_O} \tag{5}$$

and
$$F = \tau + \frac{U\alpha}{h_O} \tag{6}$$

It should be noted that the parameters on the right side of eqs. 4 and 6 are not constants, although they tend to fall in particular ranges as a function of the environmental conditions. The functional dependencies of the variable parameters are listed in table 2.

Table 2.

Title: Major Factors Influencing Solar and Thermal Heat Transfer

Description: The solar and thermal performance of window is dependent upon several parameters which, in turn, are dependent upon material and environmental parameters.

Parameter	Dependence
h_I, h_O, U	° Surface properties of window (i.e. emittance), ° airflow conditions near window, glass surface temperature, ° temperature difference between glass surface and air, ° temperature of surrounding surfaces,
τ, α	° solar radiation spectral composition and incident angle.

The shading coefficient (SC) is defined as the ratio of the shading factor of a particular fenestration system to the shading factor of a reference glass, namely double-strength, single pane clear glass:

$$SC = \frac{F}{F_{REF}} \tag{7}$$

The shading coefficient concept is used to relate the solar heat gain to a baseline case, so that the solar heat gain can be calculated for any case simply by scaling the heat gain which would occur for the reference glass. While the shading factor of the reference glass is nearly constant for most cases (approx. 0.87), the shading factor of the window of interest may vary, particularly if the window has a significant solar absorptance. Thus, although shading coefficient values are usually considered to be constants for each window type, some variation can occur with different weather conditions.

The solar transmittance of most fenestration systems is a function of the incident angle and the spectral composition of the incoming solar radiation. The solar radiation incident upon a window is composed of a direct beam component and a diffuse sky component. The diffuse component exhibits little variation in incident angle so the diffuse transmittance varies only through a small range. The incident angle of the direct beam radiation is a function of the position of the solar disk relative to the window. For clear glass, the transmittance remains fairly constant until the incident angle exceeds 50°, at which point the transmittance begins to decrease sharply.

The effect of varying spectral distribution of incoming solar radiation on actual transmittance is much smaller than the effect of incident angle, but can contribute to small variations if atmospheric conditions are unusual.

3.2 THERMAL PERFORMANCE

As described earlier, the thermal transmittance (U-factor) is determined by the interior and exterior surface coefficients. Each surface coefficient is composed of a convective component and a radiative component, and is dependent upon the airflow conditions and the temperatures of the window and its surroundings. Considerable variation can occur in the values of these parameters, depending upon the design and location of the window.

For the case of free convection along a vertical panel such as a window, the interior convective heat transfer coefficient can be estimated from the relation[2]:

$$h_c = 0.19(\Delta T)^{0.33} \tag{8}$$

where

h_c = convective surface coefficient
ΔT = temperature difference between window surface and interior air (°F) ($\Delta °F = 1.8 \Delta T °C$).

For the case of forced convection, when air continuously sweeps across the window, such as would occur if a fan unit was near the window, h_c could be larger. Sometimes a fixed value is used, such as 8.29 $w/m^2 \cdot K$ (1.46 $Btu/hr \cdot ft^2 \cdot °F$) [10].

The radiative surface coefficient is a function of the temperatures and emittances of the radiating surfaces. If the room is assumed to be a cavity, it would appear to have an emittence of one. Thus:

$$h_r = \frac{\varepsilon\sigma(T_G^4 - T_R^4)}{T_G - T_R} \tag{9}$$

where h_r = radiative surface coefficient
ε = emittance of interior window surface
σ = Stefan-Boltzmann constant
T_G = interior glass surface temperature, absolute units
T_R = mean radiant temperature of room, absolute units.

From eq. 8 it is seen that h_r can be reduced if the emittence is reduced, as can be accomplished through application of a low emittence film to the interior glass surface. The total interior surface coefficient is the sum of the two components:

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[2] Op.cit. Chapter 2, Heat Transfer (equations 8-10).

$$h_I = h_r + h_c \tag{10}$$

The exterior surface coefficient is more difficult to quantify objectively, due to the difficulty in specifying the temperature of the surroundings and the air-flow conditions at the exterior window surface. The ASHRAE handbook estimates the exterior surface coefficient on the basis of wind speed, with a value of 22.7 w/m2•K (4.0 Btu/h•ft2•F) for a wind speed of 6.7 m/s (7.5 mph), and a value of 34.1 w/m2•K (6.0 Btu/h•ft2•F) for a wind speed of 3.4 m/s (15.0 mph). These values are only estimates since exterior surface coefficients are also dependent upon wind direction and exposure conditions [13]. However, these values are useful for comparing the performance of different window systems on a relative basis under equivalent conditions.

Equations 3 through 10 were used to develop an analytical model of a typical window system. Using the measured material properties of the films and various combinations of solar radiation, wind, and air temperature conditions as input parameters, an iterative computer procedure was used to solve for the window temperature, the interior surface coefficient components and the thermal transmittance. The model assumes that the interior surfaces are at the same temperature as the interior air, and that free convection occurs at the interior window surface.

The model was used to generate plots of the nighttime thermal transmittance as a function of the indoor-outdoor air temperature difference, for values of the exterior surface coefficient of 5.7, 11.4, 22.7 and 34.1 w/m2•K (one, two, four, and six Btu/h•ft^2•F). These plots indicate a range of expected U-values for each glass/film combination estimated in this report, plus the clear glass case, and are found in figures 3a-g, located at the back of the report.

As seen in these figures, the magnitude of the U-factor increases with greater temperature differences, but changes very slowly once the temperature difference is greater than 8.3°C (15°F). The exterior surface coefficient is seen to have a stronger impact on the U-value, with variations of 20 percent or more possible due to a typical change in h_O.

3.3 SOLAR CONTROL PERFORMANCE

The computer model was also used to calculate the shading factor F for each glass/film option. Because F is a function of U, it will also vary with the exterior surface coefficient and the air temperature difference. The level of solar radiation will also impact the shading factor, especially if the window system has a significant absorptance, since absorbed solar radiation will cause the glass temperature to increase. The calculated shading factor plots are presented in figures 4a-g.

For design purposes, ASHRAE specifies particular conditions under which U-values and shading factors are to be calculated. These conditions are

winter U-factor	° 38.9°C (70°F) temperature difference ° no solar radiation ° h_O = 34.1 w/m^2•K (6.0 Btu/h•ft^2•F)

summer shading factor ° 5.6°C (10°F) temperature difference
° h_0 = 22.7 w/m^2•K (4.0 Btu/h•ft^2•F).

Values of these parameters, calculated using the foregoing conditions, are listed in table 3 along with shading coefficients.

Table 3.

Title: Design Values for Solar and Thermal Properties of Six Solar Films

Description: The winter thermal transmittance (U-value), shading factor and shading coefficient are listed as calculated using standard ASHRAE procedure, for each film and clear glass

Type	Winter U-value (Btu/h•ft2•F)	(w/m2•K)	Shading Factor	Shading Coefficient
Clear	1.17	6.6	0 87	1.0
Film A	0.84	4.8	0.17	0.20
B	1.17	6.6	0.20	0.23
C	0.84	4.8	0.27	0.31
D	1.17	6.6	0.30	0.34
E	1.07	6.1	0.32	0.37
F	1.18	6.7	0.62	0.71

3.4 COMFORT

Alteration of the solar/thermal properties of a window through application of a solar film may significantly influence comfort conditions within the interior space near the window. This would be especially true for office areas near large windows subject to high levels of incident solar radiation. The use of solar film impacts comfort conditions in two main ways:

1. Rejection of solar heat through reflection and/or absorption of incident solar radiation.

2. Reflection of room temperature infrared radiation from the interior window surface (requires the use of a low emittance film). This results in a higher mean radiant temperature, improving comfort conditions near the window.

The effect of rejection of solar heat is more significant than the effect of infrared radiation reflection, due to the relative magnitudes of the radiation components. As a general rule, building occupants would not be comfortable if they were working at a location near a window such that direct beam solar radiation was striking them for long periods of time. In addition, high rates of solar heat gain can result in an increase in air and surface temperatures within the interior space near the window, since a finite amount of time is required for the HVAC system to respond to the solar heat gain. This situation can occur during any season, depending on the solar radiation levels and window exposures. Overheating may be experienced near a south-facing window even in the dead of winter, due to the low solar altitudes during this time. However, reducing solar heat gain in winter through the use of a solar control device may improve comfort at the expense of energy, since the solar heat gain may be reducing the heating energy requirement for the entire building. During the cooling season a solar control device would be beneficial both from the standpoint of comfort and energy.

While solar films do provide significant reduction in solar heat gain, additional solar control strategies may be required in areas with high cooling loads and high levels of solar radiation. This may be accomplished through the use of interior shading such as blinds, drapes or louvers [14]. These types of interior shading devices can be adjusted by building occupants as required to maintain comfort conditions, and to reduce undesirable solar heat gain.

4. MEASUREMENTS

4.1 PURPOSE

The purpose of the measurement portion of the study was to determine the physical, thermal, and optical characteristics and properties of the solar films, and to monitor the energy related performance of a window with and without solar film installed. This allows for verification of the calculated U-values and shading coefficients, and provides a detailed look at the various window heat-transfer mechanisms.

The measurements are summarized in table 4.

Table 4.

Title: Measurement Parameters, Apparatus and Method

Description: The individual measurement parameters, measurement apparatus and methods are listed for each of the components of the measurement portion of the study

Parameter	Apparatus	Method
Small samples:		
solar transmittance solar reflectance infrared transmittance	spectrophotometer	ASTM E424 A
surface emittance	infrared reflectometer	
Full size windows:		
solar transmittance	pyranometers	ASTM E424 B Ratio of transmitted to incident solar radiation
Net window heat transfer U-factor, shading factor	calorimeter	Energy balance of guarded window calorimeter
Window temperature	calorimeter	Type T thermocouples, 30 gage

4.2 SMALL SAMPLE TESTS

Highly accurate measurements were made of the solar transmittance and reflectance, the infrared transmittance and the surface emittance for clear glass and for each film/glass combination. These laboratory measurements use an artificial energy source to simulate solar radiation, so the spectral composition and level of the incident radiation is constant and reproducible for each test, providing a good basis for comparison of the physical properties of the solar films. When actually installed in a building exposed to sunlight (as will be described in the next section), the actual transmitance of any window will vary as a function of the spectral distribution and incident angle of the incoming solar radiation. The transmittance of a window to direct beam (parallel ray) solar radiation is strongly dependent upon incident angle due to the increased reflectance at sharp incident angles. Of the energy not reflected at one of the glass or film surfaces, the portion transmitted is determined by the product of the spectral distribution of the incident solar radiation and the spectral transmittance.

4.2.1 Solar Transmittance and Reflectance

The spectral transmittance of the glass/film materials was measured utilizing a Cary 17D Spectrophotometer[1] with a 76 mm (3 in) diameter integrating sphere [15]. Measurements of spectral transmittance relative to air were made over the spectral range from 300 to 2150 mm. The illumination and viewing mode were normal-diffuse. The transmittance measurements were made by placing the test specimen in direct contact with the sphere aperture so that the incident monochromatic radiation was normal to the plane of the specimen. The sphere aperture had approximate dimensions of 25 by 10 mm (1 by 3/8 in). The incident beam was approximately 24.4 x 6.2 mm (0.96 by 0.24 in) and it intersected the test specimen near the center. The solar energy transmitted was obtained by integrating over the spectral solar energy distribution, as reported by Parry Moon [16], for sea level and air mass 2 (AM 2 sun's rays 60° from normal). The weighted ordinates calculation method from ASTM E 424 was used to integrate the solar energy distribution at 50 Nm intervals, normalized to 100 percent. The spectral transmittance data were digitized by the spectrophotometer and fed directly into a computer which performed the integration calculations after correcting for the baseline. Due to the optics associated with the integrating sphere and moisture in the atmosphere, the 100 percent baseline contained several absorption bands for which corrections were made.

The solar reflectance was measured in a similar manner, with the positions of the light source and sample reversed, and the absorptance was calculated from the reflectance and transmittance.

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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.

The integrated values of the transmittance, reflectance and absorptance are listed in table 4, while the detailed spectral plots are found in figures 5a-g.

4.2.2 Infrared Surface Emittance

The surface emittance was determined using an infrared reflectometer, with a low temperature heat source. Since all of the materials are essentially opaque to infrared radiation, the emittance (ε) is found by:

$$\varepsilon = (1-\rho) \tag{11}$$

The measured emittances are listed in table 5. As seen there, the low emittance films were found to have surface emittance as low as 0.28, compared to a high of 0.87 for film F and 0.85 for clear glass. Even some of the so-called normal emittance films exhibit a lower surface emittance than the clear glass, a characteristic which would lead to reduced heat loss. Spectral emittance measurements of films A, B, C, and clear glass, are found in figures 5h-k.

Table 5.

Title: Measured Integrated Average Solar Properties of Six Films and Clear Glass

Description: The measured solar properties are listed for each of the films and clear glass

Type	Reflectance, ρ	Absorptance, α	Transmittance, τ	Emittance, ε
Clear	0.08	0.11	0.82	0.85
Film A	0.55	0.33	0.12	0.28
B	0.53	0.32	0.15	0.61
C	0.41	0.37	0.22	0.39
D	0.25	0.58	0.17	0.64
E	0.19	0.63	0.18	0.67
F	0.07	0.41	0.52	0.87

4.3 FULL SIZE WINDOW TESTS

Measurements were made using full size windows in a manner such as would be found in a typical office building, to determine typical data regarding window heat gain and thermal/solar performance characteristics. The intent of this portion of the study was to measure the important parameters as they occur while a window is exposed to typical interior and exterior conditions, including solar radiation, outdoor wind and air temperature conditions and interior temperature and airflow conditions.

These measurements were accomplished through the use of a specially constructed window calorimeter, suitably instrumented to monitor and record all the data required to perform and complete the analysis. The calorimeter, or box, was operated continuously, and each of the seven window types was installed periodically and tested under various conditions through summer, fall, and winter seasons.

Additional measurements of glazing surface temperature and transmittance were made using four side-by-side test windows.

The calorimeter was constructed in the shape of a large box (approximately 100 ft3; 2.8 m3), without an absorber plate located inside the window opening. This design was chosen since it more closely resembles a typical office space, and allows for air circulation across the inner glass surface, as would typically occur. Solar energy transmitted by the window will be absorbed and reflected by the box walls and floor, possibly causing an increase in surface temperature. This, in turn, leads to heat transfer from the box walls and floor to the box air, as would occur in a typical office. Due to the low thermal conductance of the box walls, virtually all of the absorbed solar radiation eventually is transferred as heat to the air. However, during those periods when the walls or floor are at an elevated temperature, heat exchange with the glazing may be influenced, as would be expected in a typical office space.

Measurements included net window heat transfer, incident and transmitted solar radiation, incident infrared radiation, surface and air temperatures, thermal transmittance, shading factor and surface heat transfer coefficients.

4.3.1 Apparatus

The window calorimeter was constructed of polystyrene with 12.7 cm (5 in.) thick walls. The overall dimensions of the box are 144.8 cm (57 in.) wide x 132.1 cm, (52 in.) deep x 198.1 cm (78 in.) high, with a window opening of 153.5 x 96.4 cm (25 x 38 in.) (see figure 6). The box is mounted flush with a south facing exterior wall (R40) with a cutout for the window so 1.5 m2 (16 ft2) of box wall and 0.6 m2 (6.6 ft2) of window area are exposed to exterior conditions. The box was mounted in the room so that none of the remaining five surfaces (floor, wall, ceiling, etc.) touched the walls, floor or ceiling of the room, thus, maintaining an air space all around the box. The room air temperature was controlled to match the box air, so no heat transfer would occur through any portions of the box envelope except for the exterior wall. The window frame was constructed of polystyrene and was 20.3 cm (8 in.) deep total, with the glass inset 2.5 cm (1 in.) from the exterior. A photograph of the window calorimeter is shown in figure 7.

The air temperature in the box was controlled using a water-to-air heat exchanger mounted inside the box, with a constantly operating circulation fan. The heat exchanger fan was a constant heat source in the box, releasing 94.1 w (321 Btu/hr). The supply air was directed downward 0.5 m (1.5 ft) above the floor, with the return located near the box ceiling facing the window opening. Thus, supply air tended to sweep the walls of the box and good mixing was achieved. An individual HVAC system, consisting of a water chiller, in-line electric heater, pump, and storage tank in series with the box heat exchanger, enabled precise control of box air temperature. A temperature sensor in the heat exchanger return air stream was used to automatically control the operation of the chiller and heater to maintain box air temperature within a small band.

The amount of heat added or extracted from the box (Q) was determined from the following equation:

$$Q = \dot{V} d C p \Delta T \qquad (12)$$

where:

$\dot{V}$ = volumetric flow rate of water,
d = density of water
C_p = specific heat of water
ΔT = temperature change of water flowing through box heat-exchanger.

The water flow rate was held constant, the specific heat of water was assumed to be a constant 4.2 (103) J/Kg•K (1 Btu/lb•°F) and the density of water was assumed to be a constant 1000 Kg/m3 (62.4 lb/ft3).

The temperature rise of the circulating water was measured using a copper-constantan thermopile with 21 pairs of junctions which produced a millivolt signal proportional to the difference between the inlet and outlet water temperatures of the box heat-exchanger. The millivolt signal was read by an analog integrator which printed hourly integrated average values of the temperature difference for each hour. A rise in water temperature indicates heat extracted from the box (cooling), while a negative temperature difference indicates heating has occurred.

The window calorimeter test set-up was instrumented with Type T thermocouples to measure various surface and air temperatures, solar pyranometers to measure incident and transmitted radiation, and infrared prygeometer to measure incident long wave (4-50 μm) (4000-50,000 Nm) radiation. Additional measurements were made of the weather parameters such as wind speed and other solar radiation components. A complete list of measurement parameters is given in table 6.

4.3.2 Data Acquisition System

All of the sensors, except the box flowmeter and thermopile, were monitored using a micro-computer controlled data acquisition system. The sensor outputs were connected to a data logger which provided thermocouple compensation and analog-to-digital conversion. The micro-computer continuously scanned all sensors, computing and printing average and instantaneous values every hour.

Subsequent processing provided separate files of reduced data, including temperature differences, derived quantities and calculated components, and allowed inclusion of the box flowmeter and thermopile readings.

Thus, the hourly measurements of box heat loss/gain, temperature, and environmental conditions enabled determination of U-values, shading factors, shading coefficients, and window energy performance.

Table 6.

Title: Measurement Sensors

Description: Each measured quantity is listed, along with the conventional units.

Quantity	Units	
a) total horizontal irradiance	w/m2	(Btu/h•ft2)
b) diffuse horizontal irradiance	"	
c) total vertical irradiance south exterior	"	
d) total vertical irradiance, inside glazing • calorimeter • four test windows	"	
e) longwave infrared radiation, south exterior vertical	"	
f) wind speed	m/s	(mph)
g) wind direction	degrees	
h) temperatures • all box walls, floor, ceiling surfaces • five test windows, interior surface • indoor, outdoor air • exterior ground surface	°C	(°F)

4.3.3 Test Procedure

The test procedure consisted of installing one of the test windows in the calorimeter, and monitoring the energy requirements of the box, along with the environmental conditions. After correcting for heat gain to the box from the heat exchanger fan, and any heat transfer between the box and the room air surrounding the interior box walls, an overall heat balance for the calorimeter yields:

$$Q_{net} = Q_{window} + Q_{wall} \tag{13}$$

or

$$Q_{net} = IFA_G + U_G A_G (T_O - T_I) + U_w A_w (T_O - T_I) \tag{14}$$

where

Q_{net} = net box heat transfer,
A_G = total window area,
A_w = total wall area,
I = incident solar radiation,
F = shading factor,
U_G = glass thermal transmittance,
U_w = wall thermal transmittance ≈ 0.142 $w/m^2 \cdot K$, (0.025 $Btu/hr \cdot °F \cdot ft^2$),
T_O = outdoor air temperature,
T_I = indoor air temperature ≈ 26°C, (78°F).

The term $U_w A_w (T_O - T_I)$ is the heat transfer through the small portion of exterior wall (less the window opening) and must be subtracted from Q_{net} to determine the heat transfer due to the window. Thus,

$$Q_{window} = Q_{net} - Q_{wall} \tag{15}$$

and

$$q = \frac{Q_{window}}{A_G} = IF + U(T_O - T_I) \tag{16}$$

where

q = heat gain per unit window area.

From this relation, it is seen that when solar radiation I is zero:

$$q = U(T_O - T_I) \tag{17}$$

or

$$U = \frac{q}{T_O - T_I} \tag{18}$$

Thus, the U-factor can be determined through measurement of q, T_O, and T_I.

The shading factor, F, cannot be measured directly, since there will nearly always be an inside-to-outside temperature difference causing some heat flow through the window and contributing to q. However, F is given by:

$$F = \frac{q - U(T_O - T_I)}{I} \tag{19}$$

This relation indicates that if the U-factor is known, F can be determined. Since the U-factor is measured continuously, the pre-dawn and post-dusk U-factors can be adjusted for daylight hours by considering the glazing temperature and wind conditions. By choosing days with constant wind conditions and correcting the U-value to account for heating of the glazing due to solar absorption, the U-factor can be calcuated and the thermal heat transfer component subtracted from the overall box heat gain, leaving only the solar component. The ratio of the solar heat gain to the incident solar radiation gives the shading factor F. The ratio of the measured F to F for the reference double-strength, single-pane glass gives the shading coefficient. F_{REF} is approximately 0.87, but varies with I as previously described.

If the air temperature inside the box had been maintained at a different temperature, say 18°C (65°F) representing winter conditions, the determination of the thermal transmittance and shading factor values would have been unaffected. This is due to the fact that the thermal transmittance was determined using the indoor-to-outdoor air temperature difference, not the absolute indoor air temperature. The shading factor is defined independently of the indoor air temperature, although the thermal transmittance does play a small part in the determination of the value of the shading factor. The impact of any small nonlinear behavior of the thermal transmittance with indoor air temperature would be overshadowed by the influence of the various driving forces including wind conditions, solar conditions and outdoor temperature. The indoor air temperature has no effect on the solar/optical properties such as transmittance.

4.4 MEASUREMENT RESULTS

4.4.1 Thermal Transmittance (U-factor)

Measurements were made of the thermal transmittance of each window type under a variety of weather conditions, covering a range of inside-to-outside temperature differences. Only nighttime measurements were used, eliminating the need to adjust for solar radiation effects. As was shown previously, the U-factor is strongly influenced by the exterior surface coefficient and the temperature difference. The measured values of U are plotted as a function of the temperature difference in figures 8a-g, for each film and clear glass. These values fall in the range that would be expected, based on the analytical considerations previously described. The vertical scatter in the plots is due to the effect of a varying exterior surface heat transfer coefficient, caused by variations in wind conditions or incident infrared radiation.

The measured U-factors indicate that the exterior surface coefficient h_0 remained in the range between 11.4 and 22.7 $w/m2 \cdot K$ (2 and 4 $Btu/(hr \cdot ft2 \cdot °F)$) for most of the testing. Separate measurements of h_0 using a heat-flow meter and thermopile also indicated that this was the case.

4.4.2 Shading Factor (F)

Shading factors were determined under a variety of solar radiation conditions for each window type, as previously described, and are presented as a function of incident solar radiation in figures 9a-g.

These measurements indicate that for the films with significant absorptance, F increases with solar radiation and is frequently greater than the design value. For the clear glass and low absorptance films, less variation in F is seen, as would be expected.

4.4.3 Solar Transmittance (τ)

The measured transmittances are plotted for each window type, as a function of the level of incident irradiance, in figure 10a-g. The scatter in these plots is due to the fact that the angular dependance of the transmittance applies mainly to the direct component of the incident solar radiation, since the diffuse component, by definition, is arriving from all angles. Thus, the effect of incident angle is much stronger during clear days than during overcast days.

5. BUILDING SIMULATION

5.1 THE DOE COMPUTER PROGRAM

The DOE computer program [17] (version 2.1) was used in this study to predict the annual building energy requirements. The DOE program is a building energy analysis tool developed by the Department of Energy for improving the energy performance of buildings. The program uses dynamic rather than steady-state calculation procedures and thus accounts for the thermal lag due to the building envelope construction. The algorithms used by the program are based on procedures developed by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers. The program performs hour-by-hour simulations of the plant (e.g. boilers, chillers, cooling towers, etc.) and HVAC system (e.g. fans, coils, pumps, etc.) as they respond to variations in the weather induced envelope load and internal heat gains.

5.2 THE BUILDING MODEL

The building considered in this study is a six-story federal office building located in Washington, D.C. The building is approximately 132 m (434 ft.) long, 29 m (96 ft.) wide, and 22 m (71 ft.) high, having a gross above grade floor area of approximately 2322 m^2 (249,984 ft^2). The north and south facades of the building each have approximately 1608 m2 (17313 ft.2) of glass area and the east and west facades each have approximately 342 m2 (3686 ft.2) of glass area. The windows are single pane, clear glass with no operable sash, overhangs, or fins, and are mounted flush with exterior wall surface. Overall, approximately 54 percent of the gross exterior wall area consists of glass (see figure 11 for photograph). The long axis of the building ran in an east-west direction, with greatest exposures to the north and south. The percentage of glass area is the same on each facade.

After obtaining blueprints of the building, a walk-through was conducted in order to gather additional information on space temperatures, occupancy, light, and equipment use. Interviews were also conducted with the personnel operating the building central equipment and operating records reviewed. On the basis of this information the building model was developed, a description of which can be found in appendix A.

5.3 CLIMATIC ZONES

The "Test Reference Year" (TRY) [18] hourly climate data tapes, prepared by the National Oceanic and Atmospheric Administration (NOAA), were used in this study. Each TRY data tape consists of one year's climate records chosen from a population of 27 years of records of the U.S. National Weather Service. The year chosen as the TRY year varies with location. The weather data are generally recorded at nearby airport weather stations. The weather variables used by the DOE program are:

Dry-bulb temperature
Wet-bulb temperature
Atmospheric pressure

Wind speed
Wind direction
Cloud amount
Cloud type

The GSA selected the following seven locations, giving a broad climatic variation, for this study:

Phoenix, Arizona
Houston, Texas
Atlanta, Georgia
Washington, D.C.
Chicago, Illinois
Boston, Massachusetts
San Jose, California

Table 7 lists the cities and their TRY annual heating and cooling degree-days. Figure 12 shows a map of the United States with each of the seven locations used in the study.

Table 7.

Title: TRY Heating and Cooling Degree Days (Base 18.3 C)* for Study Cities

CITY	HDD	CDD
Phoenix	842	1852
Houston	888	1525
Atlanta	1627	816
Washington, D.C.	2312	828
Chicago	3439	396
Boston	3238	374
San Jose	465	223

* Multiplication of the above HDD's and CDD's by 1.8 will give values in degree days base 65°F.

5.4 SIMULATION VERIFICATION

A computer run was made on the Washington, D.C. TRY weather tape. The results of this run were then compared with the most recent annual energy consumption records (1980) for the building, to assure that the building model, together with the DOE computer program, adequately simulated the actual building. Figure 13 shows the monthly energy consumptions for both the simulated and actual building.

The predicted values for steam consumption track the metered values extremely well (with the exception of the very high February metered value). It should be noted that the TRY weather tape was from a different year than the measured data. The predicted results for the prime heating months were expected to be somewhat greater than the metered values since the TRY weather tape heating degree-days (base 18.2°C) are 7 percent greater than for the year 1980 (2133 vs. 2162).

The predicted values for electric consumption also track the metered values well except for the extremely low metered values for the months of March, April, and June. The previous years metered values show an average increase of slightly less than 10 percent each month in electric energy consumption from February thru July. This correlates very well with the predicted results. It is unclear why the metered results are so low for March, April, and June in 1980. The metered results for the prime cooling months were expected to be higher than the predicted values since the cooling degreedays for 1980 are much higher than for the Washington, D.C. TRY weather tape (1115 vs. 828).

5.5 COMPUTER SIMULATION RESULTS FOR SEVEN CLIMATIC ZONES

Seven computer simulations were run for each city. A baseline run was made to establish the energy performance of the building with clear window glass. In this run it was assumed that clear glass covered the window areas on all four building facades. Six additional runs were made, one for each different solar film. In these runs it was assumed that the solar film had been placed on the east, south, and west glazing surfaces of the building. The U-values and shading coefficients used in this study for the clear glass and clear glass with six different solar films are listed in table 3. A total of 49 computer simulations were run.

Figure 14 shows the heating and electrical consumption results of the baseline runs for the building in each of the seven different locations plotted as functions of heating and cooling degree days, respectively. The building heating energy consumption is highly climate dependent, since it is primarily driven by ambient temperature and wind conditions. The building electric energy consumption, on the other hand, does not exhibit much climatic variation. This is because this building (like most office buildings) consumes a large quantity of electric energy for lighting and office equipment (see table 8) and the majority of the electric cooling energy is used to eliminate these internal heat gains. Thus there is little climate dependence in the electric cooling energy consumption and even less in the total electric energy consumption. The cooling energy consumption is about 5 percent of the total electric energy consumption for this building as simulated.

Table 9 lists the annual heating and electric energy consumptions for all seven locations. The table shows that the effect of the solar films, in all cases was to decrease the annual electric energy consumptions and increase the annual heating energy consumptions. The annual electric energy consumptions decrease due to the reduction (by the solar films) in solar heat gains during cooling periods. Likewise, the annual heating energy consumptions increase due to the reduction in beneficial solar heat gains during heating periods. Table 10

Table 8.

Title: Energy Consumptions (MBTU) for the Subsystems of the Simulated Building (Washington, D.C. with Clear Glass)

	Energy Type			
	Steam		Electricity	
In Situ	MBtu	(GJ)	MBtu	(GJ)
Category of Use				
Space Heat	10383.52	(10954.61)	0	
Space Cool	0		1250.56	(1319.34)
HVAC Auxiliary	0		3637.84	(3837.92)
Domestic Hot Water	1067.16	(1125.85)	0	
Auxiliary Solar	0		0	
Lights	0		11073.30	(11682.33)
Vertical Trans.	0		1491.62	(1573.60)
Miscellaneous Equipment	0		2350.68	(2479.97)
TOTAL	11450.68	(12080.47)	19803.89	(20893.10)

Table 9.

Title: Annual Heating and Electrical Consumptions for Simulated Building Without and With Solar Films for Study Locations

Electrical Consumption (Megawatt Hours)

City	Clear	Film A	Film B	Film C	Film D	Film E	Film F
****	********	********	********	********	********	********	********
Phoenix	5908.6	5780.8	5795.2	5796.7	5810.1	5811.3	5863.5
Houston	5893.3	5775.6	5784.4	5792.0	5800.2	5803.4	5852.0
Atlanta	5809.6	5692.9	5698.5	5708.8	5713.7	5717.8	5769.1
Washington	5802.5	5698.2	5705.0	5710.2	5716.7	5718.7	5763.3
Chicago	5759.2	5657.8	5666.6	5668.6	5675.9	5677.7	5719.6
Boston	5756.5	5661.3	5668.9	5670.4	5676.5	5678.6	5719.9
San Jose	5652.8	5560.5	5564.6	5570.2	5574.0	5576.3	5614.4

Heating Consumption (Megawatt Hours)

City	Clear	Film A	Film B	Film C	Film D	Film E	Film F
****	********	********	********	********	********	********	********
Phoenix	1205.1	1289.8	1307.1	1271.6	1288.6	1277.2	1237.6
Houston	1278.6	1346.0	1369.5	1330.2	1354.5	1341.9	1309.1
Atlanta	2289.2	2383.5	2424.8	2361.6	2402.9	2382.4	2336.7
Washington	3355.1	3471.4	3533.3	3440.7	3501.6	3471.7	3415.8
Chicago	5042.8	5171.7	5271.6	5135.1	5232.1	5189.3	5120.1
Boston	4967.2	5107.8	5209.8	5066.2	5165.5	5120.7	5049.5
San Jose	1172.9	1304.4	1322.9	1274.8	1295.3	1279.8	1216.8

Table 10.

Title: Annual Electrical Consumption Decreases and Heating Consumption Increases Due to Solar Films for Study Locations

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Decrease in Electrical Consumption (Megawatt Hours)

City	Film A	Film B	Film C	Film D	Film E	Film F
**********	******	******	******	******	******	******
Phoenix	127.7	113.4	111.9	98.4	97.3	45.1
Houston	117.8	109.0	101.4	93.2	90.0	41.3
Atlanta	116.6	111.0	100.8	95.8	91.7	40.4
Washington	104.3	97.6	92.3	85.8	83.8	93.3
Chicago	101.4	92.6	90.5	83.2	81.5	39.6
Boston	95.2	87.6	86.1	80.0	77.9	36.6
San Jose	92.3	88.2	82.6	78.8	76.5	38.4

Increase in Heating Consumption (Megawatt Hours)

City	Film A	Film B	Film C	Film D	Film E	Film F
**********	******	******	******	******	******	******
Phoenix	84.7	102.0	66.5	83.5	72.1	32.5
Houston	67.4	90.8	51.6	75.9	63.3	30.5
Atlanta	94.3	135.7	72.4	113.7	93.2	47.5
Washington	116.3	178.1	85.6	146.5	116.6	60.7
Chicago	128.9	228.8	92.3	189.3	146.5	77.4
Boston	140.6	242.6	99.0	198.4	153.5	82.3
San Jose	131.6	150.0	102.0	122.5	106.9	43.9

lists the annual electric energy decreases and heating energy increases for all the cities. A comparison of increases and decreases in energy use for each city shows that none of the solar films produce a net annual decrease in energy consumption for Chicago, Boston, and San Jose. In fact, of the locations examined, those that have fewer cooling degree-days than Washington, D.C. are not, in general, good candidates for the use of solar films on glazed areas, unless cooling energy is significantly more costly than heating energy. Table 10 also shows that solar films having both a low U-value and a low shading coefficient are most effective in reducing overall energy consumption. This is because the low shading coefficient value results in a decrease in the solar heat gain. This causes a decrease in the cooling energy and an increase in the heating energy. However, the low U-value results in a reduced conduction heat loss during heating periods which tends to offset some of the heating energy increases due to reduced solar heat gain.

5.6 ECONOMICS OF SOLAR FILMS

In order to determine if a particular solar film is cost effective consideration must be given to energy costs, purchase and installation costs, and maintenance costs. In this report the first year dollar savings, the discounted payback period, and the savings to investment ratio are used to determined if a solar film is cost effective. An installed film cost of one dollar per square foot is used in this analysis.

Table 11 shows the minimum ratio of the cost of electric energy per kWh to heating energy per kWh that must exist in order for the particular solar film to show a first year dollar savings (table 11 is calculated from the results of table 10). For example, if the cost of electric energy were \$0.073/kWh (\$25.00/MBtu) and the cost of heating energy (steam) were \$0.044/kWh (\$15.00/MBtu) then any solar film showing a ratio of 1.6 or less in table 11 would have a first year dollar savings. Thus, for Washington, D.C., solar films A, C, E, and F would have a first year dollar savings.

Tables 12-18 show the first year dollar savings, discounted payback periods, and savings to investment ratios for gas,oil, or steam as the heating energy for all six solar films under given conditions for all seven locations for a useful life of 10 and 15 years.

The first year dollar savings were calculated from the following equation:

$$\text{First year dollar savings} = (EC * ECD) - (HEC * HCI) \tag{20}$$

Where

EC = electricity cost per kWh,
ECD = electrical consumption decrease (from table 9),
HEC = heating energy cost per kWh,
HCI = heating consumption increase (from table 9).

In the above calculation, electrical demand rates were not considered and for gas and oil savings an annual system efficiency of 70 percent was assumed (i.e., the heating energy increase from table 9 were divided by 0.7). The first year energy costs were typical costs for each region.

The discounted payback period was determined by calculating the cumulative savings in energy costs at yearly intervals until the savings met or exceeded the investment cost. That is, $MPWF_E$ and $MPWF_H$ were found for a year (Y) such that the following equation was satisfied:

$$E\$ * MPWF_E(Y) - H\$ * MPWF_H(Y) \geq COST \tag{21}$$

where

COST = material, installation, and maintenance costs for useful life of solar film,
ULIFE = useful life of solar film,
E\$ = EC * ECD = base year electricity dollar savings,
$MPWF_E(Y)$ = modified uniform present worth discount factor for electricity for given year (Y) (the values for $MPWF_E$ are taken from the tables in

appendix B and are based on a 7 percent real discount rate and include projected real escalation rates in energy cost), [19]

H$ = HEC * HCI = base year increase in cost for heating,

$MPWF_H(Y)$ = modified uniform present worth discount factor for heating energy for a given year(Y) (from tables in appendix B).

Table 11.

Title: Minimum Ratio of Unit Cost of Electricity to Unit Cost of Heating Fuel* that Must Exist in order for Solar Film to Show First Year Dollar Savings

City **********	Film A ******	Film B ******	Film C ******	Film D ******	Film E ******	Film F ******
Phoenix	.7	.9	.6	.8	.7	.7
Houston	.6	.8	.5	.8	.7	.7
Atlanta	.8	1.2	.7	1.2	1.0	1.2
Washington	1.1	1.8	.9	1.7	1.4	1.5
Chicago	1.3	2.5	1.0	2.3	1.8	2.0
Boston	1.5	2.8	1.1	2.5	2.0	2.2
San Jose	1.4	1.7	1.2	1.6	1.4	1.1

NOTE: The ratio of actual cooling to heating energy costs calculated for a particular location must be at least equal to the minimum ratio shown in the table for that film to show a first year dollar savings. For example, in Phoenix the electricity cost per kWh divided by heating cost per kWh must be at least equal to 0.7 for Film A to show a first year dollar savings, while Film B would require a ratio of at least 0.9.

The savings-to-investment ratios were calculated from the following equation:

$$\text{Savings-to-investment ratio} = \frac{E\$*MPWF_E(ULIFE) - H\$*MPWF_H(ULIFE)}{COST} \qquad (22)$$

Tables 12-18 shows that in all locations either Film A or Film C is the most cost effective. The solar films are most cost effective when gas is the heating energy, followed by oil and then steam. This is because, for a given unit of energy, gas is less expensive than oil, and oil is less expensive than steam. The solar films tend to be more cost effective in the warmer climates (e.g., Phoenix, Houston, and Atlanta) where there are substantial cooling requirements rather than in colder climates (e.g., Chicago and Boston) or very mild climates (e.g., San Jose) where there are typically small cooling requirements.

In applying the results of tables 12-18 to determining if solar films should be used on a specific building the following points should be kept in mind:

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* The costs mentioned in table 11 are the costs the building owner/operator must pay. The table was calculated assuming the heating fuel was purchased steam (i.e., efficiency = 100%).

Table 12.

Title: Solar Film Cost-Effectiveness For Phoenix

First Year Energy Savings (Dollars) for Six Solar Films

Heating Energy	Film A	Film B	Film C	Film D	Film E	Film F
**************	******	******	******	******	******	******
Gas	5939.	4644.	5383.	4149.	4344.	2036.
Oil	4676.	3124.	4391.	2905.	3270.	1552.
Steam	4151.	2491.	3978.	2386.	2822.	1350.

Pay-Back Periods (Years) for Six Solar Films

Heating Energy	Film A	Film B	Film C	Film D	Film E	Film F
**************	******	******	******	******	******	******
Gas	5.0	6.0	5.0	7.0	7.0	20.0
Oil	6.0	9.0	6.0	10.0	8.0	>25.0
Steam	7.0	17.0	7.0	17.0	12.0	>25.0

Savings-to-Investment Ratios for Six Solar Films (10 Years)

Heating Energy	Film A	Film B	Film C	Film D	Film E	Film F
**************	******	******	******	******	******	******
Gas	2.0	1.5	1.8	1.4	1.5	.7
Oil	1.7	1.1	1.6	1.0	1.2	.6
Steam	1.4	.8	1.3	.8	.9	.4

Savings-to-Investment Ratios for Six Solar Films (15 Years)

Heating Energy	Film A	Film B	Film C	Film D	Film E	Film F
**************	******	******	******	******	******	******
Gas	2.6	2.0	2.4	1.8	1.9	.9
Oil	2.0	1.3	1.9	1.2	1.4	.7
Steam	1.7	1.0	1.7	.9	1.2	.6

Assumptions: Electricity Cost = $ .062/kWh
Heating Fuel Cost = $ .016 (Gas), .027 (Oil), .045 (Steam)/kWh
10 Year Present Worth Factor = 9.2 (Gas), 8.0 (Oil), 8.7 (Steam), 8.3 (Elec.)
15 Year Present Worth Factor = 12.1 (Gas), 11.5 (Oil), 11.5 (Steam), 10.7 (Elec.)
Material and Installment Cost = $23476.($1.0 per sq. ft. of glass)

Table 13.

Title: Solar Film Cost-Effectiveness For Houston

First Year Energy Savings (Dollars) for Six Solar Films

Heating Energy	Film A	Film B	Film C	Film D	Film E	Film F
Gas	4871.	4077.	4289.	3512.	3541.	1605.
Oil	3308.	1970.	3093.	1752.	2073.	898.
Steam	2889.	1406.	2773.	1280.	1680.	709.

Pay-Back Periods (Years) for Six Solar Films

Heating Energy	Film A	Film B	Film C	Film D	Film E	Film F
Gas	6.0	7.0	7.0	8.0	8.0	>25.0
Oil	8.0	>25.0	9.0	>25.0	>25.0	>25.0
Steam	11.0	>25.0	11.0	>25.0	>25.0	>25.0

Savings-to-Investment Ratios for Six Solar Films (10 Years)

Heating Energy	Film A	Film B	Film C	Film D	Film E	Film F
Gas	1.7	1.4	1.5	1.2	1.2	.6
Oil	1.2	.7	1.1	.7	.8	.3
Steam	1.0	.4	.9	.4	.5	.2

Savings-to-Investment Ratios for Six Solar Films (15 Years)

Heating Energy	Film A	Film B	Film C	Film D	Film E	Film F
Gas	1.8	1.8	2.0	1.6	1.6	.7
Oil	1.5	.9	1.4	.8	.9	.4
Steam	1.3	.5	1.2	.5	.7	.3

Assumptions: Electricity Cost = $ .050/kWh
Heating Fuel Cost = $ .011 (Gas), .027 (Oil), .045 (Steam)/kWh
10 Year Present Worth Factor = 9.3 (Gas), 8.0 (Oil), 8.8 (Steam), 8.3 (Elec.)
15 Year Present Worth Factor = 12.5 (Gas), 11.4 (Oil), 11.8 (Steam), 11.0 (Elec.)
Material and Installment Cost = $23476.($1.0 per sq. ft. of glass)

Table 14.

Title: Solar Film Cost-Effectiveness For Atlanta

First Year Energy Savings (Dollars) for Six Solar Films

Heating Energy	Film A	Film B	Film C	Film D	Film E	Film F
Gas	4110.	2909.	3754.	2584.	2816.	1102.
Oil	2566.	688.	2569.	723.	1291.	325.
Steam	1980.	-154.	2120.	17.	713.	30.

Pay-Back Periods (Years) for Six Solar Films

Heating Energy	Film A	Film B	Film C	Film D	Film E	Film F
Gas	7.0	14.0	8.0	18.0	13.0	>25.0
Oil	10.0	>25.0	11.0	>25.0	>25.0	>25.0
Steam	21.0	>25.0	18.0	>25.0	>25.0	>25.0

Savings-to-Investment Ratios for Six Solar Films (10 Years)

Heating Energy	Film A	Film B	Film C	Film D	Film E	Film F
Gas	1.4	.9	1.3	.8	.9	.3
Oil	1.0	.4	1.0	.4	.5	.2
Steam	.6	---	.7	---	.2	---

Savings-to-Investment Ratios for Six Solar Films (15 Years)

Heating Energy	Film A	Film B	Film C	Film D	Film E	Film F
Gas	1.7	1.1	1.6	1.0	1.1	.4
Oil	1.2	.3	1.2	.3	.6	.2
Steam	.8	---	.9	---	.2	---

Assumptions: Electricity Cost = $ .053/kWh
Heating Fuel Cost = $ .015 (Gas), .027 (Oil), .045 (Steam)/kWh
10 Year Present Worth Factor = 10.0 (Gas), 8.0 (Oil), 9.0 (Steam), 8.5 (Elec.)
15 Year Present Worth Factor = 14.1 (Gas), 11.4 (Oil), 12.0 (Steam), 11.3 (Elec.)
Material and Installment Cost = $23476.($1.0 per sq. ft. of glass)

Table 15.

Title: Solar Film Cost-Effectiveness For Washington

First Year Energy Savings (Dollars) for Six Solar Films

Heating Energy	Film A	Film B	Film C	Film D	Film E	Film F
**************	******	******	******	******	******	******
Gas	4325.	2085.	4318.	2124.	2819.	1151.
Oil	3239.	422.	3520.	757.	1731.	585.
Steam	2436.	-808.	2929.	-255.	926.	166.

Pay-Back Periods (Years) for Six Solar Films

Heating Energy	Film A	Film B	Film C	Film D	Film E	Film F
**************	******	******	******	******	******	******
Gas	7.0	>25.0	7.0	>25.0	16.0	>25.0
Oil	8.0	>25.0	7.0	>25.0	>25.0	>25.0
Steam	17.0	>25.0	11.0	>25.0	>25.0	>25.0

Savings-to-Investment Ratios for Six Solar Films (10 Years)

Heating Energy	Film A	Film B	Film C	Film D	Film E	Film F
**************	******	******	******	******	******	******
Gas	1.4	.5	1.4	.5	.8	.3
Oil	1.2	.3	1.3	.4	.7	.2
Steam	.8	---	1.0	---	.2	.0

Savings-to-Investment Ratios for Six Solar Films (15 Years)

Heating Energy	Film A	Film B	Film C	Film D	Film E	Film F
**************	******	******	******	******	******	******
Gas	1.7	.5	1.8	.6	1.0	.4
Oil	1.5	.1	1.6	.3	.8	.2
Steam	1.0	---	1.2	---	.2	---

Assumptions: Electricity Cost = $ .073/kWh
Heating Fuel Cost = $ .020 (Gas), .026 (Oil), .045 (Steam)/kWh
10 Year Present Worth Factor = 9.0 (Gas), 8.0 (Oil), 8.9 (Steam), 8.4 (Elec.)
15 Year Present Worth Factor = 13.5 (Gas), 11.4 (Oil), 11.9 (Steam), 11.1 (Elec.)
Material and Installment Cost = $23476.($1.0 per sq. ft. of glass)

Table 16.

Title: Solar Film Cost-Effectiveness For Chicago

First Year Energy Savings (Dollars) for Six Solar Films

Heating Energy	Film A	Film B	Film C	Film D	Film E	Film F
Gas	4065.	1275.	4131.	1506.	2325.	993.
Oil	1955.	-2470.	2621.	-1593.	-73.	-274.
Steam	1155.	-3891.	2048.	-2768.	-983.	-754.

Pay-Back Periods (Years) for Six Solar Films

Heating Energy	Film A	Film B	Film C	Film D	Film E	Film F
Gas	7.0	>25.0	7.0	>25.0	>25.0	>25.0
Oil	>25.0	>25.0	10.0	>25.0	>25.0	>25.0
Steam	>25.0	>25.0	23.0	>25.0	>25.0	>25.0

Savings-to-Investment Ratios for Six Solar Films (10 Years)

Heating Energy	Film A	Film B	Film C	Film D	Film E	Film F
Gas	1.3	.2	1.4	.3	.7	.3
Oil	.8	---	1.0	---	.1	---
Steam	.3	---	.7	---	---	---

Savings-to-Investment Ratios for Six Solar Films (15 Years)

Heating Energy	Film A	Film B	Film C	Film D	Film E	Film F
Gas	1.7	.1	1.8	.3	.8	.3
Oil	.9	---	1.2	---	---	---
Steam	.4	---	.8	---	---	---

Assumptions: Electricity Cost = $ .068/kWh
Heating Fuel Cost = $ .015 (Gas), .027 (Oil), .045 (Steam)/kWh
10 Year Present Worth Factor = 9.6 (Gas), 8.0 (Oil), 8.8 (Steam), 8.4 (Elec.)
15 Year Present Worth Factor = 13.5 (Gas), 11.4 (Oil), 11.8 (Steam), 11.1 (Elec.)
Material and Installment Cost = $23476.($1.0 per sq. ft. of glass)

Table 17.

Title: Solar Film Cost-Effectiveness For Boston

First Year Energy Savings (Dollars) for Six Solar Films

Heating Energy	Film A	Film B	Film C	Film D	Film E	Film F
Gas	4239.	643.	4645.	1253.	2364.	818.
Oil	3387.	-827.	4045.	51.	1434.	319.
Steam	1606.	-3898.	2792.	-2460.	-510.	-723.

Pay-Back Periods (Years) for Six Solar Films

Heating Energy	Film A	Film B	Film C	Film D	Film E	Film F
Gas	8.0	>25.0	6.0	>25.0	>25.0	>25.0
Oil	8.0	>25.0	7.0	>25.0	>25.0	>25.0
Steam	>25.0	>25.0	12.0	>25.0	>25.0	>25.0

Savings-to-Investment Ratios for Six Solar Films (10 Years)

Heating Energy	Film A	Film B	Film C	Film D	Film E	Film F
Gas	1.2	---	1.4	.1	.5	.1
Oil	1.2	---	1.4	.0	.5	.1
Steam	.5	---	.9	---	---	---

Savings-to-Investment Ratios for Six Solar Films (15 Years)

Heating Energy	Film A	Film B	Film C	Film D	Film E	Film F
Gas	1.4	---	1.7	---	.5	.1
Oil	1.2	---	1.6	---	-.3	---
Steam	.6	---	1.1	---	---	---

Assumptions: Electricity Cost = $ .087/kWh
Heating Fuel Cost = $ .020 (Gas), .024 (Oil), .047 (Steam)/kWh
10 Year Present Worth Factor = 9.5 (Gas), 8.0 (Oil), 8.1 (Steam), 8.1 (Elec.)
15 Year Present Worth Factor = 12.9 (Gas), 11.4 (Oil), 10.5 (Steam), 10.1 (Elec.)
Material and Installment Cost = $23476.($1.0 per sq. ft. of glass)

Table 18.

Title: Solar Film Cost-Effectiveness For San Jose

First Year Energy Savings (Dollars) for Six Solar Films

Heating Energy	Film A	Film B	Film C	Film D	Film E	Film F
**************	******	******	******	******	******	******
Gas	2643.	1957.	2736.	2020	2238.	1351.
Oil	682.	-279.	1217.	195.	644.	696.
Steam	-134.	-1210.	584.	-566.	-20.	423.

Pay-Back Periods (Years) for Six Solar Films

Heating Energy	Film A	Film B	Film C	Film D	Film E	Film F
**************	******	******	******	******	******	******
Gas	15.0	>25.0	13.0	>25.0	22.0	>25.0
Oil	>25.0	>25.0	>25.0	>25.0	>25.0	>25.0
Steam	>25.0	>25.0	>25.0	>25.0	>25.0	>25.0

Savings-to-Investment Ratios for Six Solar Films (10 Years)

Heating Energy	Film A	Film B	Film C	Film D	Film E	Film F
**************	******	******	******	******	******	******
Gas	.8	.6	.9	.6	.7	.4
Oil	.3	---	.5	.1	.3	.3
Steam	---	---	.1	---	---	.1

Savings-to-Investment Ratios for Six Solar Films (15 Years)

Heating Energy	Film A	Film B	Film C	Film D	Film E	Film F
**************	******	******	******	******	******	******
Gas	1.0	.7	1.1	.7	.9	.6
Oil	.1	---	.4	---	.2	.3
Steam	---	---	.1	---	---	.1

Assumptions: Electricity Cost = $ .062/kWh
Heating Fuel Cost = $ .016 (Gas), .027 (Oil), .045 (Steam)/kWh
10 Year Present Worth Factor = 9.2 (Gas), 8.0 (Oil), 8.7 (Steam), 8.3 (Elec.)
15 Year Present Worth Factor = 12.1 (Gas), 11.5 (Oil), 11.5 (Steam), 10.7 (Elec.)
Material and Installment Cost = $23476.($1.0 per sq. ft. of glass)

1. The cost effectiveness of the films will be somewhat better than shown because demand electrical charges will be less for a building having solar films on the glazing surfaces.

2. The cost effectiveness of solar films is directly related to internal heat generation (i.e., the higher the building internal heat generation the more cost effective are solar films).

3. The cost effectiveness of solar films is dependent on the glass orientation. Buildings with the major glazing areas in the east/west facades (buildings with major axis running north/south) are better candidates for solar films than buildings with the major glazing areas in the north/south facades (buildings with major axis running east/west). This is due to the fact that south facing windows provide beneficial solar heat gain in winter when solar altitudes are low, but not as much solar heat gain in summer, when solar altitudes are higher.

6. CONCLUSIONS AND RECOMMENDATIONS

The results of this investigation indicate that solar films can be cost-effective and produce a net annual reduction in building energy requirements in some cases, particularly for buildings with high cooling loads relative to heating loads. This is due to the fact that the major benefit derived from solar film utilization stems from its solar energy rejection capabilities. Thus solar films will reduce cooling energy requirements in almost all cases. However, during the heating season solar film use will reduce beneficial solar heat gains, leading to increased heating energy requirements. A net reduction in annual building energy requirements will occur if the reduction in cooling energy exceeds the increase in heating energy.

The magnitude of any energy cost savings will be dependent upon the relative costs of heating and cooling energy. If the cost of heating energy is significantly less than the cost of cooling energy, a change in cooling energy requirements would produce a larger dollar savings than a equivalent change in heating energy requirements. As explained in detail in section 5, solar films are most effective in the southern and southwest regions of the United States, with no savings apparent in the northern regions. Regions with climates similar to Washington, D.C. are near the crossover point, where heating requirements begin to dominate cooling requirements and expected savings are small.

In all cases, the most cost-effective films are the low emittance ones. The optimum shading coefficient is dependent on the magnitude of the cooling energy requirements, with lower values of shading coefficient most effective in regions with large cooling loads. Of the films examined in this study, film A (low emittance, low shading coefficient) was the most cost-effective in the regions with high cooling requirements, while film C (low emittance, moderate shading coefficient) was most cost-effective in regions similar to Washington, D.C.

Solar films can also improve comfort and glare conditions near windows, and this factor may make it desirable to use solar films even if the expected energy or dollar savings is marginal. Additional benefits of solar film use include reduction in transmission of ultra-violet radiation (a major cause of material degradation) and reduced chance of glass breakage or shattering due to impact.

The building used for this study was oriented with its major axis east-west, so the south facade presented a large glass surface area. In this configuration, the use of solar film on the southern building glazing greatly reduces beneficial solar heat gain in winter when the sun is low in the south sky, causing an increase in heating energy requirements. If the building had been oriented with major glazing facades east and west (major axis in a north/south direction) the cost effectiveness of the films would be expected to be enhanced. This is because solar film would significantly reduce cooling requirements due to solar heat gain during late afternoon hours when low solar altitudes would lead to high cooling loads.

7. GLOSSARY

1. Absorptance - the total amount of radiant solar energy neither reflected nor transmitted by the glazing.

2. Building energy analysis program - a computer procedure for dynamically simulating the annual energy performance of a building, usually on an hourly basis.

3. Calorimeter - an apparatus for measuring total window heat transfer.

4. Convective heat transfer - heat transfer which occurs in a fluid by the mixing of one portion of the fluid with another portion due to gross movements of the mass of fluid.

5. Daylighting - the utilization of natural light in interior spaces, in place of electric lighting.

6. Emittance - the ratio of radiation intensity from a surface to the radiation intensity from a black body at the same temperature.

7. Greenhouse effect - a phenomenon which occurs due to the fact that glass transmits a large amount of shorter wavelength solar radiation, but is essentially opaque to infrared radiation emitted by room surfaces, resulting in 'oneway' transmission of energy.

8. Illuminance - the luminous flux (visible light) per unit area on a surface exposed to radianet energy.

9. Infrared radiation - energy emitted at the surface of a body which has been thermally excited.

10. Pyranometer - sensor used to measure the level of incident solar radiation.

11. Radiative heat transfer - thermal energy exchange between two bodies.

12. Reflectance - the ratio of the total radiant flux reflected by a surface to the total incident on the surface.

13. Reflectometer - device used to measure the reflectance of a material, within a specified wavelength band.

14. Shading coefficient (SC) - the ratio of solar heat gain for a particular fenestration to the solar heat gain for a reference single glazing.

15. Shading factor (F) - the ratio of solar heat gain to the incident solar radiation level.

16. Spectrophotometer - device used to measure the spectral solar-optical properties, such as reflectance and transmittance of a material.

17. Solar heat gain - heat gain due to the incidence of solar radiation, including both transmitted energy and energy absorbed by the glazing which is subsequently transferred to the interior by convection and radiation.

18. Solar radiation (irradiance) - electromagnetic energy from the sun, composed of diffuse (sky) and direct (beam) radiation within the ultraviolet, visible and short-wave infrared portions of the spectrum.

19. Solar window film - thin plastic sheet which is bonded directly to the glass surace; designed to alter the solar/thermal properties of the window to improve performance.

20. Surface (film) heat transfer coefficient - the thermal transmission, in unit time, to or from unit area of a surface in contact with its surroundings for unit difference between the temperature of the surface and the surroundings.

21. Thermal transmittance (U-factor) - the thermal transmission per unit time through a unit area of a body, including its boundary films, divided by the difference between the fluid temperature on either side of the body.

22. Transmittance - the ratio of radiant energy flux transmitted by a body to the amount incident upon it.

23. Window management - selectively altering the solar/thermal characteristics of a window system, either manually or automatically, through the use of various items such as films, screens, shades, drapers or louvers.

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APPENDIX A

A.1 DESCRIPTION OF BUILDING MODEL

° Infiltration was simulated using air change (AC) method - the rates and profile were as follows:

1. Basement - none
2. Garage .8AC - all hours
3. All Floors - .6AC when main fans are off for perimeter zones - none for interior zone
4. Lobby - 2.0AC peak during entry and exit of occupants

° Partitions between zones were treated as having a U factor of 5.68 W(m2°K) (1.0/(ft2hr°C) representing a fairly free convective flow with doors open [10].

° Lighting levels were simulated at 21.5 W/m2 (2 W/ft2) in office areas and 10.8 W/m2 (1 W/ft2) watt per sq. ft. in Basement and Garage.

° Equipment levels (typewriters, copy machines, CRTs, etc.) were simulated at 16.1 W/m2 (1.5 W/ft2) in office areas.

° Computers and associated air conditioning systems were simulated as a single energy user at 150KW for all hours.

° Custom Weighting Factor method was used to generate weighting factors for the simulation.

° Average Domestic Hot Water load was estimated at 0.88 KW (3000 Btu/hr).

° Thermostat Setpoints simulated were as follows:

1. Basement - 18.3°C (65°F)
2. Garage - 12.8°C (55°F)
3. Offices - 18.3°C (65°F) heating - 25.6°C (78°F) cooling

° Elevator loads were included in the simulation

° Occupant loads were simulated using standard operating schedules

° Air Handling System type and fan operating hours input were as follows:

1. Basement - Single Zone Heat and Vent - 100 percent outside air - fans on all hours
2. Garage - same as basement
3. Perimeter Offices - Two pipe fan coil heating only October 15 through May 15 - cooling only May 16 to October 14

Fan hours on at 0600 - off at 1700 Weekdays only off weekends and holidays

4. Interior Offices - Interior Offices - Reheat fan system heating only October 15 through May 15 - cooling only May 16 through October 14
Fan hours on at 0600 - off at 1700 Weekdays only off weekends and holidays

ASSUMPTIONS OR SIMPLIFICATIONS USED FOR PREPARING INPUT

- The DOE 2 program can only accept three (3) separate plenum inputs. The ground floor, 1st floor and lobby were all simulated as being served by a single interior air system with a common return air plenum. This left a plenum for the typical floors (2 through 5), and another for the top floor (6).

- Since the second floor was treated as a typical floor with a typical plenum, the conference rooms over the lobby areas were treated as office space.

- The penthouse equipment room was not input as an unconditioned space. The roof areas of the 6th floor plenum excluded the surface area in contact with the penthouse.

- A standard outdoor reset of supply air temperatures on the reheat fan systems was input to simulate the combined effect of manual daily settings of preheat, outside air, and chilled water reset.

- A minimum percent outside air for the reheat fan systems was input as 5 percent even though the operator maintains dampers "closed" in very cold weather. The 5 percent was used to reflect leakage of dampers in the closed position.

- The chilled water plant in the study building (A) also serves an adjacent building (B). To simulate Building B two chillers were input of a size to accommodate Building B's load, with no attempt to evaluate the loading of Building A.

- The exhaust fans in the building were assumed to have the same operating schedules as supply units. The fan static air pressure and fan efficiencies were combined into a single input.

TABLE B-1--UPW* DISCOUNT FACTORS ADJUSTED FOR ENERGY PRICE ESCALATION[1]
DOE REGION I
(MAINE, NEW HAMPSHIRE, VERMONT, MASSACHUSETTS, CONNECTICUT, RHODE ISLAND)

	RESIDENTIAL SECTOR				COMMERCIAL SECTOR					INDUSTRIAL SECTOR						TRANSPORTATION
SP	ELEC	DIST	LPG	NATGAS	ELEC	DIST	RESID	NATGAS	COAL	ELEC	DIST	RESID	NATGAS	MFBI	COAL	GASLNE
1	.98	.96	.96	1.02	.98	.96	1.02	1.02	.99	.98	.96	1.02	1.02	1.03	1.06	.98
2	1.95	1.88	1.88	2.05	1.95	1.88	2.06	2.05	1.98	1.95	1.88	2.06	2.05	2.08	2.20	1.95
3	2.90	2.75	2.76	3.10	2.90	2.76	3.11	3.11	2.95	2.90	2.76	3.11	3.10	3.17	3.41	2.90
4	3.84	3.60	3.60	4.17	3.84	3.60	4.19	4.18	3.92	3.84	3.60	4.19	4.18	4.29	4.69	3.84
5	4.70	4.40	4.40	5.19	4.70	4.41	5.22	5.19	4.80	4.70	4.41	5.22	5.19	5.35	5.86	4.73
6	5.50	5.18	5.18	6.14	5.49	5.18	6.21	6.15	5.60	5.49	5.18	6.21	6.15	6.36	6.92	5.57
7	6.23	5.92	5.91	7.04	6.22	5.93	7.16	7.06	6.32	6.21	5.93	7.16	7.06	7.32	7.88	6.37
8	6.90	6.62	6.62	7.90	6.89	6.64	8.07	7.92	6.98	6.87	6.64	8.07	7.92	8.23	8.76	7.12
9	7.51	7.30	7.30	8.70	7.51	7.33	8.95	8.73	7.58	7.47	7.33	8.95	8.74	9.10	9.56	7.84
10	8.07	7.98	7.97	9.47	8.06	8.01	9.82	9.50	8.15	8.02	8.01	9.81	9.53	9.96	10.30	8.54
11	8.57	8.64	8.63	10.20	8.57	8.68	10.67	10.25	8.68	8.50	8.69	10.67	10.28	10.82	11.01	9.23
12	9.03	9.30	9.29	10.90	9.02	9.36	11.52	10.96	9.18	8.94	9.36	11.52	11.00	11.66	11.67	9.91
13	9.44	9.96	9.94	11.57	9.43	10.03	12.36	11.64	9.64	9.33	10.03	12.35	11.69	12.50	12.30	10.58
14	9.82	10.61	10.59	12.21	9.80	10.69	13.19	12.29	10.09	9.68	10.70	13.18	12.36	13.32	12.88	11.23
15	10.15	11.25	11.23	12.82	10.14	11.35	14.01	12.91	10.50	10.00	11.36	14.00	13.00	14.14	13.43	11.87
16	10.46	11.88	11.87	13.40	10.44	12.01	14.83	13.51	10.89	10.28	12.02	14.81	13.61	14.95	13.95	12.50
17	10.73	12.52	12.50	13.95	10.71	12.67	15.63	14.08	11.26	10.53	12.68	15.62	14.19	15.76	14.44	13.12
18	10.98	13.14	13.13	14.48	10.96	13.32	16.43	14.62	11.61	10.76	13.33	16.41	14.76	16.55	14.90	13.73
19	11.21	13.76	13.75	14.98	11.19	13.97	17.22	15.14	11.93	10.96	13.98	17.20	15.30	17.34	15.33	14.32
20	11.41	14.37	14.36	15.46	11.39	14.61	18.00	15.64	12.24	11.14	14.62	17.97	15.81	18.12	15.74	14.91
21	11.60	14.98	14.97	15.92	11.57	15.25	18.77	16.12	12.53	11.31	15.26	18.74	16.31	18.89	16.12	15.48
22	11.76	15.58	15.58	16.36	11.74	15.89	19.54	16.58	12.80	11.45	15.90	19.50	16.79	19.66	16.48	16.04
23	11.91	16.18	16.18	16.78	11.89	16.52	20.29	17.01	13.05	11.58	16.53	20.25	17.25	20.41	16.82	16.60
24	12.05	16.77	16.77	17.18	12.02	17.15	21.04	17.43	13.29	11.70	17.16	21.00	17.68	21.16	17.14	17.14
25	12.17	17.36	17.36	17.56	12.14	17.77	21.79	17.83	13.52	11.81	17.79	21.74	18.11	21.90	17.44	17.67

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[1] These "modified" uniform present worth discount (UPW*) factors are based on a 7 percent discount rate and include the EIA projected real escalation rates in energy prices developed from the Mid-Term Energy Forecasting System (MEFS), for the periods mid-1981 to mid-1985, mid-1985 to mid-1990, and mid-1990 to mid-1995 and beyond. The formula for calculating these UPW* factors is the following: For 1 to k escalation periods,

$$\text{UPW*} = \sum_{j=1}^{n_1} \left(\frac{1+e_1}{1+d}\right)^j + \left(\frac{1+e_1}{1+d}\right)^{n_1} \sum_{j=1}^{n_2} \left(\frac{1+e_2}{1+d}\right)^j + \left(\frac{1+e_1}{1+d}\right)^{n_1} \left(\frac{1+e_2}{1+d}\right)^{n_2} \sum_{j=1}^{n_3} \left(\frac{1+e_3}{1+d}\right)^j + .. + \left(\frac{1+e_1}{1+d}\right)^{n_1} \left(\frac{1+e_2}{1+d}\right)^{n_2} .. \left(\frac{1+e_{k-1}}{1+d}\right)^{n_{k-1}} \sum_{j=1}^{n_k} \left(\frac{1+e_k}{1+d}\right)^j ,$$

where n_k = the length of the period for a given escalation rate in a given period, and the subscript k indicates the escalation period;

d = the discount rate; and $\sum_{j=1}^{n_k} \left(\frac{1+e}{1+d}\right)^j = \left(\frac{1+e}{d-e}\right)\left(1 - \left(\frac{1+e}{1+d}\right)^{n_k}\right)$.

NOTE:

ELEC - Electricity	MFBI - Natural Gas (MFBI)
DIST - Distillate	COAL - Steam Coal
RESID - Residual	GASLNE - Gasoline
NATGAS - Natural Gas	SP - Study Period

Study Period 1 is Mid-1981 to Mid-1982.

TABLE B-2--UPW* DISCOUNT FACTORS ADJUSTED FOR ENERGY PRICE ESCALATION[1]
DOE REGION 2
(NEW YORK, NEW JERSEY, PUERTO RICO, VIRGIN ISLANDS)

	RESIDENTIAL SECTOR				COMMERCIAL SECTOR					INDUSTRIAL SECTOR						TRANSPORTATION
SP	ELEC	DIST	LPG	NATGAS	ELEC	DIST	RESID	NATGAS	COAL	ELEC	DIST	RESID	NATGAS	MFBI	COAL	GASLNE
1	.98	.96	.96	1.02	.98	.95	1.02	1.02	.99	.98	.96	1.02	1.02	1.02	1.06	.98
2	1.95	1.88	1.88	2.05	1.95	1.88	2.06	2.05	1.97	1.95	1.88	2.06	2.05	2.05	2.20	1.95
3	2.90	2.76	2.76	3.11	2.90	2.75	3.11	3.11	2.95	2.91	2.76	3.11	3.11	3.11	3.41	2.90
4	3.84	3.60	3.60	4.18	3.84	3.60	4.19	4.18	3.91	3.84	3.60	4.19	4.18	4.18	4.69	3.84
5	4.70	4.41	4.40	5.19	4.70	4.40	5.22	5.19	4.83	4.70	4.41	5.22	5.19	5.21	5.91	4.73
6	5.50	5.18	5.18	6.15	5.49	5.18	6.21	6.15	5.71	5.48	5.18	6.21	6.16	6.19	7.08	5.57
7	6.22	5.92	5.91	7.05	6.22	5.92	7.16	7.06	6.54	6.19	5.93	7.16	7.07	7.14	8.19	6.36
8	6.89	6.63	6.62	7.91	6.89	6.64	8.07	7.92	7.34	6.84	6.64	8.07	7.94	8.04	9.25	7.12
9	7.51	7.32	7.29	8.72	7.50	7.32	8.95	8.74	8.10	7.43	7.33	8.95	8.77	8.91	10.26	7.83
10	8.09	7.99	7.96	9.49	8.08	8.00	9.81	9.52	8.81	7.98	8.01	9.81	9.56	9.77	11.21	8.54
11	8.62	8.66	8.63	10.23	8.61	8.68	10.66	10.26	9.48	8.50	8.68	10.66	10.32	10.61	12.10	9.22
12	9.12	9.32	9.28	10.94	9.11	9.35	11.50	10.98	10.11	8.98	9.36	11.50	11.05	11.45	12.95	9.90
13	9.59	9.98	9.93	11.61	9.58	10.02	12.34	11.66	10.71	9.42	10.03	12.33	11.75	12.28	13.74	10.56
14	10.03	10.63	10.58	12.25	10.01	10.68	13.16	12.31	11.27	9.84	10.69	13.15	12.42	13.10	14.49	11.21
15	10.44	11.28	11.22	12.86	10.42	11.34	13.97	12.93	11.80	10.23	11.35	13.97	13.06	13.91	15.19	11.85
16	10.82	11.92	11.85	13.44	10.80	12.00	14.78	13.53	12.30	10.59	12.01	14.77	13.68	14.70	15.85	12.47
17	11.17	12.55	12.48	14.00	11.15	12.65	15.57	14.10	12.77	10.93	12.66	15.56	14.27	15.49	16.48	13.09
18	11.51	13.18	13.10	14.53	11.48	13.30	16.36	14.65	13.21	11.25	13.31	16.34	14.84	16.27	17.07	13.69
19	11.81	13.81	13.71	15.04	11.79	13.94	17.14	15.17	13.62	11.55	13.96	17.11	15.39	17.05	17.62	14.28
20	12.10	14.43	14.32	15.53	12.08	14.58	17.91	15.67	14.02	11.82	14.60	17.87	15.91	17.81	18.14	14.86
21	12.37	15.04	14.93	15.99	12.35	15.22	18.66	16.15	14.39	12.08	15.24	18.62	16.41	18.56	18.63	15.43
22	12.63	15.65	15.52	16.43	12.60	15.85	19.42	16.61	14.73	12.32	15.87	19.37	16.90	19.31	19.10	15.98
23	12.86	16.25	16.12	16.85	12.84	16.48	20.16	17.05	15.06	12.54	16.50	20.10	17.36	20.04	19.53	16.53
24	13.08	16.85	16.71	17.25	13.05	17.11	20.89	17.46	15.37	12.75	17.13	20.83	17.80	20.77	19.94	17.07
25	13.29	17.44	17.29	17.64	13.26	17.73	21.61	17.86	15.66	12.94	17.76	21.55	18.23	21.49	20.33	17.59

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[1] These "modified" uniform present worth discount (UPW*) factors are based on a 7 percent discount rate and include the EIA projected real escalation rates in energy prices developed from the Mid-Term Energy Forecasting System (MEFS), for the periods mid-1981 to mid-1985, mid-1985 to mid-1990, and mid-1990 to mid-1995 and beyond. The formula for calculating these UPW* factors is the following: For 1 to k escalation periods,

$$\mathrm{UPW}^* = \sum_{j=1}^{n_1} \left(\frac{1+e_1}{1+d}\right)^j + \left(\frac{1+e_1}{1+d}\right)^{n_1} \sum_{j=1}^{n_2} \left(\frac{1+e_2}{1+d}\right)^j + \left(\frac{1+e_1}{1+d}\right)^{n_1} \left(\frac{1+e_2}{1+d}\right)^{n_2} \sum_{j=1}^{n_3} \left(\frac{1+e_3}{1+d}\right)^j +..+ \left(\frac{1+e_1}{1+d}\right)^{n_1} \left(\frac{1+e_2}{1+d}\right)^{n_2} .. \left(\frac{1+e_{k-1}}{1+d}\right)^{n_{k-1}} \sum_{j=1}^{n_k} \left(\frac{1+e_k}{1+d}\right)^j ,$$

where n_k = the length of the period for a given escalation rate in a given period, and the subscript k indicates the escalation period;

d = the discount rate; and $\sum_{j=1}^{n_k} \left(\frac{1+e}{1+d}\right)^j = \left(\frac{1+e}{d-e}\right)\left(1 - \left(\frac{1+e}{1+d}\right)^{n_k}\right).$

NOTE:

ELEC - Electricity	MFBI - Natural Gas (MFBI)
DIST - Distillate	COAL - Steam Coal
RESID - Residual	GASLNE - Gasoline
NATGAS - Natural Gas	SP - Study Period

Study Period 1 is Mid-1981 to Mid-1982.

TABLE B-3--UPW* DISCOUNT FACTORS ADJUSTED FOR ENERGY PRICE ESCALATION[1]
DOE REGION 3
(PENNSYLVANIA, MARYLAND, WEST VIRGINIA, VIRGINIA, DISTRICT OF COLUMBIA, DELAWARE)

	RESIDENTIAL SECTOR				COMMERCIAL SECTOR					INDUSTRIAL SECTOR						TRANSPORTATION
SP	ELEC	DIST	LPG	NATGAS	ELEC	DIST	RESID	NATGAS	COAL	ELEC	DIST	RESID	NATGAS	MFBI	COAL	GASLNE
1	.98	.96	.96	1.02	.98	.96	1.02	1.02	.99	.98	.96	1.02	1.02	1.02	1.06	.98
2	1.95	1.88	1.88	2.05	1.95	1.88	2.06	2.05	1.97	1.95	1.88	2.06	2.05	2.05	2.20	1.95
3	2.91	2.75	2.76	3.11	2.91	2.76	3.11	3.10	2.95	2.90	2.76	3.11	3.11	3.11	3.41	2.90
4	3.84	3.60	3.60	4.18	3.84	3.60	4.19	4.18	3.91	3.84	3.60	4.19	4.18	4.18	4.69	3.84
5	4.72	4.40	4.40	5.20	4.72	4.41	5.22	5.20	4.83	4.73	4.41	5.22	5.22	5.20	5.92	4.73
6	5.55	5.18	5.17	6.19	5.55	5.18	6.21	6.19	5.72	5.56	5.18	6.21	6.21	6.19	7.10	5.57
7	6.34	5.92	5.91	7.13	6.34	5.93	7.16	7.15	6.56	6.34	5.92	7.16	7.18	7.13	8.23	6.36
8	7.07	6.63	6.61	8.04	7.07	6.64	8.07	8.06	7.37	7.08	6.64	8.07	8.10	8.04	9.30	7.12
9	7.76	7.31	7.28	8.91	7.76	7.33	8.93	8.94	8.14	7.78	7.32	8.94	9.00	8.90	10.33	7.84
10	8.41	7.98	7.95	9.74	8.41	8.01	9.79	9.78	8.87	8.44	8.00	9.80	9.86	9.76	11.30	8.54
11	9.01	8.65	8.61	10.53	9.01	8.68	10.64	10.60	9.56	9.05	8.67	10.64	10.69	10.60	12.22	9.23
12	9.58	9.32	9.26	11.30	9.58	9.36	11.47	11.37	10.20	9.62	9.34	11.48	11.49	11.43	13.08	9.91
13	10.11	9.97	9.90	12.03	10.11	10.02	12.30	12.12	10.82	10.16	10.01	12.31	12.26	12.25	13.90	10.57
14	10.60	10.63	10.54	12.73	10.60	10.69	13.11	12.84	11.39	10.66	10.67	13.12	13.00	13.06	14.67	11.22
15	11.07	11.27	11.17	13.40	11.07	11.35	13.91	13.53	11.93	11.13	11.32	13.92	13.71	13.86	15.39	11.87
16	11.50	11.91	11.79	14.04	11.50	12.00	14.70	14.19	12.45	11.57	11.98	14.72	14.40	14.65	16.07	12.49
17	11.91	12.55	12.40	14.66	11.91	12.66	15.48	14.83	12.93	11.98	12.62	15.50	15.06	15.43	16.72	13.11
18	12.29	13.18	13.01	15.25	12.29	13.30	16.25	15.44	13.39	12.37	13.27	16.28	15.70	16.19	17.33	13.72
19	12.64	13.81	13.62	15.82	12.65	13.95	17.01	16.03	13.82	12.73	13.90	17.04	16.31	16.95	17.90	14.32
20	12.97	14.43	14.21	16.36	12.98	14.59	17.76	16.59	14.22	13.07	14.54	17.79	16.91	17.70	18.44	14.90
21	13.28	15.04	14.80	16.89	13.29	15.22	18.50	17.13	14.60	13.38	15.17	18.54	17.47	18.44	18.95	15.47
22	13.58	15.65	15.38	17.38	13.58	15.85	19.23	17.65	14.96	13.68	15.79	19.27	18.02	19.16	19.43	16.04
23	13.85	16.26	15.96	17.86	13.86	16.48	19.95	18.15	15.30	13.96	16.41	20.00	18.55	19.88	19.88	16.59
24	14.10	16.86	16.53	18.32	14.11	17.10	20.66	18.63	15.62	14.22	17.03	20.71	19.06	20.59	20.31	17.13
25	14.34	17.45	17.09	18.76	14.35	17.72	21.36	19.09	15.93	14.46	17.64	21.42	19.55	21.29	20.71	17.67

[1] These "modified" uniform present worth discount (UPW*) factors are based on a 7 percent discount rate and include the EIA projected real escalation rates in energy prices developed from the Mid-Term Energy Forecasting System (MEFS), for the periods mid-1981 to mid-1985, mid-1985 to mid-1990, and mid-1990 to mid-1995 and beyond. The formula for calculating these UPW* factors is the following: For 1 to k escalation periods,

$$\text{UPW*} = \sum_{j=1}^{n_1}\left(\frac{1+e_1}{1+d}\right)^j + \left(\frac{1+e_1}{1+d}\right)^{n_1}\sum_{j=1}^{n_2}\left(\frac{1+e_2}{1+d}\right)^j + \left(\frac{1+e_1}{1+d}\right)^{n_1}\left(\frac{1+e_2}{1+d}\right)^{n_2}\sum_{j=1}^{n_3}\left(\frac{1+e_3}{1+d}\right)^j + .. + \left(\frac{1+e_1}{1+d}\right)^{n_1}\left(\frac{1+e_2}{1+d}\right)^{n_2} .. \left(\frac{1+e_{k-1}}{1+d}\right)^{n_{k-1}}\sum_{j=1}^{n_k}\left(\frac{1+e_k}{1+d}\right)^j ,$$

where n_k = the length of the period for a given escalation rate in a given period, and the subscript k indicates the escalation period;

d = the discount rate; and $\sum_{j=1}^{n_k}\left(\frac{1+e}{1+d}\right)^j = \left(\frac{1+e}{d-e}\right)\left(1 - \left(\frac{1+e}{1+d}\right)^{n_k}\right).$

NOTE:

ELEC - Electricity	MFBI - Natural Gas (MFBI)
DIST - Distillate	COAL - Steam Coal
RESID - Residual	GASLNE - Gasoline
NATGAS - Natural Gas	SP - Study Period

Study Period 1 is Mid-1981 to Mid-1982.

TABLE B-4--UPW* DISCOUNT FACTORS ADJUSTED FOR ENERGY PRICE ESCALATION[1]
DOE REGION 4
(KENTUCKY, TENNESSEE, NORTH CAROLINA, SOUTH CAROLINA, MISSISSIPPI, ALABAMA, GEORGIA, FLORIDA, CANAL ZONE)

	RESIDENTIAL SECTOR				COMMERCIAL SECTOR					INDUSTRIAL SECTOR						TRANSPORTATION
SP	ELEC	DIST	LPG	NATGAS	ELEC	DIST	RESID	NATGAS	COAL	ELEC	DIST	RESID	NATGAS	MFBI	COAL	GASLNE
1	.98	.96	.96	1.02	.98	.96	1.02	1.02	.99	.98	.96	1.02	1.02	1.02	1.06	.98
2	1.95	1.88	1.88	2.05	1.95	1.88	2.06	2.05	1.97	1.95	1.88	2.06	2.05	2.05	2.20	1.95
3	2.91	2.76	2.76	3.10	2.90	2.76	3.11	3.11	2.95	2.90	2.76	3.11	3.11	3.11	3.40	2.90
4	3.84	3.60	3.60	4.18	3.84	3.60	4.19	4.18	3.92	3.84	3.60	4.19	4.18	4.18	4.68	3.84
5	4.73	4.41	4.40	5.21	4.73	4.41	5.22	5.22	4.85	4.73	4.41	5.22	5.23	5.21	5.91	4.73
6	5.58	5.18	5.17	6.21	5.57	5.18	6.21	6.23	5.74	5.58	5.18	6.21	6.25	6.19	7.10	5.57
7	6.37	5.92	5.91	7.18	6.37	5.93	7.16	7.21	6.60	6.39	5.92	7.16	7.24	7.14	8.24	6.37
8	7.13	6.64	6.61	8.11	7.12	6.64	8.08	8.16	7.43	7.16	6.64	8.07	8.21	8.05	9.34	7.12
9	7.85	7.32	7.28	9.02	7.84	7.32	8.95	9.09	8.23	7.89	7.32	8.95	9.16	8.92	10.39	7.84
10	8.53	7.99	7.95	9.89	8.52	8.00	9.82	9.99	8.97	8.58	8.00	9.82	10.08	9.79	11.38	8.54
11	9.16	8.67	8.61	10.73	9.15	8.68	10.68	10.86	9.67	9.23	8.67	10.68	10.98	10.65	12.31	9.23
12	9.76	9.33	9.26	11.54	9.74	9.35	11.54	11.70	10.32	9.85	9.34	11.54	11.85	11.52	13.17	9.91
13	10.32	10.00	9.90	12.33	10.31	10.02	12.39	12.51	10.93	10.42	10.01	12.39	12.69	12.37	13.98	10.58
14	10.85	10.66	10.54	13.08	10.83	10.69	13.23	13.30	11.50	10.97	10.67	13.24	13.52	13.23	14.73	11.23
15	11.35	11.31	11.17	13.81	11.33	11.35	14.07	14.07	12.04	11.48	11.33	14.08	14.32	14.08	15.44	11.88
16	11.82	11.96	11.79	14.52	11.79	12.00	14.90	14.81	12.54	11.96	11.98	14.91	15.10	14.93	16.10	12.51
17	12.26	12.60	12.40	15.20	12.23	12.65	15.73	15.53	13.00	12.42	12.63	15.74	15.85	15.78	16.72	13.13
18	12.67	13.24	13.01	15.86	12.65	13.30	16.55	16.22	13.44	12.84	13.28	16.57	16.59	16.62	17.30	13.74
19	13.06	13.87	13.62	16.49	13.03	13.95	17.37	16.90	13.85	13.25	13.92	17.39	17.30	17.46	17.84	14.34
20	13.43	14.50	14.21	17.10	13.40	14.59	18.18	17.55	14.23	13.63	14.56	18.20	18.00	18.30	18.34	14.92
21	13.77	15.13	14.80	17.69	13.74	15.22	18.98	18.18	14.58	13.99	15.19	19.01	18.67	19.13	18.81	15.50
22	14.10	15.75	15.38	18.26	14.06	15.86	19.78	18.79	14.92	14.32	15.82	19.81	19.33	19.96	19.26	16.07
23	14.40	16.36	15.96	18.82	14.37	16.49	20.58	19.38	15.23	14.64	16.44	20.61	19.97	20.79	19.67	16.63
24	14.69	16.98	16.53	19.35	14.65	17.11	21.37	19.96	15.52	14.94	17.07	21.40	20.59	21.61	20.06	17.17
25	14.96	17.58	17.09	19.86	14.92	17.73	22.15	20.51	15.79	15.23	17.68	22.19	21.20	22.43	20.42	17.71

[1] These "modified" uniform present worth discount (UPW*) factors are based on a 7 percent discount rate and include the EIA projected real escalation rates in energy prices developed from the Mid-Term Energy Forecasting System (MEFS), for the periods mid-1981 to mid-1985, mid-1985 to mid-1990, and mid-1990 to mid-1995 and beyond. The formula for calculating these UPW* factors is the following: For 1 to k escalation periods,

$$UPW^* = \sum_{j=1}^{n_1}\left(\frac{1+e_1}{1+d}\right)^j + \left(\frac{1+e_1}{1+d}\right)^{n_1}\sum_{j=1}^{n_2}\left(\frac{1+e_2}{1+d}\right)^j + \left(\frac{1+e_1}{1+d}\right)^{n_1}\left(\frac{1+e_2}{1+d}\right)^{n_2}\sum_{j=1}^{n_3}\left(\frac{1+e_3}{1+d}\right)^j +..+ \left(\frac{1+e_1}{1+d}\right)^{n_1}\left(\frac{1+e_2}{1+d}\right)^{n_2} .. \left(\frac{1+e_{k-1}}{1+d}\right)^{n_{k-1}}\sum_{j=1}^{n_k}\left(\frac{1+e_k}{1+d}\right)^j ,$$

where n_k = the length of the period for a given escalation rate in a given period, and the subscript k indicates the escalation period;

d = the discount rate; and $\sum_{j=1}^{n_k}\left(\frac{1+e}{1+d}\right)^j = \left(\frac{1+e}{d-e}\right)\left(1-\left(\frac{1+e}{1+d}\right)^{n_k}\right)$.

NOTE:

ELEC - Electricity	MFBI - Natural Gas (MFBI)
DIST - Distillate	COAL - Steam Coal
RESID - Residual	GASLNE - Gasoline
NATGAS - Natural Gas	SP - Study Period

Study Period 1 is Mid-1981 to Mid-1982.

TABLE B-5--UPW* DISCOUNT FACTORS ADJUSTED FOR ENERGY PRICE ESCALATION[1]
DOE REGION 5
(MINNESOTA, WISCONSIN, MICHIGAN, ILLINOIS, INDIANA, OHIO)

	RESIDENTIAL SECTOR				COMMERCIAL SECTOR					INDUSTRIAL SECTOR						TRANSPORTATION
SP	ELEC	DIST	LPG	NATGAS	ELEC	DIST	RESID	NATGAS	COAL	ELEC	DIST	RESID	NATGAS	MFBI	COAL	GASLNE
1	.98	.96	.96	1.02	.98	.96	1.02	1.02	.99	.98	.96	1.02	1.02	1.02	1.06	.98
2	1.95	1.88	1.88	2.05	1.95	1.88	2.06	2.05	1.98	1.95	1.88	2.06	2.05	2.05	2.20	1.95
3	2.90	2.76	2.76	3.10	2.90	2.76	3.11	3.11	2.95	2.91	2.75	3.11	3.11	3.11	3.40	2.90
4	3.84	3.60	3.60	4.18	3.84	3.60	4.19	4.18	3.92	3.84	3.60	4.19	4.18	4.18	4.69	3.84
5	4.73	4.41	4.41	5.19	4.72	4.41	5.22	5.20	4.84	4.73	4.41	5.23	5.20	5.21	5.91	4.73
6	5.56	5.18	5.18	6.16	5.56	5.19	6.22	6.17	5.72	5.57	5.18	6.22	6.18	6.20	7.07	5.57
7	6.35	5.92	5.92	7.08	6.34	5.93	7.17	7.09	6.56	6.37	5.93	7.17	7.10	7.15	8.19	6.37
8	7.09	6.64	6.62	7.95	7.09	6.65	8.08	7.97	7.36	7.12	6.64	8.09	7.98	8.06	9.25	7.12
9	7.79	7.32	7.30	8.78	7.79	7.34	8.96	8.80	8.12	7.84	7.33	8.97	8.83	8.93	10.26	7.84
10	8.45	8.00	7.97	9.57	8.44	8.02	9.71	9.60	8.83	8.50	8.02	9.73	9.64	9.69	11.20	8.54
11	9.05	8.67	8.63	10.34	9.05	8.70	10.37	10.38	9.50	9.12	8.70	10.38	10.42	10.34	12.09	9.23
12	9.62	9.34	9.29	11.07	9.61	9.38	10.94	11.12	10.12	9.69	9.38	10.95	11.18	10.90	12.92	9.91
13	10.15	10.01	9.94	11.78	10.14	10.06	11.43	11.84	10.71	10.22	10.05	11.45	11.91	11.39	13.69	10.58
14	10.64	10.67	10.59	12.46	10.63	10.73	11.86	12.54	11.26	10.72	10.73	11.88	12.61	11.81	14.42	11.24
15	11.09	11.33	11.23	13.12	11.08	11.40	12.23	13.20	11.77	11.18	11.40	12.25	13.29	12.17	15.10	11.88
16	11.52	11.98	11.87	13.75	11.51	12.07	12.55	13.85	12.25	11.61	12.06	12.57	13.95	12.49	15.74	12.51
17	11.92	12.63	12.50	14.35	11.90	12.73	12.83	14.47	12.70	12.01	12.73	12.84	14.58	12.76	16.33	13.14
18	12.28	13.28	13.12	14.93	12.27	13.39	13.07	15.06	13.12	12.38	13.39	13.08	15.19	12.99	16.89	13.75
19	12.63	13.92	13.74	15.49	12.61	14.05	13.27	15.64	13.51	12.72	14.05	13.29	15.78	13.19	17.41	14.35
20	12.95	14.55	14.36	16.03	12.93	14.71	13.45	16.19	13.88	13.04	14.70	13.47	16.36	13.37	17.90	14.94
21	13.24	15.19	14.96	16.55	13.23	15.36	13.61	16.73	14.23	13.34	15.35	13.63	16.91	13.52	18.36	15.52
22	13.52	15.82	15.57	17.05	13.51	16.01	13.75	17.24	14.55	13.62	16.00	13.76	17.44	13.65	18.79	16.08
23	13.78	16.44	16.16	17.53	13.76	16.65	13.86	17.74	14.85	13.87	16.65	13.88	17.95	13.76	19.19	16.64
24	14.02	17.06	16.76	17.99	14.00	17.30	13.96	18.21	15.14	14.11	17.29	13.98	18.45	13.86	19.57	17.19
25	14.24	17.68	17.34	18.43	14.23	17.94	14.05	18.68	15.40	14.33	17.93	14.07	18.92	13.94	19.92	17.73

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[1] These "modified" uniform present worth discount (UPW*) factors are based on a 7 percent discount rate and include the EIA projected real escalation rates in energy prices developed from the Mid-Term Energy Forecasting System (MEFS), for the periods mid-1981 to mid-1985, mid-1985 to mid-1990, and mid-1990 to mid-1995 and beyond. The formula for calculating these UPW* factors is the following: For 1 to k escalation periods,

$$\text{UPW*} = \sum_{j=1}^{n_1} \left(\frac{1 + e_1}{1 + d}\right)^j + \left(\frac{1 + e_1}{1 + d}\right)^{n_1} \sum_{j=1}^{n_2} \left(\frac{1 + e_2}{1 + d}\right)^j + \left(\frac{1 + e_1}{1 + d}\right)^{n_1} \left(\frac{1 + e_2}{1 + d}\right)^{n_2} \sum_{j=1}^{n_3} \left(\frac{1 + e_3}{1 + d}\right)^j + .. + \left(\frac{1 + e_1}{1 + d}\right)^{n_1} \left(\frac{1 + e_2}{1 + d}\right)^{n_2} .. \left(\frac{1 + e_{k-1}}{1 + d}\right)^{n_{k-1}} \sum_{j=1}^{n_k} \left(\frac{1 + e_k}{1 + d}\right)^j ,$$

where n_k = the length of the period for a given escalation rate in a given period, and the subscript k indicates the escalation period;

d = the discount rate; and $\sum_{j=1}^{n_k} \left(\frac{1 + e}{1 + d}\right)^j = \left(\frac{1 + e}{d - e}\right)\left(1 - \left(\frac{1 + e}{1 + d}\right)^{n_k}\right)$.

NOTE:

ELEC - Electricity	MFBI - Natural Gas (MFBI)
DIST - Distillate	COAL - Steam Coal
RESID - Residual	GASLNE - Gasoline
NATGAS - Natural Gas	SP - Study Period

Study Period 1 is Mid-1981 to Mid-1982.

TABLE B-6--UPW* DISCOUNT FACTORS ADJUSTED FOR ENERGY PRICE ESCALATION[1]
DOE REGION 6
(TEXAS, NEW MEXICO, OKLAHOMA, ARKANSAS, LOUISIANA)

	RESIDENTIAL SECTOR				COMMERCIAL SECTOR					INDUSTRIAL SECTOR						TRANSPORTATION
SP	ELEC	DIST	LPG	NATGAS	ELEC	DIST	RESID	NATGAS	COAL	ELEC	DIST	RESID	NATGAS	MFBI	COAL	GASLNE
1	.98	.96	.96	1.02	.98	.96	1.02	1.02	.99	.98	.96	1.02	1.02	1.02	1.06	.98
2	1.95	1.88	1.88	2.05	1.95	1.88	2.06	2.05	1.97	1.95	1.88	2.06	2.05	2.05	2.20	1.95
3	2.90	2.76	2.76	3.11	2.90	2.76	3.11	3.11	2.95	2.90	2.76	3.11	3.11	3.11	3.41	2.90
4	3.84	3.60	3.60	4.18	3.84	3.60	4.19	4.18	3.92	3.84	3.60	4.19	4.18	4.18	4.69	3.84
5	4.72	4.41	4.41	5.18	4.72	4.41	5.22	5.18	4.83	4.72	4.41	5.22	5.18	5.18	5.91	4.73
6	5.54	5.18	5.18	6.12	5.54	5.18	6.21	6.11	5.70	5.54	5.19	6.22	6.11	6.11	7.06	5.57
7	6.31	5.92	5.92	6.99	6.31	5.93	7.17	6.99	6.52	6.31	5.93	7.17	6.99	6.99	8.16	6.37
8	7.03	6.63	6.62	7.81	7.03	6.64	8.08	7.80	7.30	7.04	6.65	8.08	7.80	7.80	9.20	7.13
9	7.71	7.31	7.30	8.57	7.71	7.33	8.95	8.57	8.05	7.71	7.34	8.96	8.57	8.57	10.18	7.84
10	8.34	7.99	7.97	9.30	8.34	8.01	9.82	9.30	8.75	8.35	8.02	9.83	9.30	9.30	11.12	8.55
11	8.94	8.66	8.63	10.00	8.94	8.69	10.69	10.00	9.41	8.95	8.70	10.69	10.01	10.01	12.00	9.24
12	9.50	9.33	9.29	10.67	9.50	9.37	11.55	10.67	10.05	9.51	9.38	11.55	10.69	10.69	12.84	9.92
13	10.02	9.99	9.94	11.30	10.03	10.04	12.40	11.32	10.64	10.04	10.05	12.41	11.34	11.34	13.64	10.59
14	10.52	10.64	10.59	11.91	10.52	10.71	13.25	11.94	11.21	10.54	10.72	13.26	11.97	11.97	14.40	11.25
15	10.98	11.29	11.23	12.50	10.98	11.37	14.10	12.54	11.75	11.01	11.39	14.10	12.57	12.57	15.11	11.90
16	11.42	11.94	11.87	13.06	11.42	12.04	14.93	13.11	12.26	11.45	12.05	14.94	13.15	13.15	15.79	12.54
17	11.83	12.58	12.50	13.59	11.83	12.70	15.77	13.66	12.75	11.86	12.71	15.78	13.70	13.70	16.44	13.16
18	12.21	13.21	13.12	14.10	12.21	13.35	16.60	14.19	13.21	12.25	13.37	16.60	14.24	14.24	17.05	13.78
19	12.57	13.84	13.74	14.59	12.58	14.00	17.42	14.69	13.64	12.62	14.02	17.43	14.75	14.75	17.63	14.38
20	12.91	14.47	14.36	15.06	12.92	14.65	18.24	15.18	14.06	12.96	14.67	18.25	15.25	15.25	18.18	14.98
21	13.23	15.09	14.97	15.51	13.24	15.30	19.05	15.64	14.45	13.28	15.32	19.06	15.72	15.72	18.70	15.56
22	13.52	15.71	15.57	15.93	13.53	15.94	19.86	16.09	14.82	13.59	15.96	19.87	16.18	16.18	19.19	16.14
23	13.80	16.32	16.17	16.34	13.82	16.58	20.66	16.52	15.17	13.87	16.60	20.68	16.62	16.62	19.66	16.70
24	14.07	16.92	16.76	16.74	14.08	17.21	21.46	16.93	15.51	14.14	17.24	21.48	17.04	17.04	20.11	17.26
25	14.31	17.52	17.35	17.11	14.33	17.84	22.26	17.32	15.82	14.40	17.87	22.27	17.45	17.45	20.53	17.80

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[1] These "modified" uniform present worth discount (UPW*) factora are baaed on a 7 percent discount rate and include the EIA projected real escalation rates in energy prices developed from the Mid-Term Energy Forecasting System (MEFS), for the periods mid-1981 to mid-1985, mid-1985 to mid-1990, and mid-1990 to mid-1995 and beyond. The formula for calculating these UPW* factors is the following: For 1 to k escalation periods,

$$\mathrm{UPW}^* = \sum_{j=1}^{n_1}\left(\frac{1+e_1}{1+d}\right)^j + \left(\frac{1+e_1}{1+d}\right)^{n_1}\sum_{j=1}^{n_2}\left(\frac{1+e_2}{1+d}\right)^j + \left(\frac{1+e_1}{1+d}\right)^{n_1}\left(\frac{1+e_2}{1+d}\right)^{n_2}\sum_{j=1}^{n_3}\left(\frac{1+e_3}{1+d}\right)^j +\ldots+ \left(\frac{1+e_1}{1+d}\right)^{n_1}\left(\frac{1+e_2}{1+d}\right)^{n_2}\cdots\left(\frac{1+e_{k-1}}{1+d}\right)^{n_{k-1}}\sum_{j=1}^{n_k}\left(\frac{1+e_k}{1+d}\right)^j,$$

where n_k = the length of the period for a given escalation rate in a given period, and the subscript k indicates the escalation period;

d = the discount rate; and $\sum_{j=1}^{n_k}\left(\frac{1+e}{1+d}\right)^j = \left(\frac{1+e}{d-e}\right)\left(1-\left(\frac{1+e}{1+d}\right)^{n_k}\right)$.

NOTE:
ELEC - Electricity
DIST - Distillate
RESID - Residual
NATGAS - Natural Gas
MFBI - Natural Gas (MFBI)
COAL - Steam Coal
GASLNE - Gasoline
SP - Study Period

Study Period 1 is Mid-1981 to Mid-1982.

TABLE B-7--UPW* DISCOUNT FACTORS ADJUSTED FOR ENERGY PRICE ESCALATION[1]
DOE REGION 7
(KANSAS, MISSOURI, IOWA, NEBRASKA)

	RESIDENTIAL SECTOR				COMMERCIAL SECTOR					INDUSTRIAL SECTOR						TRANSPORTATION
SP	ELEC	DIST	LPG	NATGAS	ELEC	DIST	RESID	NATGAS	COAL	ELEC	DIST	RESID	NATGAS	MFBI	COAL	GASLNE
1	.98	.96	.96	1.02	.98	.96	1.02	1.02	.99	.98	.96	1.02	1.02	1.02	1.06	.98
2	1.95	1.88	1.88	2.05	1.95	1.88	2.06	2.05	1.97	1.95	1.88	2.06	2.05	2.05	2.19	1.95
3	2.91	2.76	2.76	3.11	2.90	2.76	3.11	3.10	2.95	2.90	2.76	3.12	3.11	3.11	3.40	2.90
4	3.84	3.60	3.60	4.18	3.84	3.60	4.19	4.17	3.91	3.84	3.60	4.19	4.18	4.18	4.68	3.84
5	4.71	4.41	4.40	5.21	4.70	4.41	5.22	5.20	4.83	4.70	4.41	5.23	5.21	5.20	5.90	4.73
6	5.50	5.19	5.18	6.20	5.50	5.19	6.21	6.19	5.71	5.49	5.18	6.22	6.21	6.19	7.06	5.57
7	6.23	5.93	5.91	7.14	6.23	5.93	7.16	7.14	6.55	6.21	5.93	7.18	7.17	7.14	8.17	6.37
8	6.91	6.64	6.62	8.05	6.90	6.65	8.07	8.05	7.34	6.87	6.65	8.09	8.10	8.05	9.22	7.13
9	7.53	7.33	7.30	8.92	7.51	7.34	8.95	8.93	8.10	7.47	7.34	8.97	8.99	8.92	10.23	7.85
10	8.11	8.01	7.97	9.75	8.10	8.02	9.71	9.78	8.82	8.04	8.02	9.73	9.85	9.67	11.18	8.55
11	8.66	8.69	8.63	10.55	8.65	8.71	10.37	10.59	9.49	8.59	8.71	10.39	10.68	10.32	12.07	9.25
12	9.19	9.36	9.29	11.32	9.17	9.39	10.94	11.38	10.13	9.10	9.39	10.96	11.49	10.87	12.91	9.93
13	9.68	10.03	9.94	12.05	9.66	10.07	11.44	12.13	10.72	9.59	10.07	11.46	12.26	11.34	13.70	10.60
14	10.15	10.70	10.59	12.76	10.13	10.74	11.87	12.85	11.29	10.06	10.74	11.89	13.00	11.75	14.45	11.25
15	10.59	11.36	11.23	13.44	10.57	11.41	12.24	13.55	11.82	10.50	11.41	12.27	13.72	12.10	15.15	11.90
16	11.01	12.02	11.87	14.09	10.99	12.08	12.57	14.22	12.31	10.92	12.08	12.59	14.41	12.40	15.81	12.54
17	11.40	12.67	12.50	14.71	11.38	12.75	12.85	14.86	12.78	11.31	12.75	12.87	15.08	12.66	16.43	13.16
18	11.77	13.32	13.13	15.31	11.75	13.42	13.09	15.48	13.22	11.69	13.42	13.12	15.72	12.88	17.02	13.78
19	12.12	13.97	13.75	15.88	12.10	14.08	13.30	16.07	13.64	12.04	14.08	13.33	16.34	13.07	17.57	14.38
20	12.46	14.62	14.37	16.43	12.44	14.74	13.49	16.65	14.03	12.38	14.74	13.51	16.94	13.23	18.08	14.97
21	12.77	15.25	14.98	16.96	12.75	15.39	13.65	17.20	14.40	12.70	15.40	13.67	17.52	13.37	18.57	15.55
22	13.07	15.89	15.58	17.47	13.05	16.05	13.78	17.73	14.75	13.00	16.05	13.81	18.07	13.49	19.03	16.13
23	13.35	16.52	16.18	17.95	13.33	16.70	13.90	18.24	15.07	13.29	16.70	13.93	18.61	13.60	19.46	16.69
24	13.61	17.15	16.78	18.42	13.60	17.35	14.01	18.73	15.38	13.57	17.35	14.03	19.13	13.68	19.87	17.24
25	13.86	17.78	17.37	18.87	13.85	17.99	14.10	19.20	15.67	13.82	18.00	14.12	19.62	13.76	20.25	17.79

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[1] These "modified" uniform present worth discount (UPW*) factors are based on a 7 percent discount rate and include the EIA projected real escalation rates in energy prices developed from the Mid-Term Energy Forecasting System (MEFS), for the periods mid-1981 to mid-1985, mid-1985 to mid-1990, and mid-1990 to mid-1995 and beyond. The formula for calculating these UPW* factors is the following: For 1 to k escalation periods,

$$\mathrm{UPW}^* = \sum_{j=1}^{n_1}\left(\frac{1+e_1}{1+d}\right)^j + \left(\frac{1+e_1}{1+d}\right)^{n_1}\sum_{j=1}^{n_2}\left(\frac{1+e_2}{1+d}\right)^j + \left(\frac{1+e_1}{1+d}\right)^{n_1}\left(\frac{1+e_2}{1+d}\right)^{n_2}\sum_{j=1}^{n_3}\left(\frac{1+e_3}{1+d}\right)^j + .. + \left(\frac{1+e_1}{1+d}\right)^{n_1}\left(\frac{1+e_2}{1+d}\right)^{n_2} .. \left(\frac{1+e_{k-1}}{1+d}\right)^{n_{k-1}}\sum_{j=1}^{n_k}\left(\frac{1+e_k}{1+d}\right)^j ,$$

where n_k = the length of the period for a given escalation rate in a given period, and the subscript k indicates the escalation period;

d = the discount rate; and $\sum_{j=1}^{n_k}\left(\frac{1+e}{1+d}\right)^j = \left(\frac{1+e}{d-e}\right)\left(1-\left(\frac{1+e}{1+d}\right)^{n_k}\right).$

NOTE:

ELEC - Electricity
DIST - Distillate
RESID - Residual
NATGAS - Natural Gas
MFBI - Natural Gas (MFBI)
COAL - Steam Coal
GASLNE - Gasoline
SP - Study Period

Study Period 1 is Mid-1981 to Mid-1982.

TABLE B-8--UPW* DISCOUNT FACTORS ADJUSTED FOR ENERGY PRICE ESCALATION[1]
DOE REGION 8
(MONTANA, NORTH DAKOTA, SOUTH DAKOTA, WYOMING, UTAH, COLORADO)

	RESIDENTIAL SECTOR				COMMERCIAL SECTOR					INDUSTRIAL SECTOR						TRANSPORTATION
SP	ELEC	DIST	LPG	NATGAS	ELEC	DIST	RESID	NATGAS	COAL	ELEC	DIST	RESID	NATGAS	MFBI	COAL	GASLNE
1	.98	.95	.95	1.02	.98	.96	1.02	1.02	.99	.98	.96	1.02	1.02	1.02	1.06	.98
2	1.95	1.88	1.88	2.05	1.95	1.88	2.06	2.05	1.97	1.95	1.88	2.06	2.05	2.05	2.20	1.95
3	2.91	2.76	2.76	3.11	2.90	2.76	3.11	3.11	2.95	2.91	2.76	3.11	3.11	3.11	3.40	2.90
4	3.84	3.60	3.60	4.18	3.84	3.60	4.19	4.18	3.91	3.84	3.60	4.19	4.18	4.18	4.68	3.84
5	4.69	4.41	4.41	5.18	4.68	4.41	5.22	5.18	4.81	4.67	4.41	5.22	5.18	5.18	5.88	4.73
6	5.44	5.18	5.18	6.12	5.43	5.19	6.22	6.12	5.65	5.39	5.18	6.22	6.12	6.12	7.00	5.57
7	6.12	5.92	5.91	6.99	6.10	5.93	7.17	6.99	6.44	6.03	5.93	7.17	6.99	7.00	8.05	6.37
8	6.73	6.64	6.62	7.81	6.71	6.65	8.08	7.81	7.18	6.59	6.64	8.08	7.81	7.82	9.03	7.12
9	7.28	7.32	7.30	8.58	7.24	7.33	8.96	8.58	7.86	7.08	7.33	8.96	8.58	8.59	9.94	7.84
10	7.78	8.00	7.96	9.30	7.73	8.02	9.83	9.31	8.51	7.52	8.01	9.83	9.31	9.32	10.80	8.54
11	8.23	8.67	8.63	9.99	8.17	8.70	10.70	10.00	9.12	7.91	8.69	10.70	10.00	10.02	11.61	9.23
12	8.64	9.34	9.28	10.65	8.57	9.38	11.56	10.66	9.69	8.25	9.37	11.57	10.66	10.68	12.37	9.91
13	9.01	10.00	9.93	11.27	8.92	10.05	12.42	11.28	10.23	8.56	10.04	12.43	11.29	11.31	13.08	10.58
14	9.34	10.66	10.58	11.86	9.25	10.73	13.28	11.88	10.73	8.83	10.71	13.29	11.89	11.91	13.75	11.24
15	9.65	11.32	11.21	12.42	9.54	11.40	14.13	12.44	11.21	9.07	11.38	14.14	12.46	12.48	14.39	11.88
16	9.92	11.97	11.85	12.95	9.80	12.07	14.98	12.98	11.65	9.28	12.05	15.00	13.01	13.03	14.98	12.52
17	10.17	12.62	12.47	13.46	10.04	12.73	15.82	13.49	12.07	9.47	12.72	15.84	13.53	13.54	15.54	13.15
18	10.40	13.26	13.09	13.94	10.26	13.40	16.67	13.97	12.46	9.64	13.38	16.69	14.02	14.04	16.06	13.76
19	10.60	13.90	13.71	14.40	10.45	14.06	17.50	14.43	12.83	9.79	14.04	17.53	14.49	14.51	16.55	14.37
20	10.79	14.54	14.31	14.83	10.63	14.72	18.34	14.87	13.18	9.92	14.69	18.37	14.94	14.95	17.02	14.96
21	10.95	15.17	14.92	15.24	10.79	15.38	19.17	15.29	13.51	10.03	15.35	19.20	15.37	15.38	17.45	15.54
22	11.11	15.79	15.51	15.63	10.93	16.03	19.99	15.68	13.82	10.14	16.00	20.03	15.78	15.78	17.86	16.12
23	11.24	16.42	16.10	16.00	11.06	16.68	20.81	16.06	14.11	10.23	16.65	20.86	16.16	16.16	18.24	16.69
24	11.37	17.04	16.69	16.35	11.17	17.33	21.63	16.42	14.38	10.31	17.30	21.68	16.53	16.53	18.61	17.24
25	11.48	17.65	17.27	16.69	11.28	17.98	22.45	16.76	14.63	10.38	17.94	22.50	16.88	16.88	18.95	17.79

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[1] These "modified" uniform present worth discount (UPW*) factors are based on a 7 percent discount rate and include the EIA projected real escalation rates in energy prices developed from the Mid-Term Energy Forecasting System (MEFS), for the periods mid-1981 to mid-1985, mid-1985 to mid-1990, and mid-1990 to mid-1995 and beyond. The formula for calculating these UPW* factors is the following: For 1 to k escalation periods,

$$UPW^* = \sum_{j=1}^{n_1} \left(\frac{1 + e_1}{1 + d}\right)^j + \left(\frac{1 + e_1}{1 + d}\right)^{n_1} \sum_{j=1}^{n_2} \left(\frac{1 + e_2}{1 + d}\right)^j + \left(\frac{1 + e_1}{1 + d}\right)^{n_1} \left(\frac{1 + e_2}{1 + d}\right)^{n_2} \sum_{j=1}^{n_3} \left(\frac{1 + e_3}{1 + d}\right)^j + .. + \left(\frac{1 + e_1}{1 + d}\right)^{n_1} \left(\frac{1 + e_2}{1 + d}\right)^{n_2} .. \left(\frac{1 + e_{k-1}}{1 + d}\right)^{n_{k-1}} \sum_{j=1}^{n_k} \left(\frac{1 + e_k}{1 + d}\right)^j ,$$

where n_k = the length of the period for a given escalation rate in a given period, and the subscript k indicates the escalation period;

d = the discount rate; and $\sum_{j=1}^{n_k} \left(\frac{1 + e}{1 + d}\right)^j = \left(\frac{1 + e}{d - e}\right)\left(1 - \left(\frac{1 + e}{1 + d}\right)^{n_k}\right)$.

NOTE:

ELEC - Electricity	MFBI - Natural Gas (MFBI)
DIST - Distillate	COAL - Steam Coal
RESID - Residual	GASLNE - Gasoline
NATGAS - Natural Gas	SP - Study Period

Study Period 1 is Mid-1981 to Mid-1982.

TABLE B-9--UPW* DISCOUNT FACTORS ADJUSTED FOR ENERGY PRICE ESCALATION[1]
DOE REGION 9
(CALIFORNIA, NEVADA, ARIZONA, HAWAII, TRUST TERRITORY OF THE PACIFIC ISLANDS, AMERICAN SAMOA, GUAM)

	RESIDENTIAL SECTOR				COMMERCIAL SECTOR					INDUSTRIAL SECTOR						TRANSPORTATION
SP	ELEC	DIST	LPG	NATGAS	ELEC	DIST	RESID	NATGAS	COAL	ELEC	DIST	RESID	NATGAS	MFBI	COAL	GASLNE
1	.98	.96	.96	1.02	.98	.96	1.02	1.02	.99	.98	.96	1.02	1.02	1.02	1.06	.98
2	1.95	1.88	1.88	2.05	1.95	1.88	2.06	2.05	1.98	1.95	1.88	2.06	2.05	2.05	2.20	1.95
3	2.90	2.76	2.76	3.11	2.90	2.76	3.11	3.11	2.95	2.90	2.76	3.11	3.11	3.11	3.41	2.90
4	3.84	3.60	3.60	4.18	3.84	3.60	4.19	4.18	3.92	3.84	3.60	4.19	4.18	4.18	4.69	3.84
5	4.71	4.41	4.41	5.17	4.71	4.41	5.22	5.17	4.83	4.71	4.41	5.23	5.17	5.21	5.91	4.73
6	5.52	5.18	5.18	6.10	5.53	5.19	6.22	6.09	5.70	5.52	5.19	6.22	6.09	6.20	7.06	5.57
7	6.28	5.93	5.92	6.96	6.28	5.94	7.17	6.95	6.52	6.28	5.94	7.17	6.95	7.15	8.15	6.37
8	6.98	6.64	6.62	7.75	6.98	6.65	8.09	7.74	7.30	6.98	6.65	8.09	7.74	8.06	9.18	7.12
9	7.63	7.32	7.30	8.50	7.64	7.35	8.97	8.48	8.04	7.63	7.35	8.97	8.48	8.94	10.16	7.84
10	8.24	8.00	7.97	9.19	8.25	8.04	9.85	9.17	8.72	8.23	8.04	9.85	9.17	9.82	11.08	8.55
11	8.80	8.68	8.63	9.85	8.81	8.72	10.72	9.83	9.37	8.79	8.72	10.72	9.82	10.70	11.93	9.24
12	9.32	9.35	9.29	10.47	9.33	9.41	11.59	10.45	9.97	9.31	9.41	11.59	10.44	11.58	12.73	9.92
13	9.81	10.02	9.94	11.05	9.82	10.09	12.45	11.03	10.53	9.79	10.09	12.46	11.03	12.47	13.47	10.59
14	10.25	10.68	10.59	11.60	10.26	10.77	13.32	11.58	11.05	10.23	10.77	13.32	11.58	13.35	14.17	11.25
15	10.67	11.34	11.23	12.12	10.68	11.45	14.17	12.10	11.55	10.64	11.45	14.18	12.10	14.23	14.82	11.89
16	11.05	12.00	11.87	12.61	11.07	12.12	15.02	12.59	12.00	11.02	12.12	15.04	12.59	15.11	15.43	12.53
17	11.41	12.65	12.50	13.07	11.43	12.80	15.87	13.05	12.43	11.37	12.80	15.89	13.05	16.00	16.00	13.15
18	11.74	13.29	13.12	13.50	11.76	13.47	16.72	13.48	12.83	11.70	13.47	16.73	13.48	16.88	16.53	13.76
19	12.05	13.93	13.74	13.91	12.07	14.14	17.56	13.89	13.21	12.00	14.14	17.58	13.90	17.77	17.03	14.37
20	12.33	14.57	14.35	14.29	12.36	14.80	18.40	14.28	13.56	12.28	14.80	18.42	14.29	18.66	17.50	14.96
21	12.60	15.21	14.96	14.66	12.62	15.47	19.23	14.64	13.88	12.54	15.47	19.25	14.65	19.54	17.93	15.54
22	12.84	15.84	15.56	15.00	12.87	16.13	20.06	14.99	14.19	12.78	16.13	20.08	15.00	20.43	18.34	16.11
23	13.07	16.46	16.16	15.32	13.10	16.79	20.88	15.31	14.48	13.00	16.79	20.91	15.33	21.32	18.72	16.67
24	13.28	17.08	16.75	15.62	13.31	17.45	21.70	15.62	14.74	13.21	17.45	21.74	15.63	22.21	19.07	17.22
25	13.48	17.70	17.34	15.91	13.51	18.10	22.52	15.90	14.99	13.40	18.10	22.56	15.93	23.10	19.40	17.76

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[1] These "modified" uniform present worth discount (UPW*) factors are based on a 7 percent discount rate and include the EIA projected real escalation rates in energy prices developed from the Mid-Term Energy Forecasting System (MEFS), for the periods mid-1981 to mid-1985, mid-1985 to mid-1990, and mid-1990 to mid-1995 and beyond. The formula for calculating these UPW* factors is the following: For 1 to k escalation periods,

$$\mathrm{UPW}^* = \sum_{j=1}^{n_1}\left(\frac{1+e_1}{1+d}\right)^j + \left(\frac{1+e_1}{1+d}\right)^{n_1}\sum_{j=1}^{n_2}\left(\frac{1+e_2}{1+d}\right)^j + \left(\frac{1+e_1}{1+d}\right)^{n_1}\left(\frac{1+e_2}{1+d}\right)^{n_2}\sum_{j=1}^{n_3}\left(\frac{1+e_3}{1+d}\right)^j + \ldots + \left(\frac{1+e_1}{1+d}\right)^{n_1}\left(\frac{1+e_2}{1+d}\right)^{n_2}\cdots\left(\frac{1+e_{k-1}}{1+d}\right)^{n_{k-1}}\sum_{j=1}^{n_k}\left(\frac{1+e_k}{1+d}\right)^j ,$$

where n_k = the length of the period for a given escalation rate in a given period, and the subscript k indicates the escalation period;

d = the discount rate; and $\sum_{j=1}^{n_k}\left(\frac{1+e}{1+d}\right)^j = \left(\frac{1+e}{d-e}\right)\left(1-\left(\frac{1+e}{1+d}\right)^{n_k}\right)$.

NOTE:

ELEC - Electricity	MFBI - Natural Gas (MFBI)
DIST - Distillate	COAL - Steam Coal
RESID - Residual	GASLNE - Gasoline
NATGAS - Natural Gas	SP - Study Period

Study Period 1 is Mid-1981 to Mid-1982.

TABLE B-10--UPW* DISCOUNT FACTORS ADJUSTED FOR ENERGY PRICE ESCALATION[1]
DOE REGION 10
(WASHINGTON, OREGON, IDAHO, ALASKA)

	RESIDENTIAL SECTOR				COMMERCIAL SECTOR					INDUSTRIAL SECTOR						TRANSPORTATION
SP	ELEC	DIST	LPG	NATGAS	ELEC	DIST	RESID	NATGAS	COAL	ELEC	DIST	RESID	NATGAS	MFBI	COAL	GASLNE
1	.98	.96	.96	1.02	.98	.96	1.02	1.02	.99	.98	.96	1.02	1.02	1.02	1.05	.98
2	1.95	1.88	1.88	2.05	1.95	1.88	2.06	2.05	1.97	1.95	1.88	2.06	2.05	2.05	2.19	1.95
3	2.91	2.76	2.76	3.11	2.90	2.76	3.11	3.11	2.95	2.90	2.76	3.11	3.11	3.11	3.40	2.90
4	3.84	3.60	3.60	4.18	3.84	3.60	4.19	4.18	3.91	3.84	3.60	4.19	4.18	4.18	4.67	3.84
5	4.75	4.41	4.41	5.14	4.75	4.41	5.22	5.14	4.88	4.78	4.41	5.22	5.13	5.21	5.96	4.73
6	5.63	5.18	5.18	6.01	5.63	5.19	6.22	6.00	5.86	5.72	5.19	6.22	5.99	6.19	7.25	5.57
7	6.49	5.93	5.92	6.79	6.49	5.94	7.18	6.77	6.84	6.66	5.94	7.17	6.75	7.14	8.54	6.37
8	7.32	6.64	6.62	7.49	7.33	6.65	8.10	7.46	7.82	7.59	6.65	8.09	7.42	8.04	9.85	7.13
9	8.12	7.33	7.30	8.12	8.13	7.35	8.98	8.08	8.81	8.53	7.35	8.97	8.02	8.91	11.16	7.85
10	8.86	8.01	7.97	8.70	8.88	8.04	9.86	8.66	9.75	9.39	8.04	9.85	8.58	9.78	12.39	8.55
11	9.55	8.69	8.63	9.25	9.57	8.72	10.74	9.19	10.63	10.17	8.72	10.73	9.10	10.65	13.56	9.24
12	10.18	9.36	9.29	9.76	10.20	9.41	11.61	9.69	11.47	10.89	9.41	11.60	9.59	11.53	14.67	9.92
13	10.76	10.03	9.94	10.23	10.78	10.09	12.49	10.15	12.26	11.54	10.09	12.46	10.03	12.40	15.71	10.59
14	11.30	10.69	10.59	10.67	11.32	10.77	13.35	10.58	13.00	12.14	10.77	13.33	10.45	13.27	16.70	11.25
15	11.79	11.35	11.23	11.07	11.82	11.45	14.22	10.98	13.71	12.68	11.45	14.19	10.84	14.15	17.64	11.90
16	12.25	12.01	11.87	11.45	12.27	12.12	15.08	11.35	14.38	13.18	12.12	15.05	11.20	15.02	18.52	12.53
17	12.67	12.66	12.50	11.81	12.69	12.80	15.94	11.69	15.01	13.63	12.80	15.90	11.53	15.90	19.35	13.16
18	13.06	13.31	13.12	12.13	13.08	13.47	16.80	12.01	15.60	14.05	13.47	16.75	11.84	16.78	20.14	13.77
19	13.42	13.96	13.74	12.44	13.44	14.14	17.66	12.31	16.17	14.42	14.14	17.60	12.12	17.65	20.89	14.37
20	13.74	14.60	14.35	12.72	13.77	14.80	18.51	12.59	16.70	14.77	14.80	18.44	12.39	18.53	21.59	14.96
21	14.05	15.23	14.96	12.99	14.07	15.47	19.36	12.84	17.20	15.09	15.47	19.28	12.64	19.41	22.26	15.54
22	14.33	15.87	15.56	13.23	14.35	16.13	20.20	13.08	17.68	15.37	16.13	20.11	12.87	20.29	22.89	16.12
23	14.59	16.49	16.16	13.46	14.61	16.79	21.04	13.30	18.13	15.64	16.79	20.95	13.08	21.18	23.49	16.68
24	14.83	17.12	16.75	13.67	14.85	17.45	21.88	13.51	18.55	15.88	17.45	21.78	13.28	22.06	24.05	17.23
25	15.05	17.74	17.34	13.87	15.07	18.10	22.72	13.70	18.95	16.10	18.10	22.60	13.46	22.94	24.58	17.77

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[1] These "modified" uniform present worth discount (UPW*) factors are based on a 7 percent discount rate and include the EIA projected real escalation rates in energy prices developed from the Mid-Term Energy Forecasting System (MEFS), for the periods mid-1981 to mid-1985, mid-1985 to mid-1990, and mid-1990 to mid-1995 and beyond. The formula for calculating these UPW* factors is the following: For 1 to k escalation periods,

$$\text{UPW*} = \sum_{j=1}^{n_1} \left(\frac{1 + e_1}{1 + d}\right)^j + \left(\frac{1 + e_1}{1 + d}\right)^{n_1} \sum_{j=1}^{n_2} \left(\frac{1 + e_2}{1 + d}\right)^j + \left(\frac{1 + e_1}{1 + d}\right)^{n_1} \left(\frac{1 + e_2}{1 + d}\right)^{n_2} \sum_{j=1}^{n_3} \left(\frac{1 + e_3}{1 + d}\right)^j + .. + \left(\frac{1 + e_1}{1 + d}\right)^{n_1} \left(\frac{1 + e_2}{1 + d}\right)^{n_2} .. \left(\frac{1 + e_{k-1}}{1 + d}\right)^{n_{k-1}} \sum_{j=1}^{n_k} \left(\frac{1 + e_k}{1 + d}\right)^j ,$$

where n_k = the length of the period for a given escalation rate in a given period, and the subscript k indicates the escalation period;

d = the discount rate; and $\sum_{j=1}^{n_k} \left(\frac{1 + e}{1 + d}\right)^j = \left(\frac{1 + e}{d - e}\right)\left(1 - \left(\frac{1 + e}{1 + d}\right)^{n_k}\right)$.

NOTE:
ELEC - Electricity
DIST - Distillate
RESID - Residual
NATGAS - Natural Gas
MFBI - Natural Gas (MFBI)
COAL - Steam Coal
GASLNE - Gasoline
SP - Study Period

Study Period 1 is Mid-1981 to Mid-1982.

TABLE B-11--UPW* DISCOUNT FACTORS ADJUSTED FOR ENERGY PRICE ESCALATION[1]
UNITED STATES AVERAGE

	RESIDENTIAL SECTOR				COMMERCIAL SECTOR					INDUSTRIAL SECTOR						TRANSPORTATION
SP	ELEC	DIST	LPG	NATGAS	ELEC	DIST	RESID	NATGAS	COAL	ELEC	DIST	RESID	NATGAS	MFBI	COAL	GASLNE
1	.98	.96	.96	1.02	.98	.96	1.02	1.02	.99	.98	.96	1.02	1.02	1.02	1.06	.98
2	1.95	1.88	1.88	2.05	1.95	1.88	2.06	2.05	1.97	1.95	1.88	2.06	2.05	2.05	2.19	1.95
3	2.90	2.76	2.76	3.11	2.90	2.76	3.11	3.10	2.95	2.90	2.76	3.11	3.10	3.11	3.40	2.90
4	3.84	3.60	3.60	4.18	3.84	3.60	4.19	4.18	3.92	3.84	3.60	4.19	4.18	4.18	4.68	3.84
5	4.72	4.41	4.40	5.19	4.72	4.41	5.22	5.19	4.84	4.72	4.41	5.22	5.18	5.14	5.90	4.73
6	5.54	5.18	5.18	6.15	5.54	5.18	6.21	6.15	5.71	5.55	5.18	6.21	6.13	6.00	7.08	5.57
7	6.31	5.92	5.91	7.06	6.31	5.93	7.16	7.07	6.54	6.33	5.93	7.16	7.02	6.76	8.20	6.37
8	7.03	6.63	6.62	7.92	7.02	6.64	8.07	7.93	7.34	7.06	6.64	8.07	7.86	7.45	9.28	7.12
9	7.71	7.31	7.29	8.74	7.69	7.33	8.95	8.75	8.09	7.75	7.33	8.94	8.66	8.06	10.31	7.84
10	8.34	7.99	7.96	9.52	8.32	8.01	9.80	9.54	8.80	8.39	8.01	9.76	9.42	8.65	11.29	8.54
11	8.93	8.66	8.63	10.26	8.90	8.69	10.62	10.30	9.46	8.99	8.68	10.54	10.15	9.22	12.21	9.23
12	9.48	9.32	9.28	10.98	9.45	9.36	11.42	11.02	10.09	9.55	9.36	11.29	10.85	9.76	13.07	9.91
13	9.99	9.99	9.93	11.66	9.96	10.03	12.19	11.71	10.67	10.07	10.03	11.99	11.52	10.28	13.89	10.58
14	10.47	10.64	10.58	12.31	10.43	10.70	12.94	12.38	11.23	10.56	10.70	12.66	12.17	10.78	14.66	11.24
15	10.91	11.29	11.21	12.94	10.87	11.36	13.67	13.01	11.75	11.01	11.36	13.29	12.80	11.26	15.39	11.88
16	11.33	11.93	11.85	13.54	11.28	12.02	14.38	13.63	12.23	11.44	12.02	13.89	13.40	11.72	16.08	12.51
17	11.72	12.57	12.47	14.11	11.66	12.68	15.07	14.21	12.69	11.83	12.67	14.47	13.97	12.16	16.73	13.13
18	12.08	13.21	13.09	14.66	12.02	13.33	15.73	14.77	13.13	12.20	13.33	15.01	14.52	12.59	17.34	13.74
19	12.42	13.84	13.71	15.18	12.36	13.98	16.38	15.31	13.53	12.55	13.97	15.52	15.06	12.99	17.92	14.34
20	12.73	14.46	14.32	15.68	12.67	14.63	17.01	15.83	13.91	12.87	14.62	16.01	15.57	13.39	18.46	14.93
21	13.03	15.08	14.92	16.16	12.96	15.27	17.62	16.32	14.27	13.17	15.26	16.47	16.06	13.76	18.98	15.51
22	13.30	15.70	15.52	16.62	13.23	15.91	18.21	16.80	14.61	13.45	15.90	16.91	16.53	14.12	19.46	16.08
23	13.56	16.31	16.11	17.06	13.48	16.54	18.78	17.25	14.93	13.71	16.54	17.32	16.98	14.47	19.92	16.64
24	13.79	16.94	16.70	17.48	13.71	17.18	19.34	17.69	15.22	13.96	17.17	17.72	17.42	14.80	20.35	17.19
25	14.02	17.51	17.28	17.88	13.93	17.80	19.87	18.10	15.50	14.19	17.79	18.09	17.84	15.12	20.76	17.72

[1] These "modified" uniform present worth discount (UPW*) factors are based on a 7 percent discount rate and include the EIA projected real escalation rates in energy prices developed from the Mid-Term Energy Forecasting System (MEFS), for the periods mid-1981 to mid-1985, mid-1985 to mid-1990, and mid-1990 to mid-1995 and beyond. The formula for calculating these UPW* factors is the following: For 1 to k escalation periods,

$$\text{UPW*} = \sum_{j=1}^{n_1} \left(\frac{1+e_1}{1+d}\right)^j + \left(\frac{1+e_1}{1+d}\right)^{n_1} \sum_{j=1}^{n_2} \left(\frac{1+e_2}{1+d}\right)^j + \left(\frac{1+e_1}{1+d}\right)^{n_1} \left(\frac{1+e_2}{1+d}\right)^{n_2} \sum_{j=1}^{n_3} \left(\frac{1+e_3}{1+d}\right)^j + .. + \left(\frac{1+e_1}{1+d}\right)^{n_1} \left(\frac{1+e_2}{1+d}\right)^{n_2} .. \left(\frac{1+e_{k-1}}{1+d}\right)^{n_{k-1}} \sum_{j=1}^{n_k} \left(\frac{1+e_k}{1+d}\right)^j ,$$

where n_k = the length of the period for a given escalation rate in a given period, and the subscript k indicates the escalation period;

d = the discount rate; and $\sum_{j=1}^{n_k} \left(\frac{1+e}{1+d}\right)^j = \left(\frac{1+e}{d-e}\right)\left(1 - \left(\frac{1+e}{1+d}\right)^{n_k}\right)$.

NOTE:

ELEC - Electricity	MFBI - Natural Gas (MFBI)
DIST - Distillate	COAL - Steam Coal
RESID - Residual	GASLNE - Gasoline
NATGAS - Natural Gas	SP - Study Period

Study Period 1 is Mid-1981 to Mid-1982.

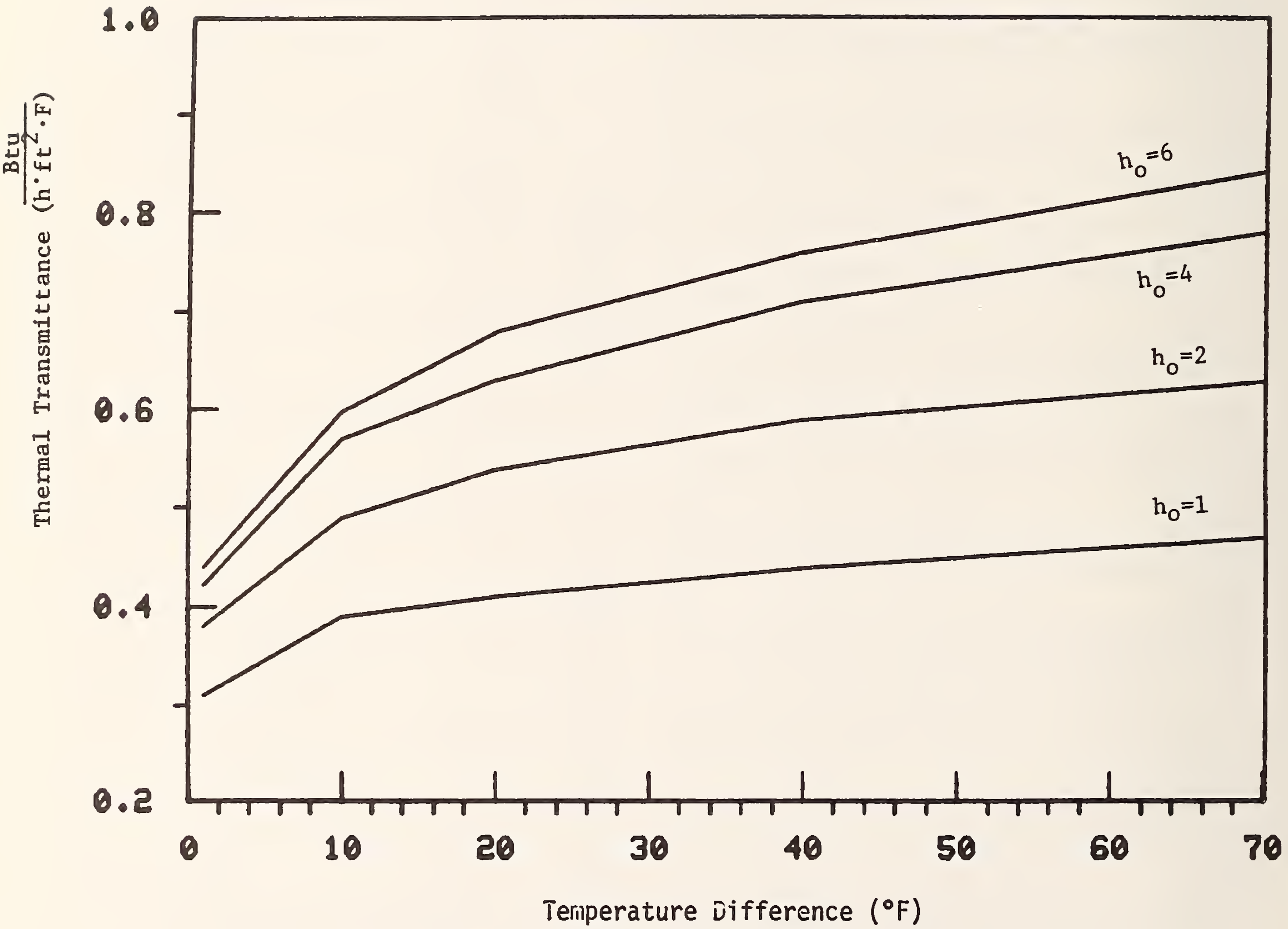

Figure 3a Calculated thermal transmittance (U-value) as a function of inside-to-outside air temperature differences, and exterior surface heat transfer coefficient for film A

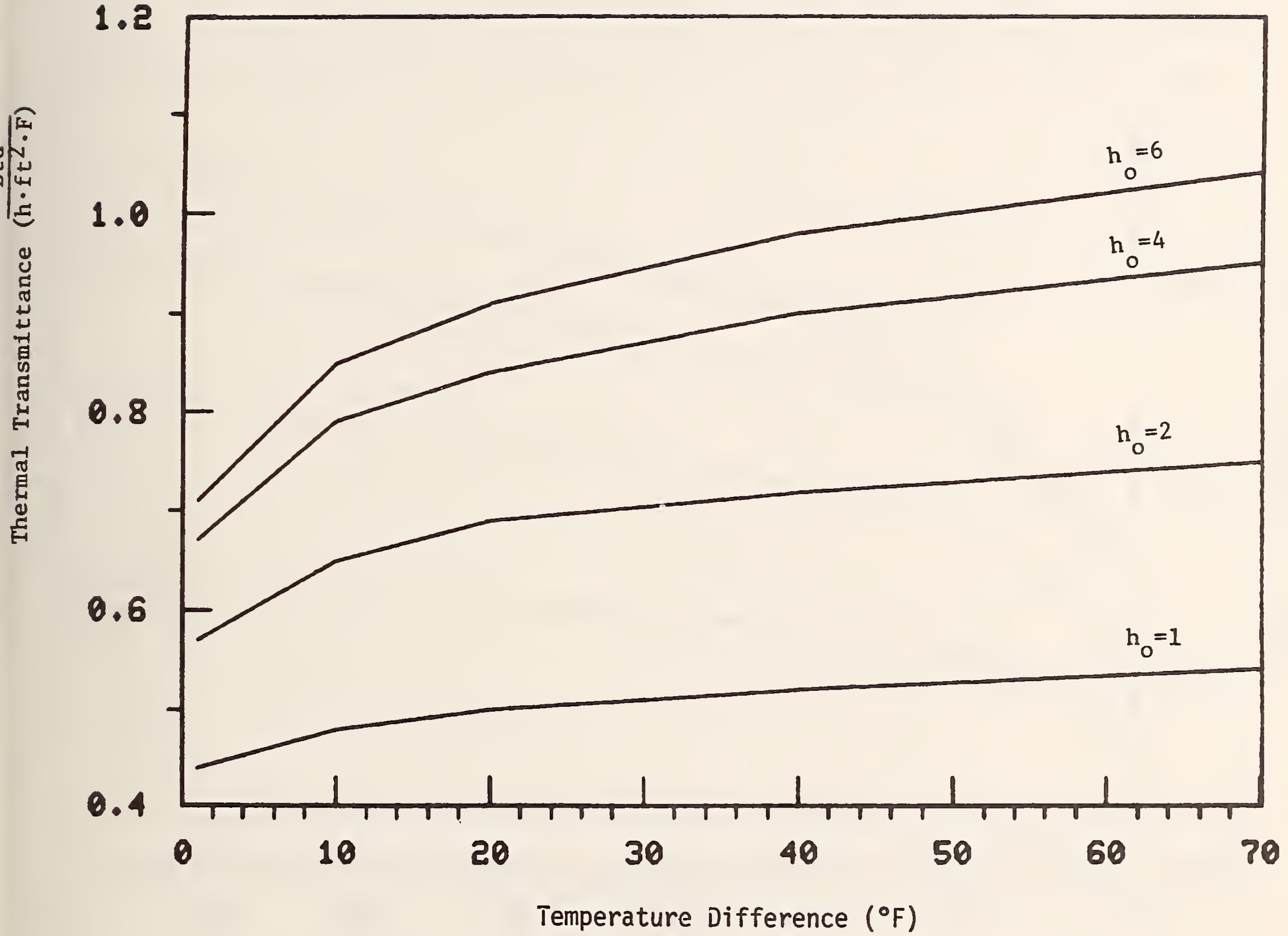

Figure 3b Calculated thermal transmittance (U-value) as a function of inside-to-outside air temperature difference, and exterior surface heat transfer coefficient for film B

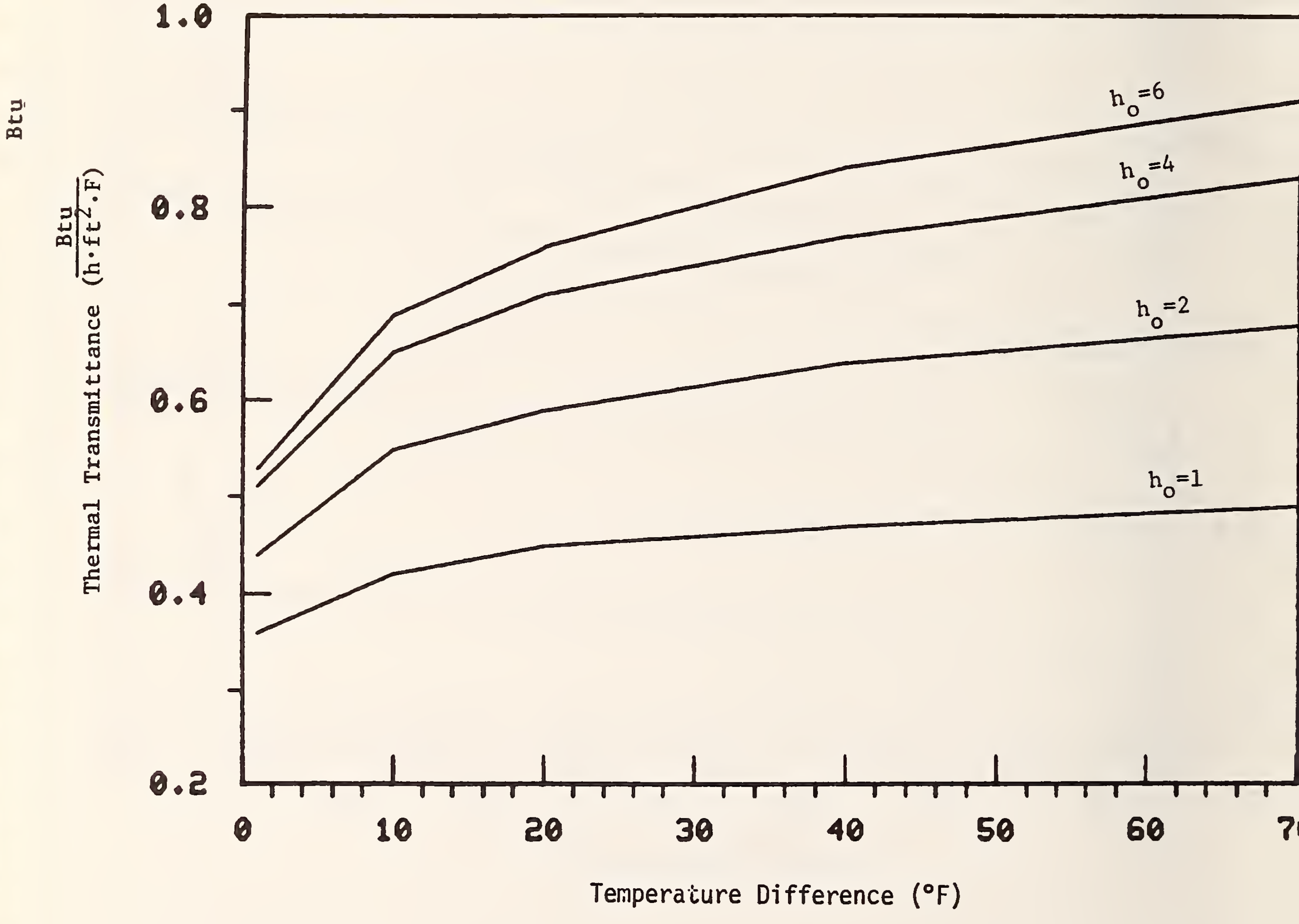

Figure 3c Calculated thermal transmittance (U-value) as a function of inside-to-outside air temperature difference, and exterior surface heat transfer coefficient for film C

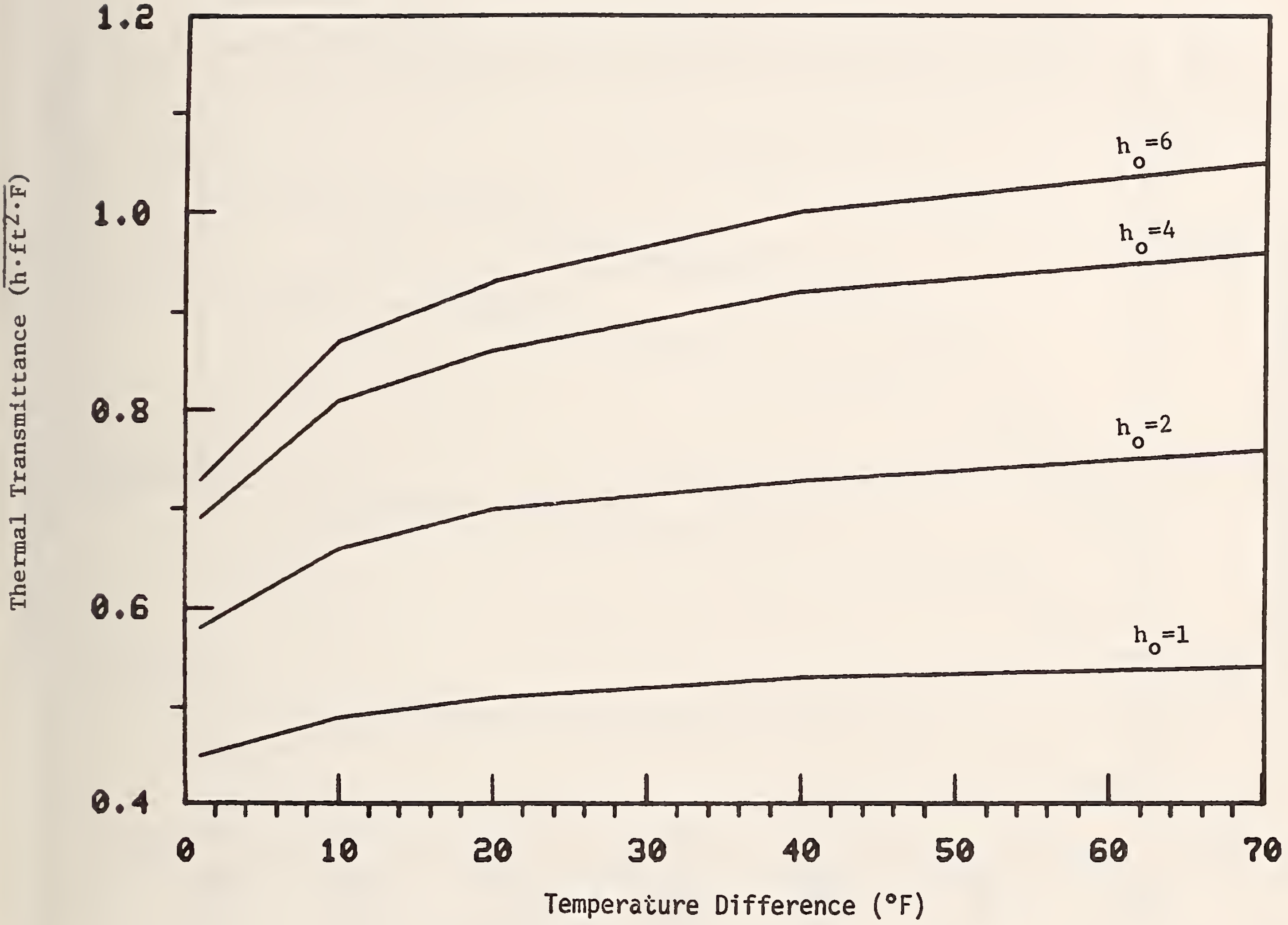

Figure 3d Calculated thermal transmittance (U-value) as a function of inside-to-outside air temperature difference, and exterior surface heat transfer coefficient for film D

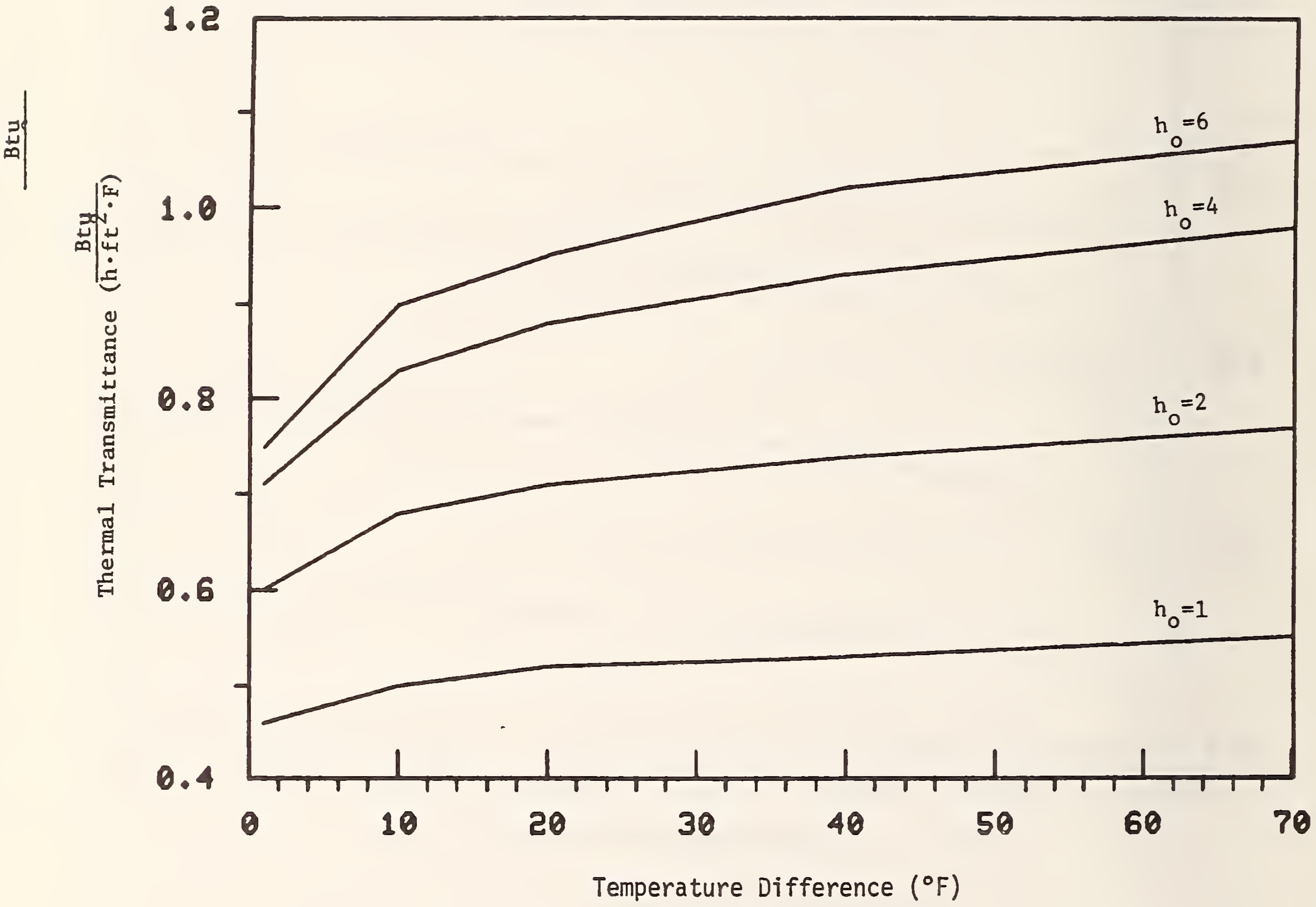

Figure 3e Calculated thermal transmittance (U-value) as a function of inside-to-outside air temperature difference, and exterior surface heat transfer coefficient for film E

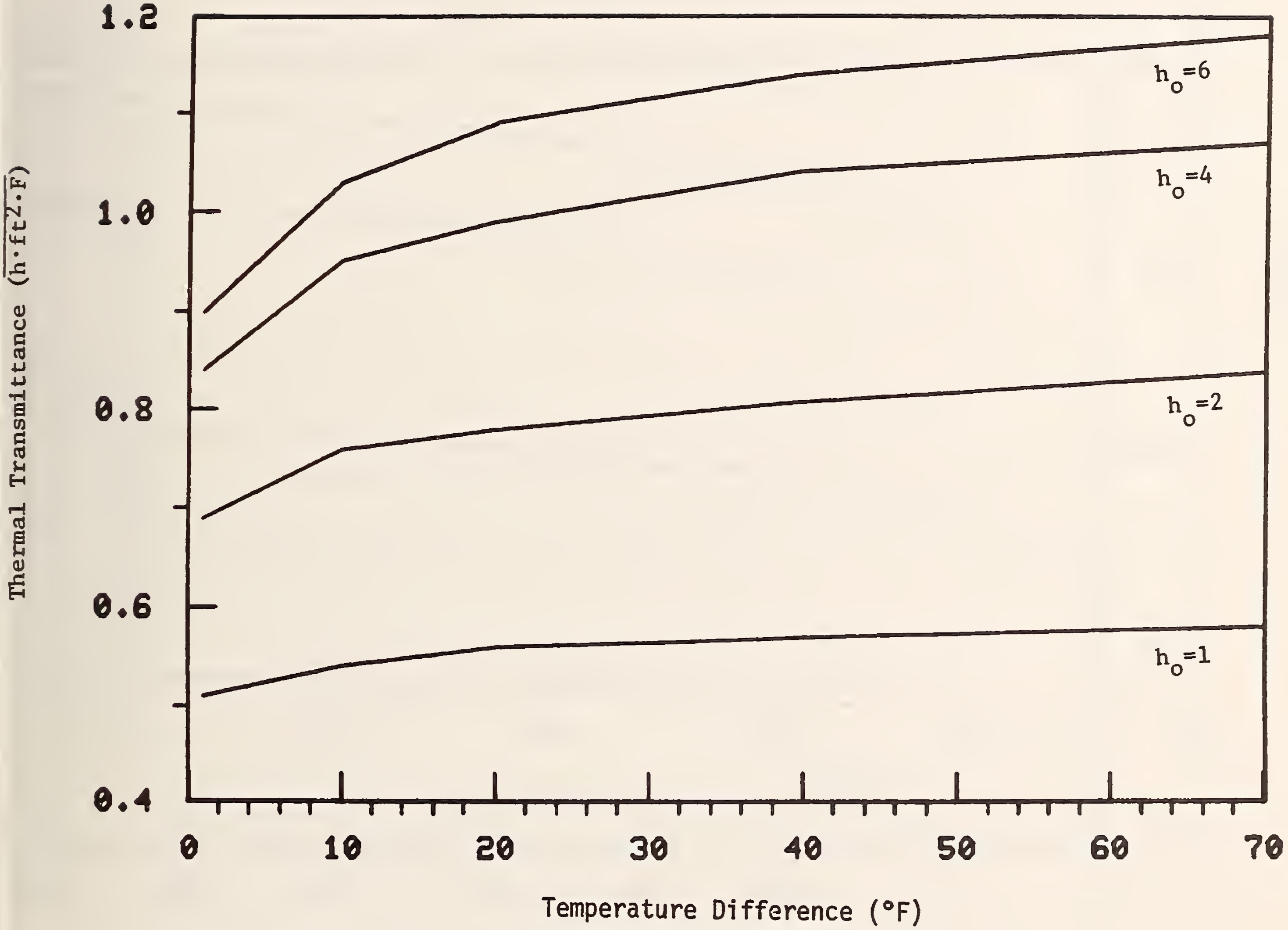

Figure 3f Calculated thermal transmittance (U-value) as a function of inside-to-outside air temperature difference, and exterior surface heat transfer coefficient for film F

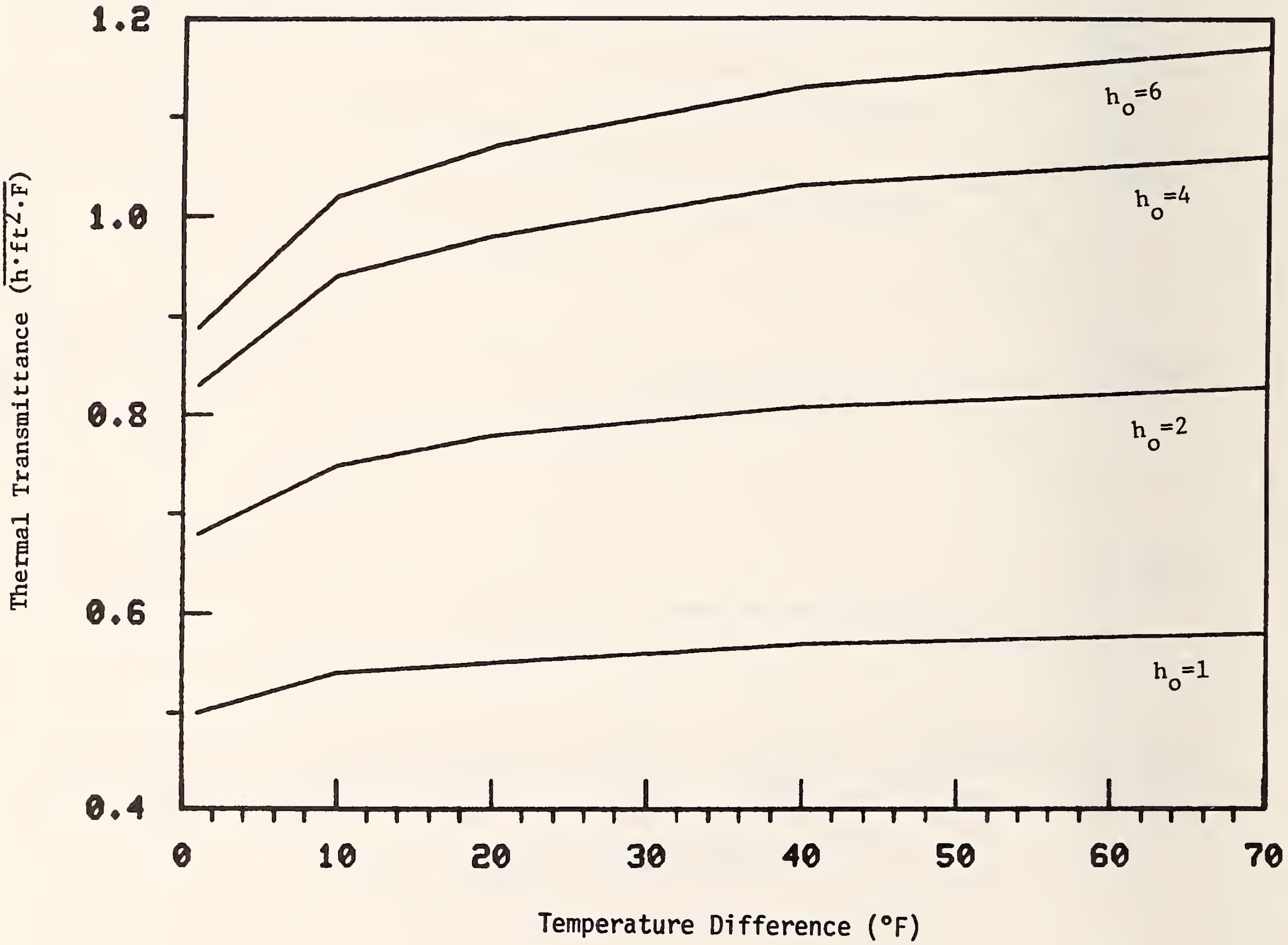

Figure 3g Calculated thermal transmittance (U-value) as a function of inside-to-outside air temperature difference, and exterior surface heat transfer coefficient for clear glass

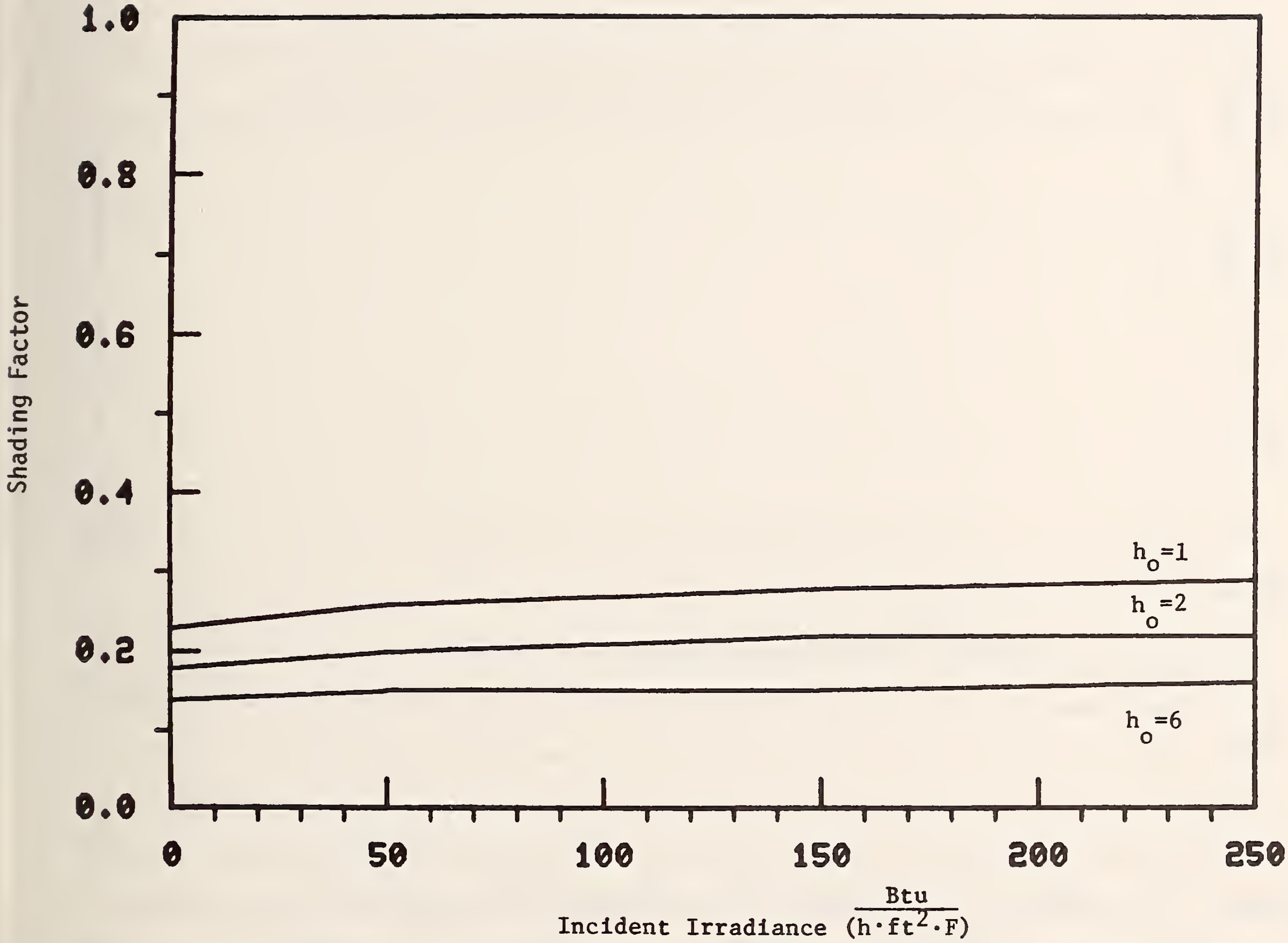

Figure 4a Calculated shading factor (F) as a function of level of incident irradiance for film A

Btu

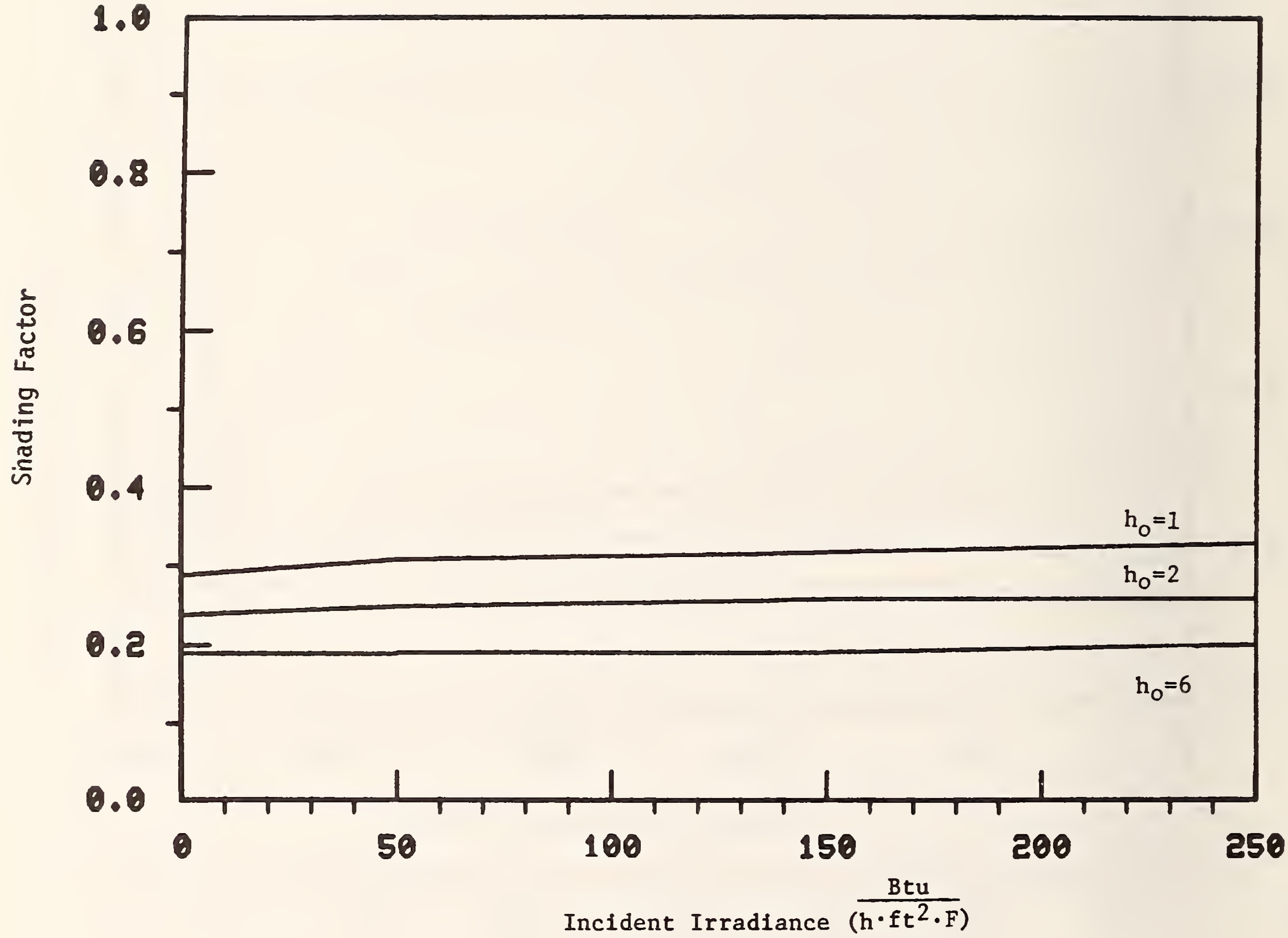

Figure 4b Calculated shading factor (F) as a function of level of incident irradiance for film B

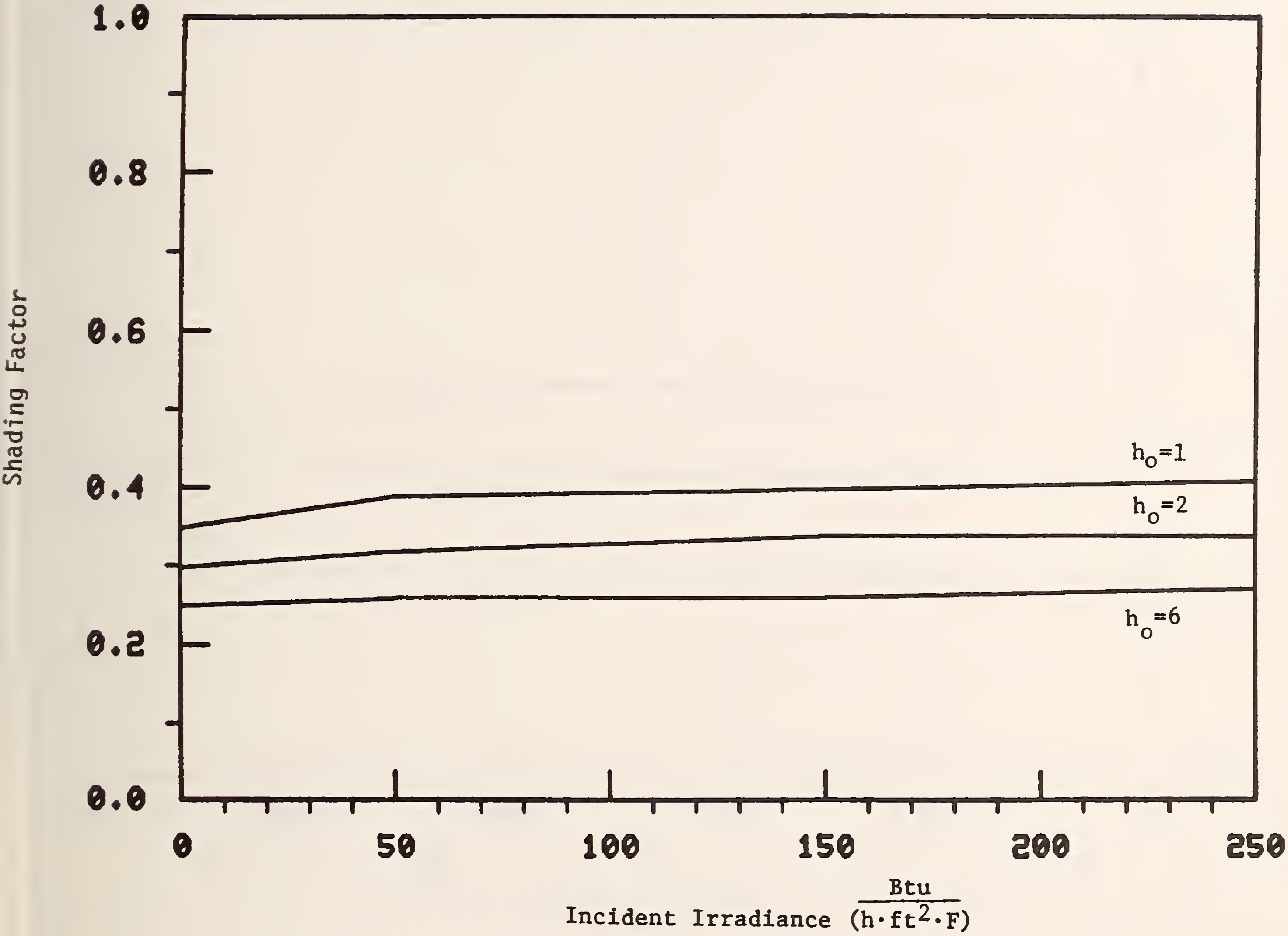

Figure 4c Calculated shading factor (F) as a function of level of incident irradiance for film C

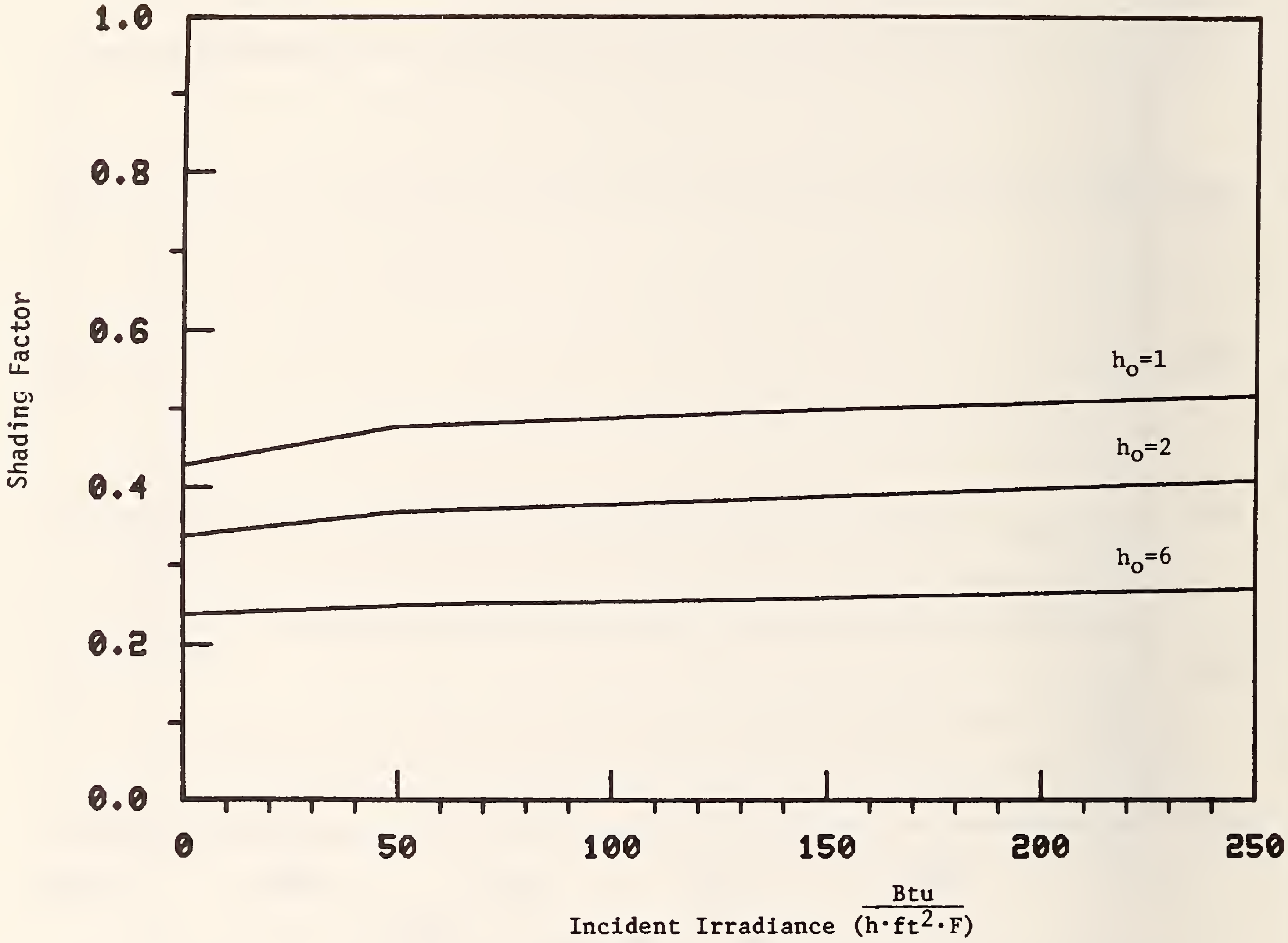

Figure 4d Calculated shading factor (F) as a function of level of incident irradiance for film D

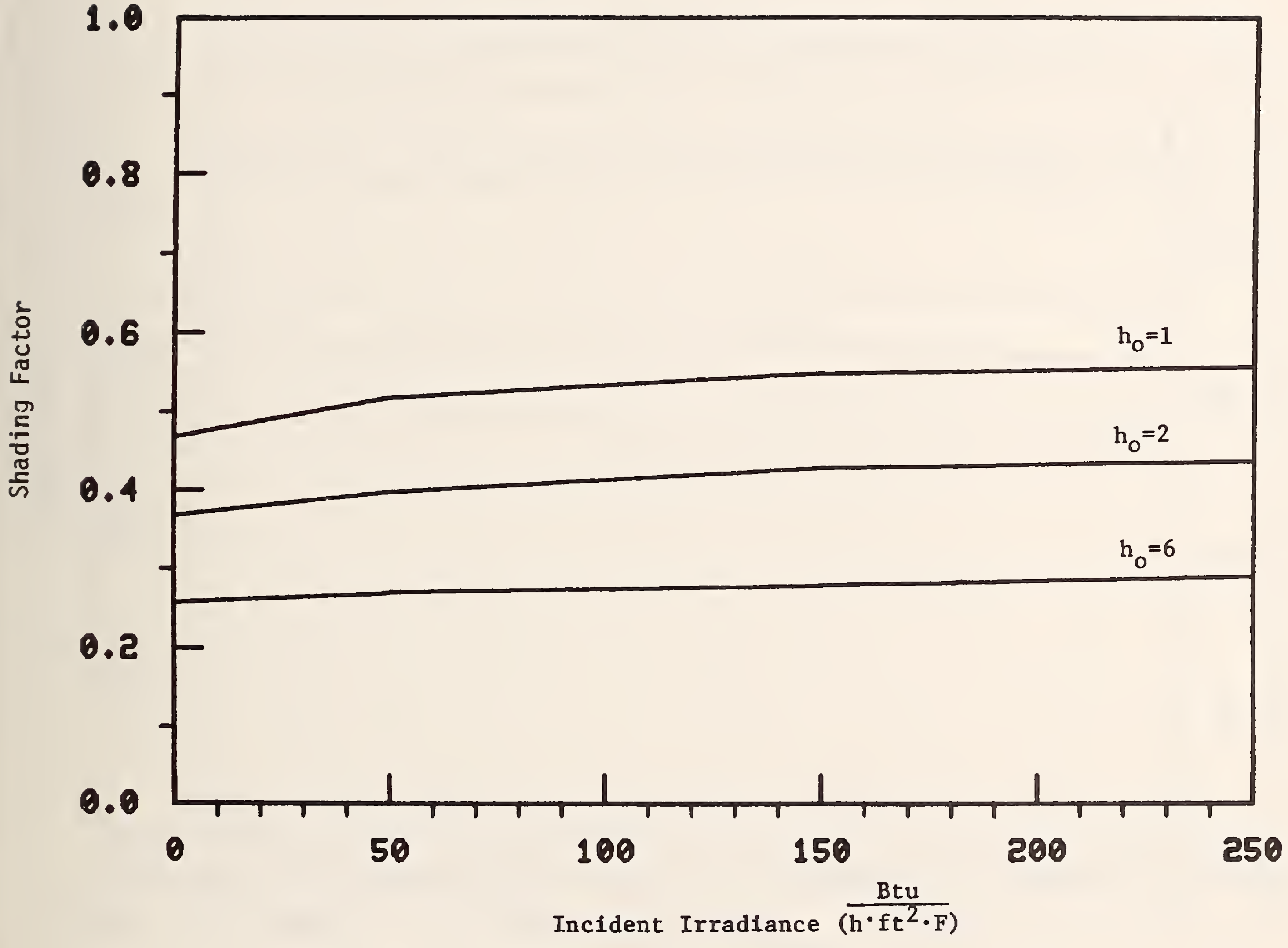

Figure 4e Calculated shading factor (F) as a function of level of incident irradiance for film E

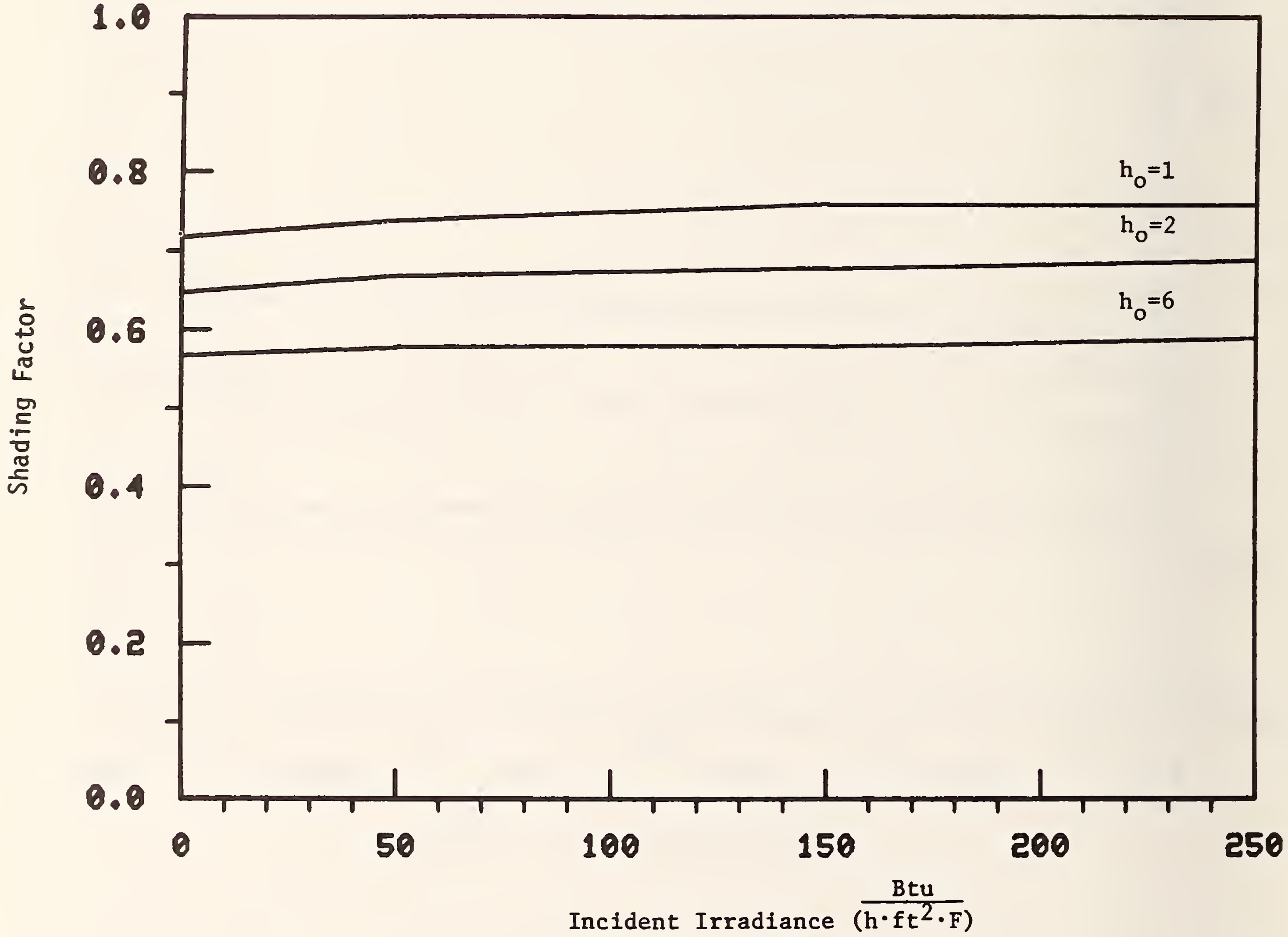

Figure 4f Calculated shading factor (F) as a function of level of incident irradiance for film F

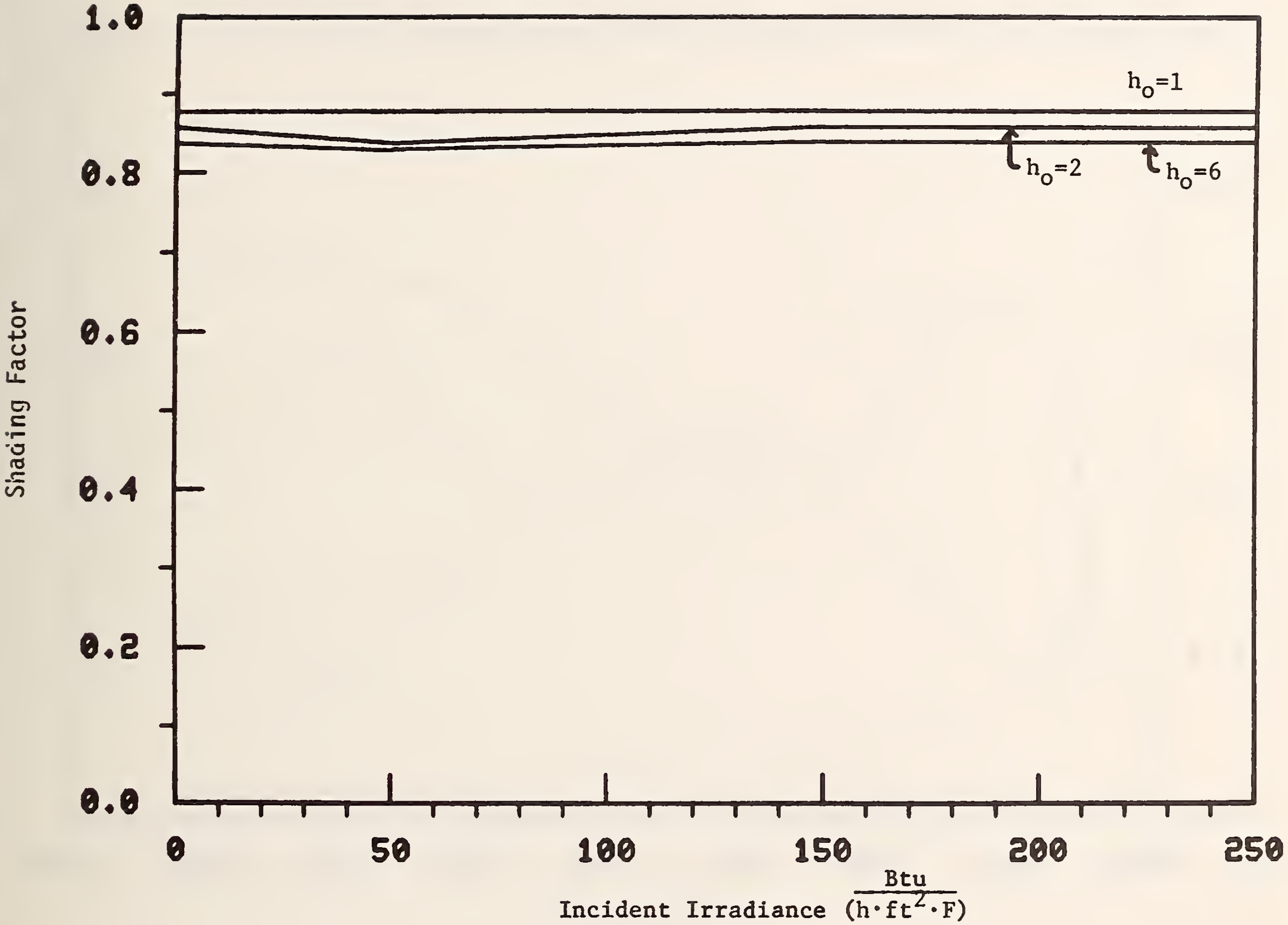

Figure 4g Calculated shading factor (F) as a function of level of incident irradiance for clear glass

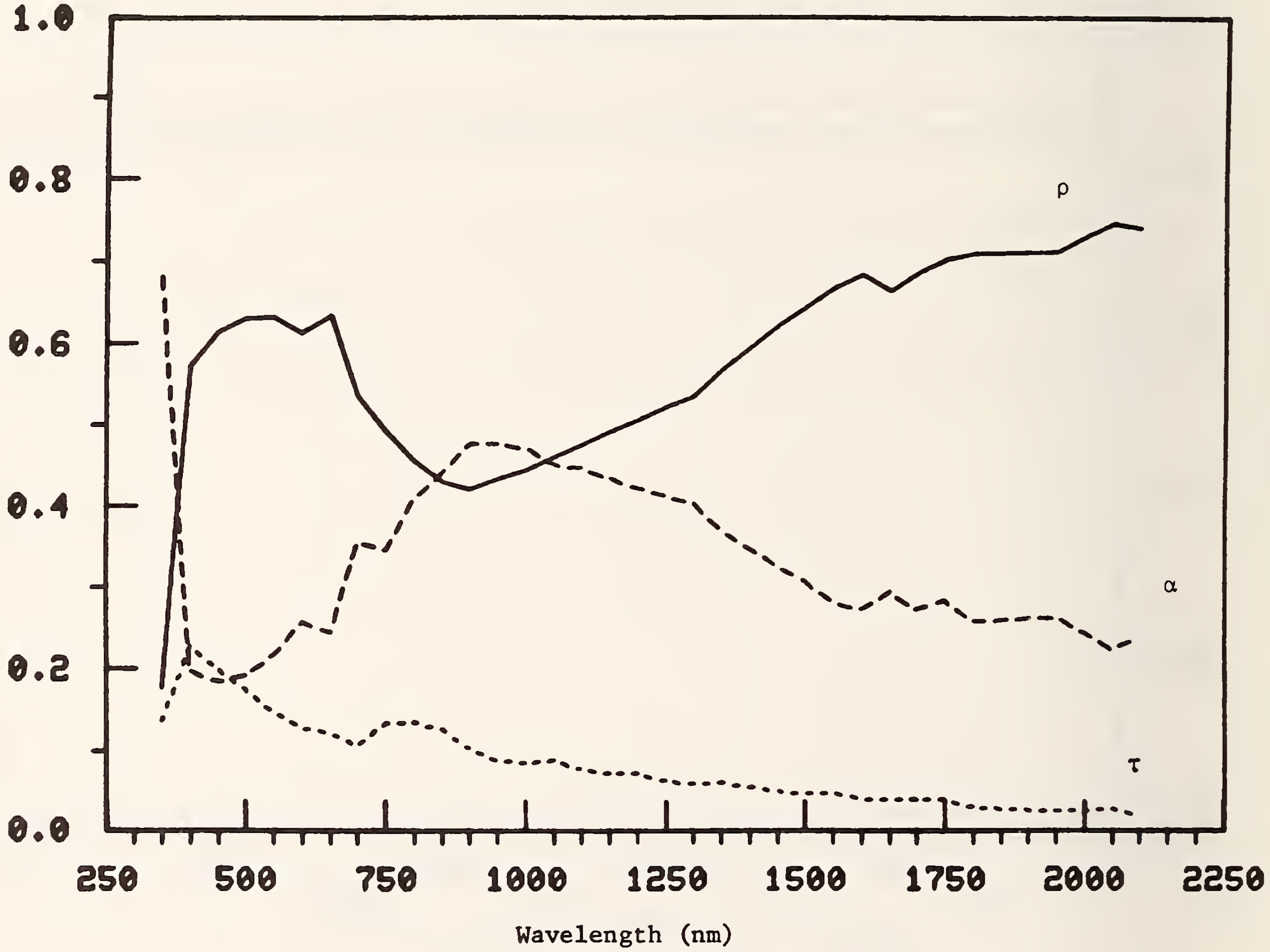

Figure 5a Measured spectral transmittance τ, reflectance ρ and absorptance α for film A

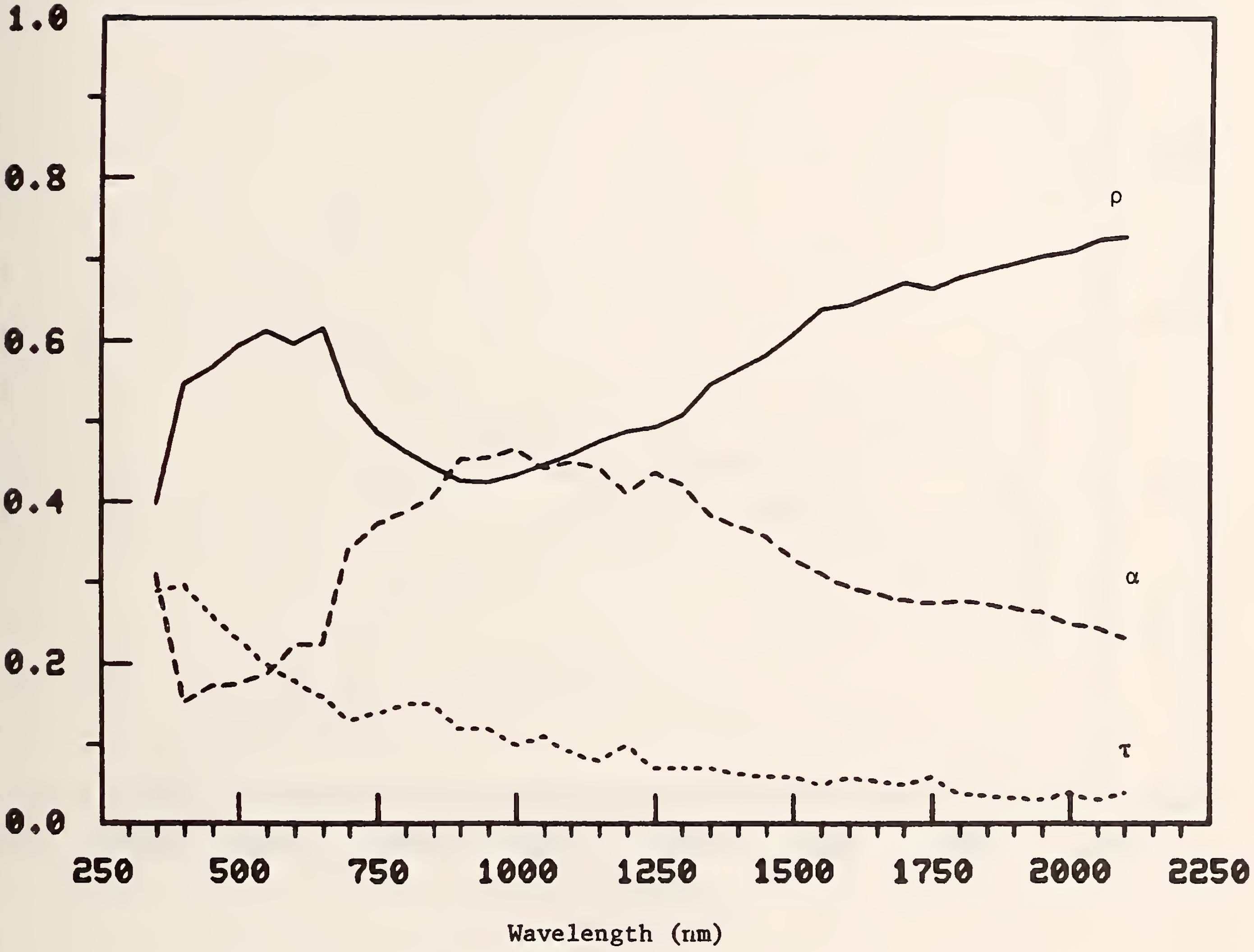

Figure 5b Measured spectral transmittance τ, reflectance ρ and absorptance α for film B

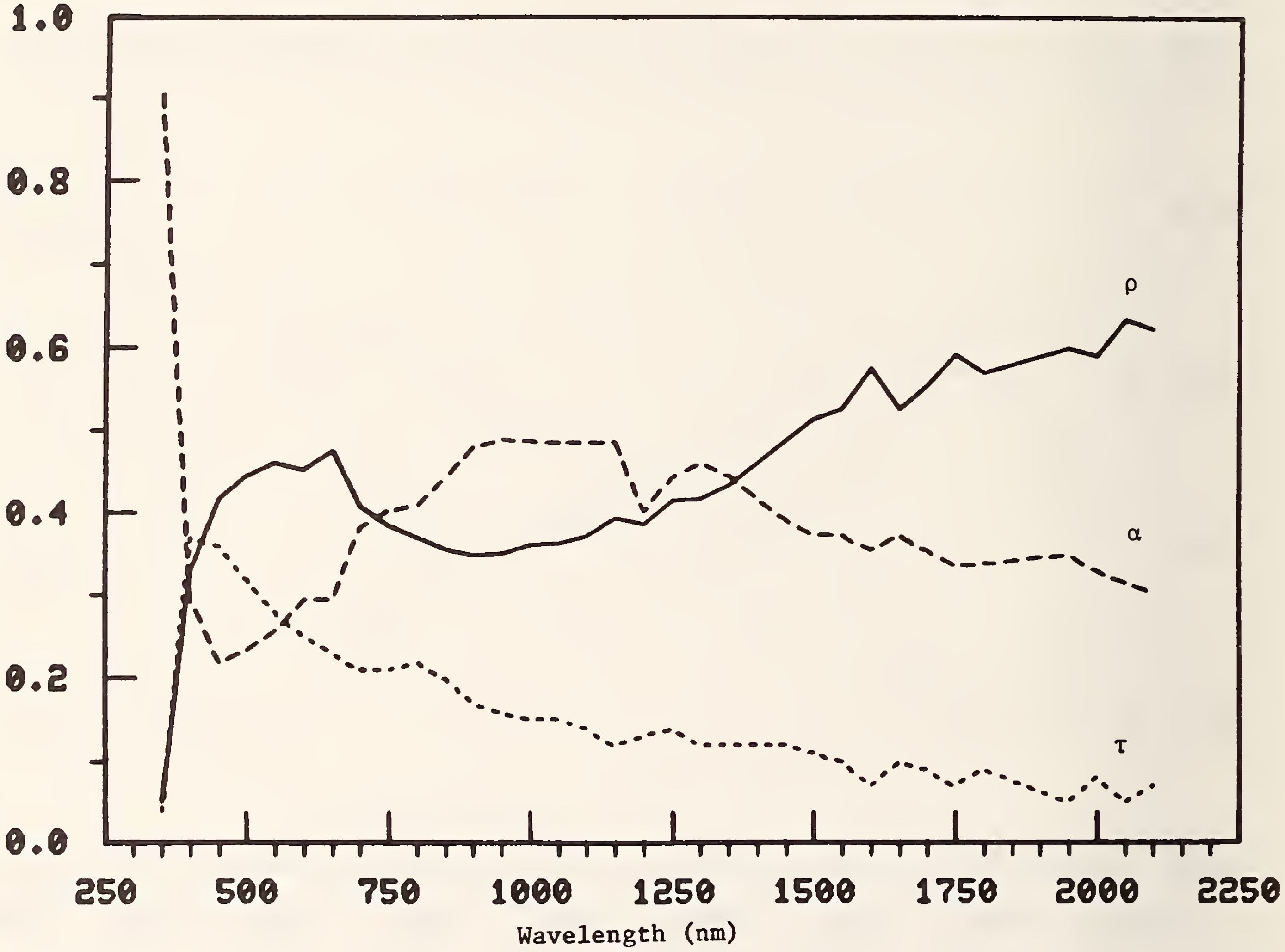

Figure 5c Measured spectral transmittance τ, reflectance ρ and absorptance α for film C

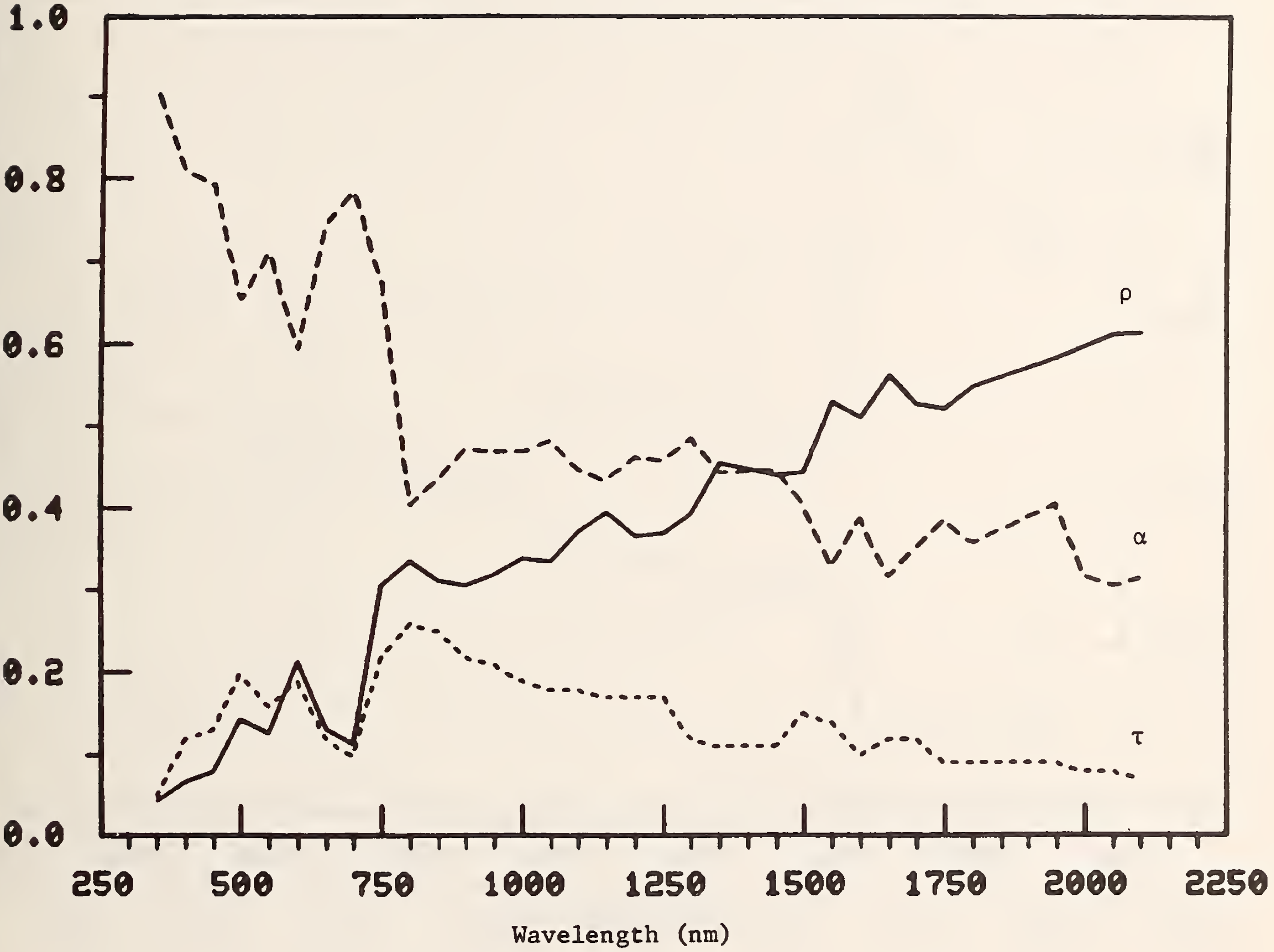

Figure 5d Measured spectral transmittance τ, reflectance ρ and absorptance α for film D

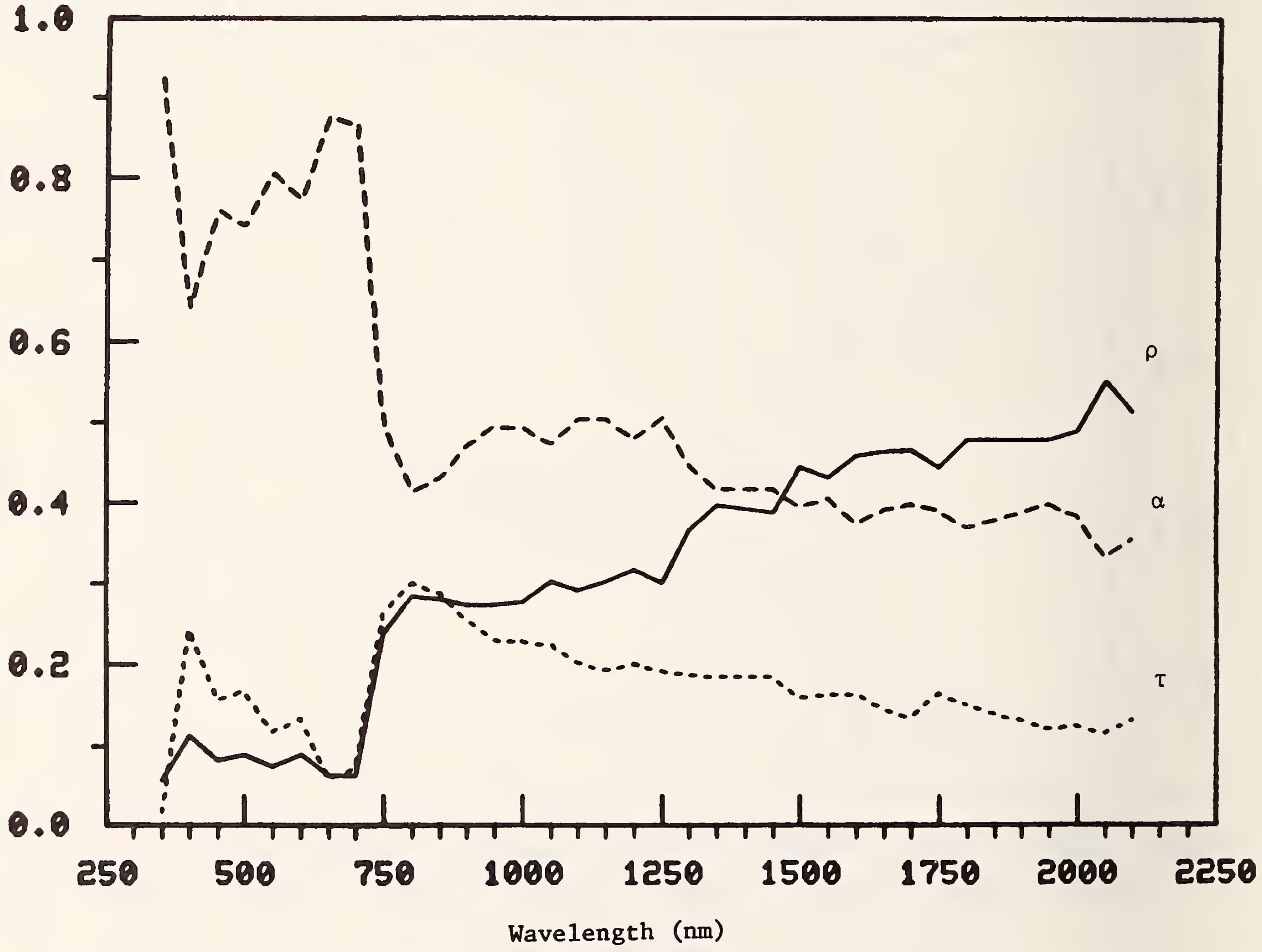

Figure 5e Measured spectral transmittance τ, reflectance ρ and absorptance α for film E

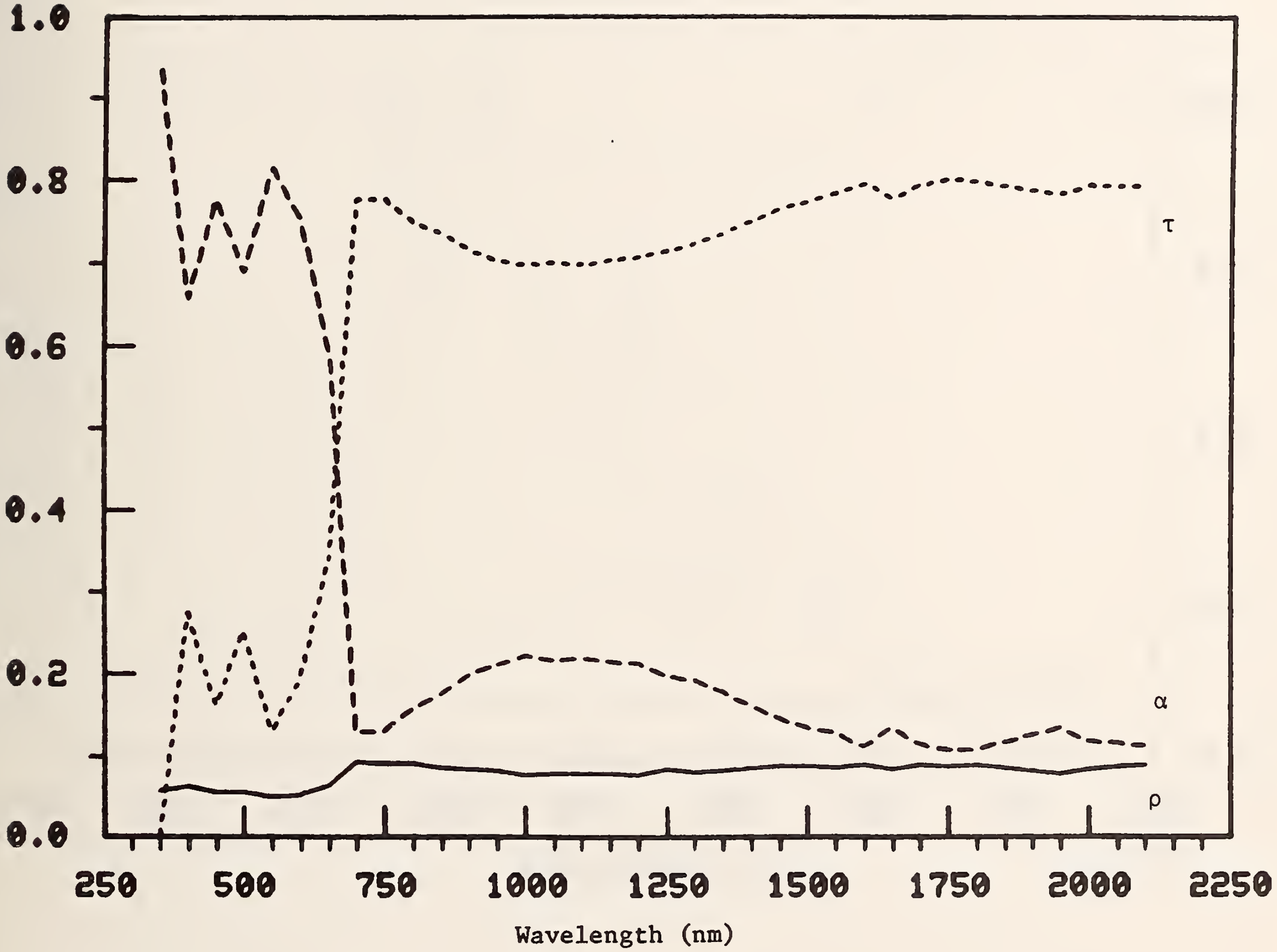

Figure 5f Measured spectral transmittance τ, reflectance α and absorptance α for film F

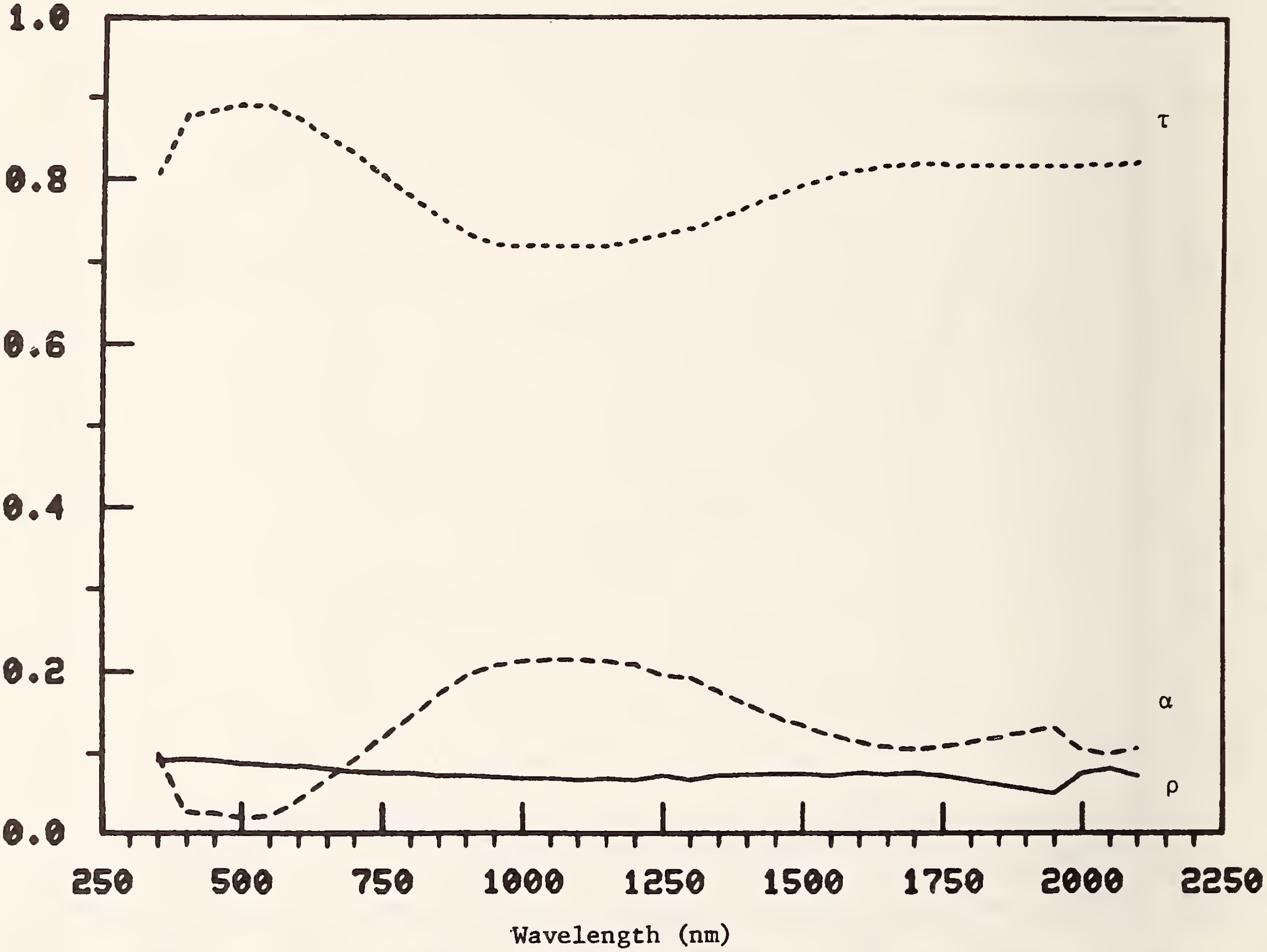

Figure 5g Measured spectral transmittance τ, reflectance α and absorptance α for clear glass

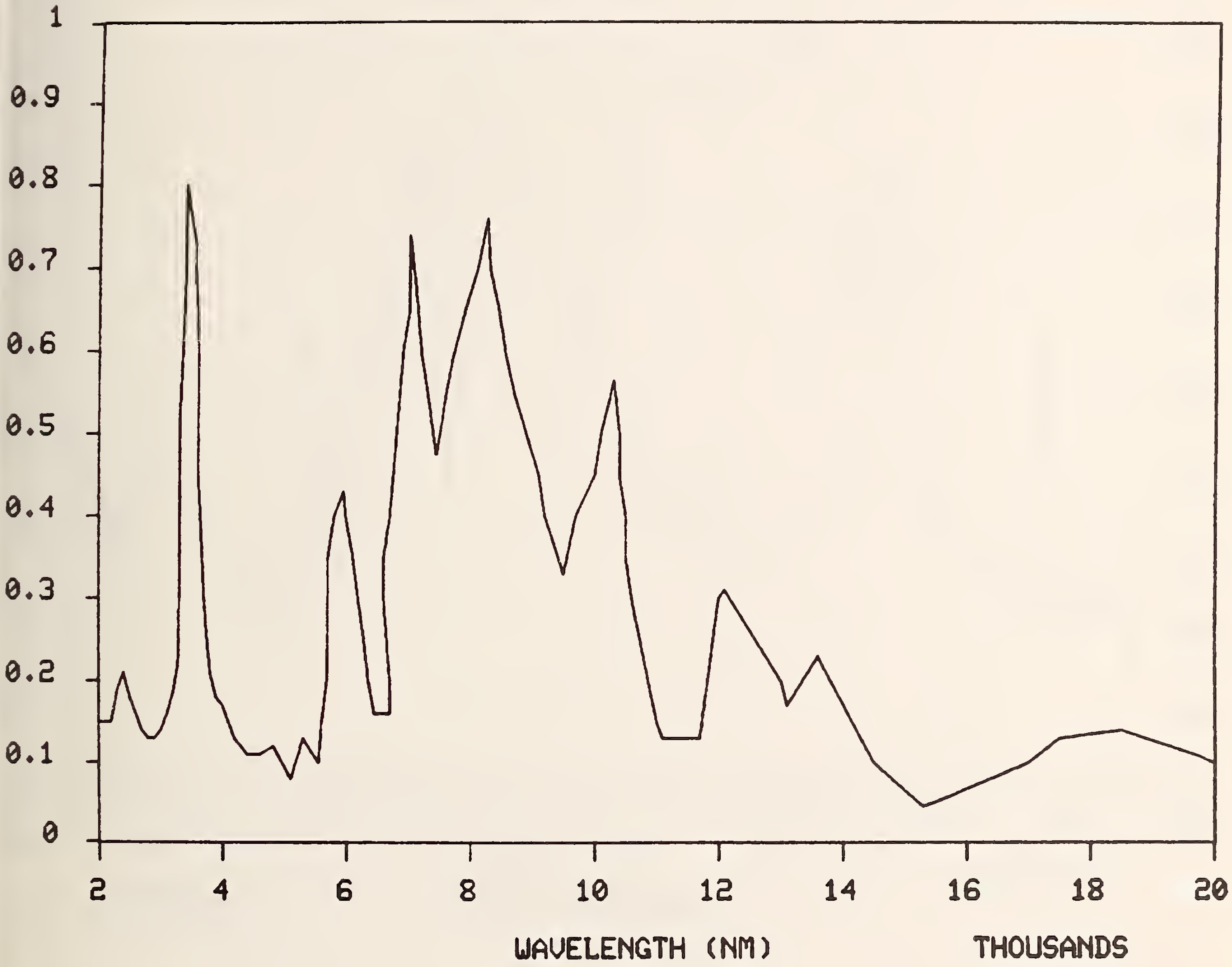

Figure 5h Measured spectral emittance for film A

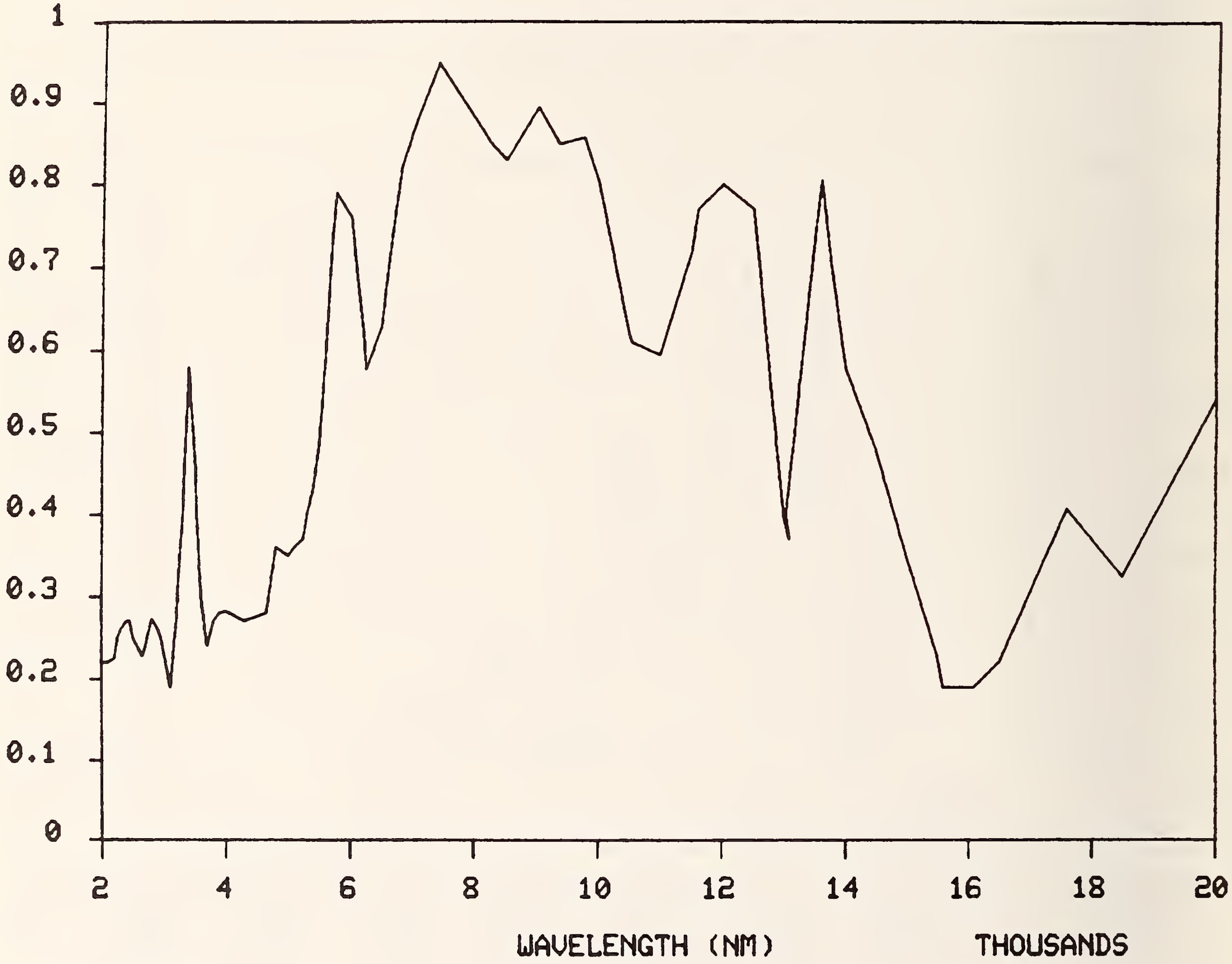

Figure 5i Measured spectral emittance for film B

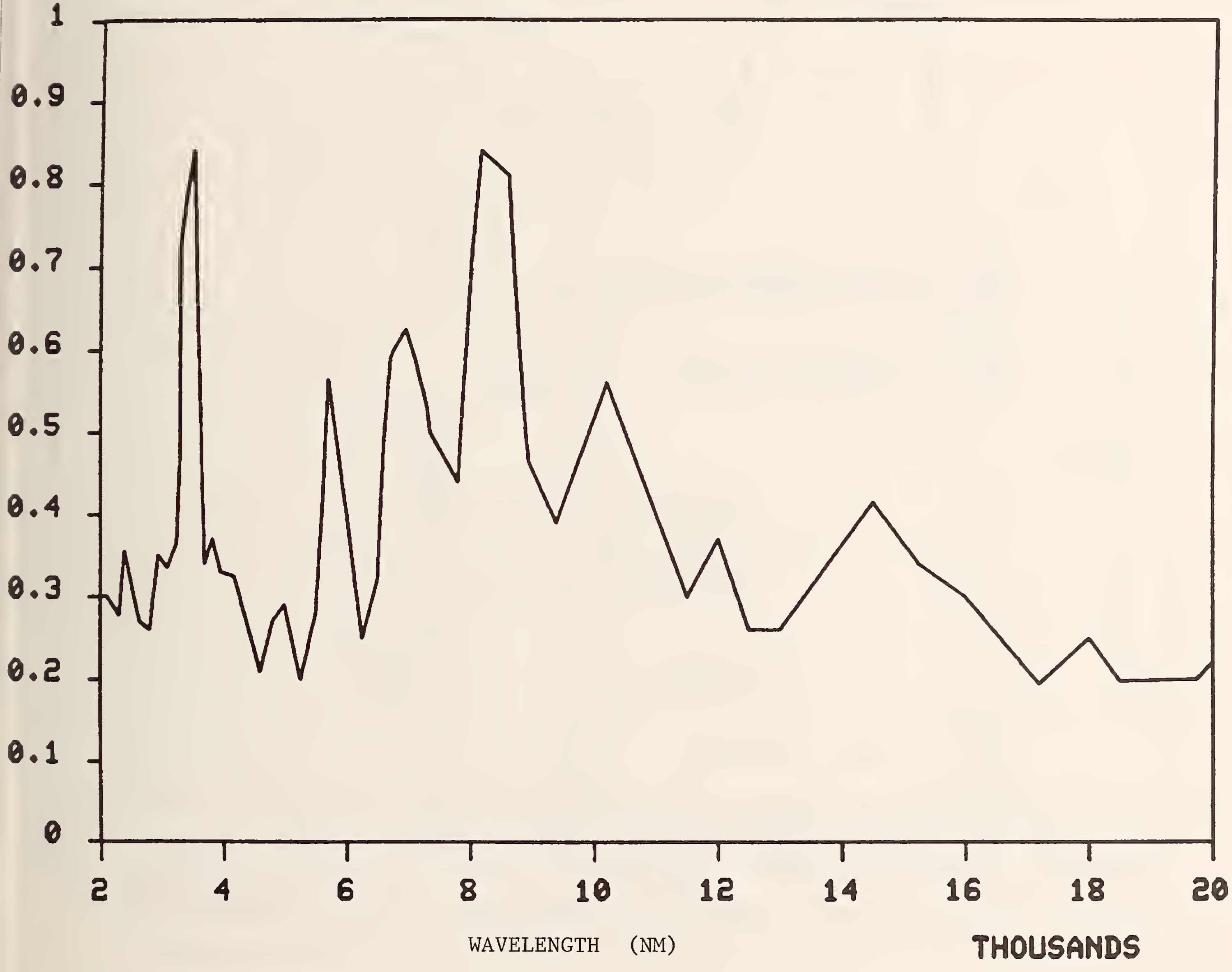

Figure 5j Measured spectral emittance for film C

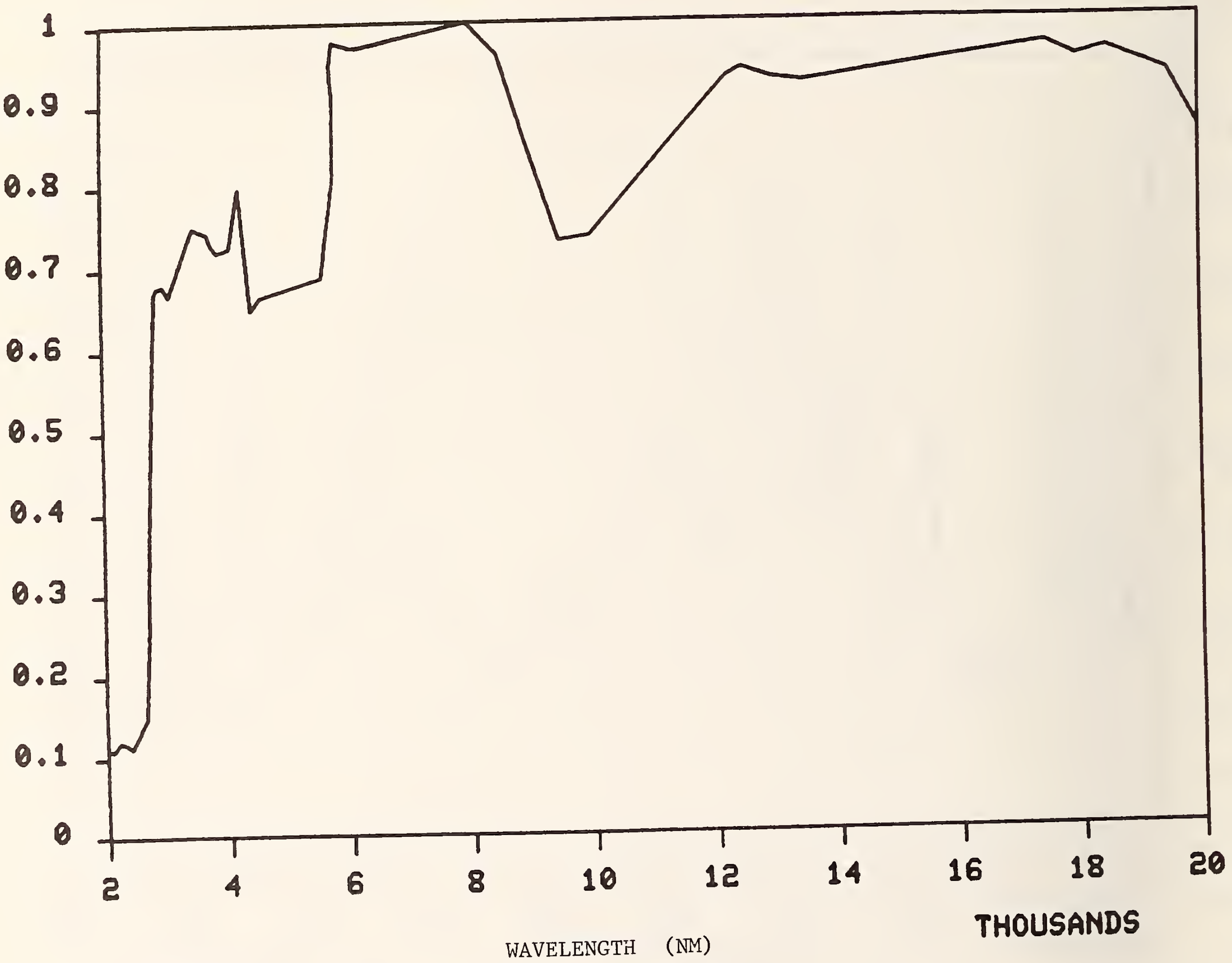

Figure 5k Measured spectral emittance for clear glass

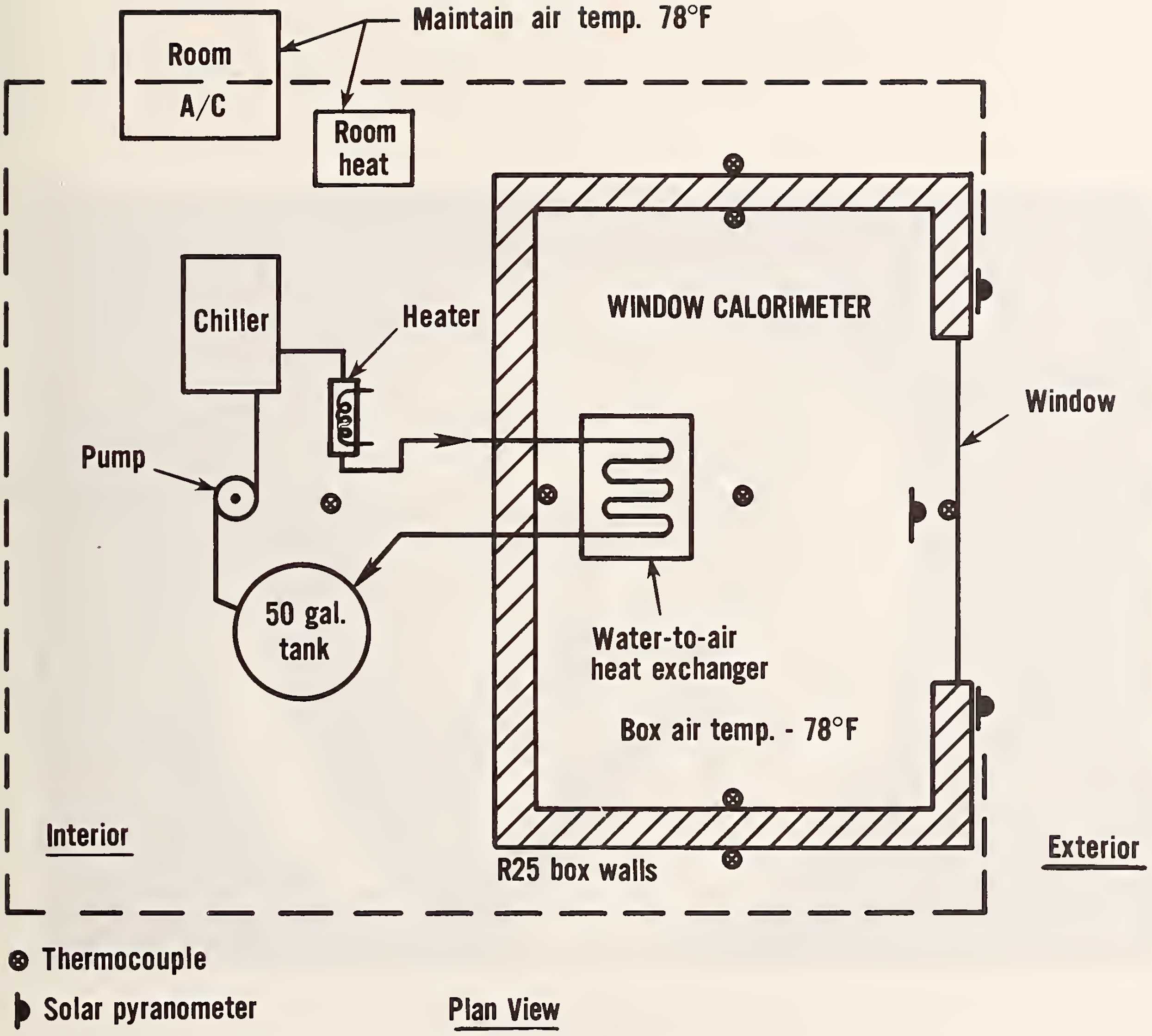

Figure 6 Schematic diagram of window calorimeter

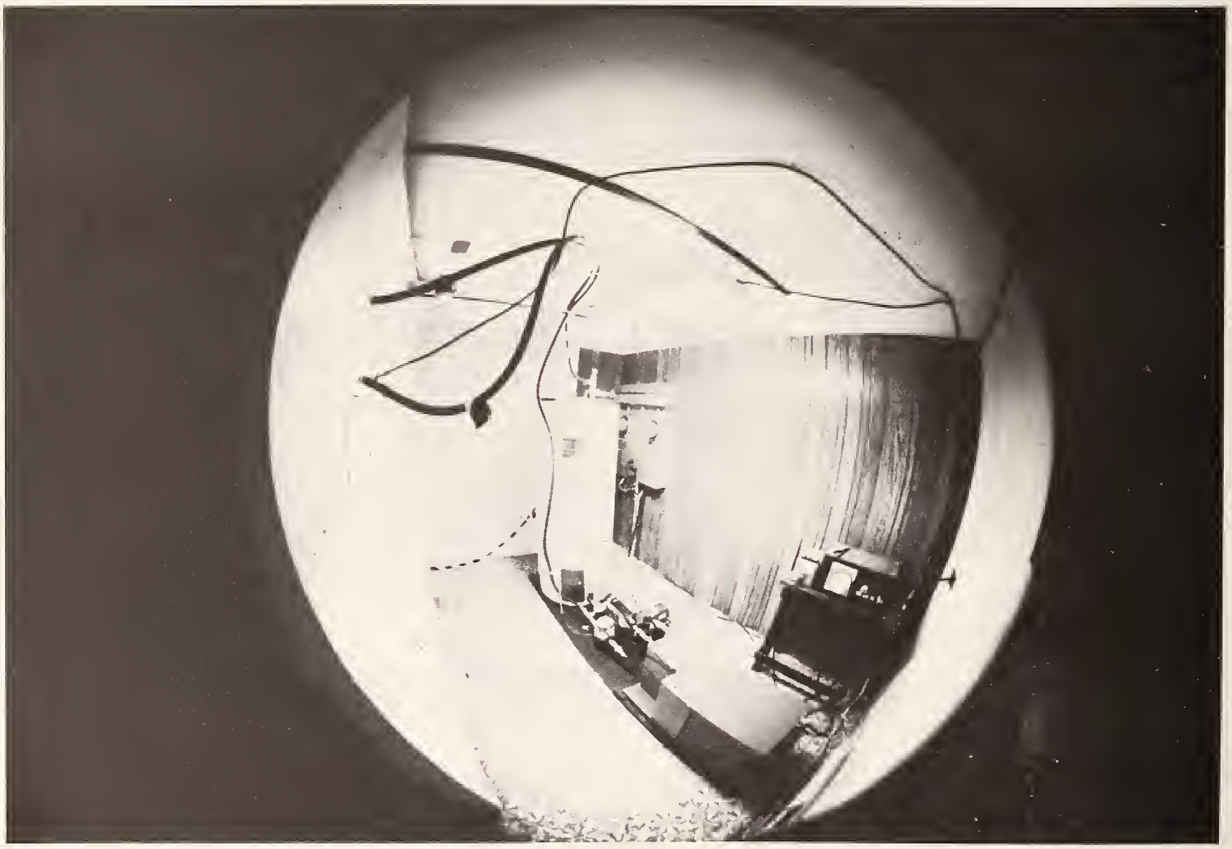

Figure 7 Photograph of window calorimeter apparatus

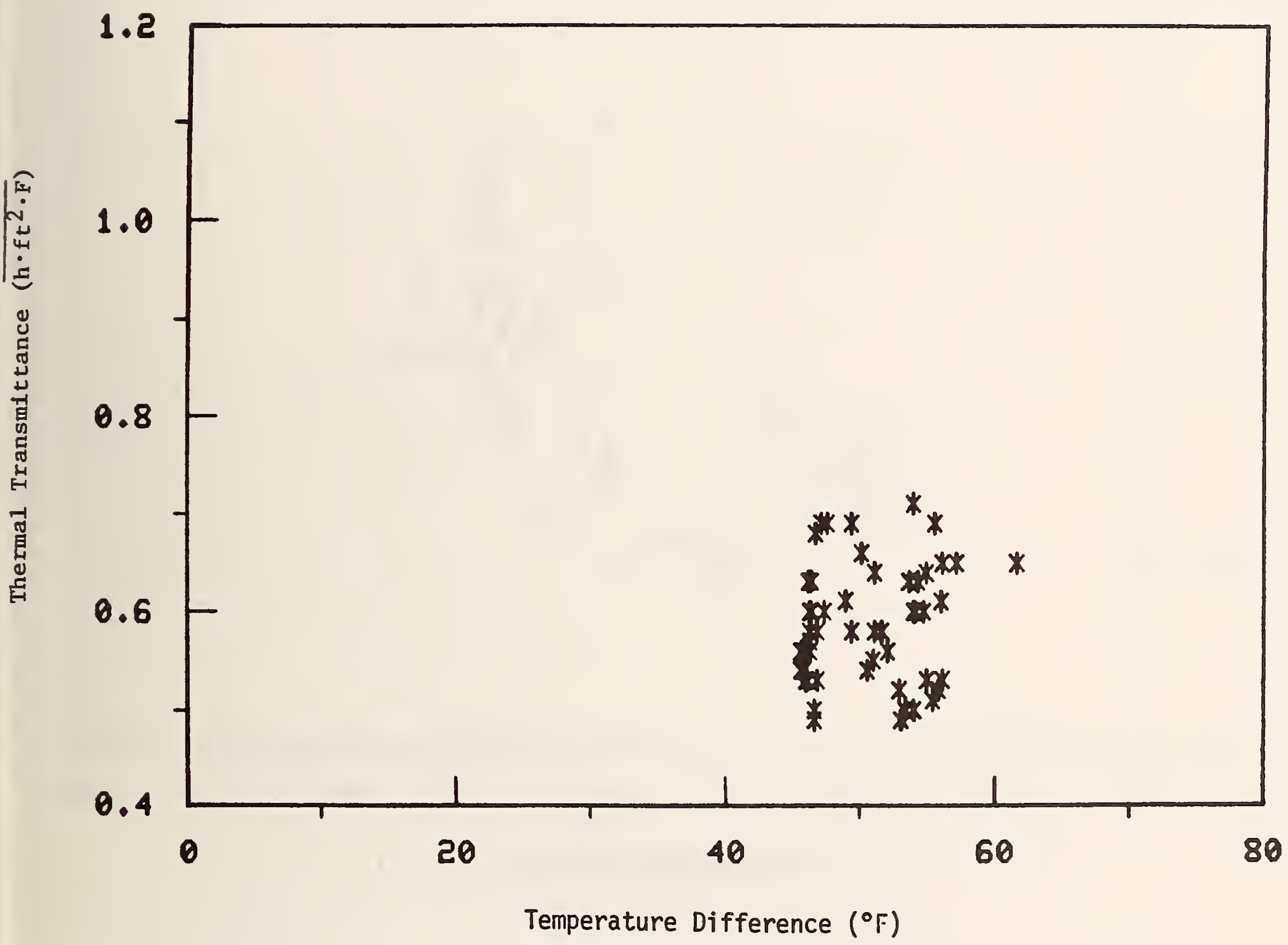

Figure 8a Measured thermal transmittance (U-value) as a function of inside-to-outside air temperature difference for film A

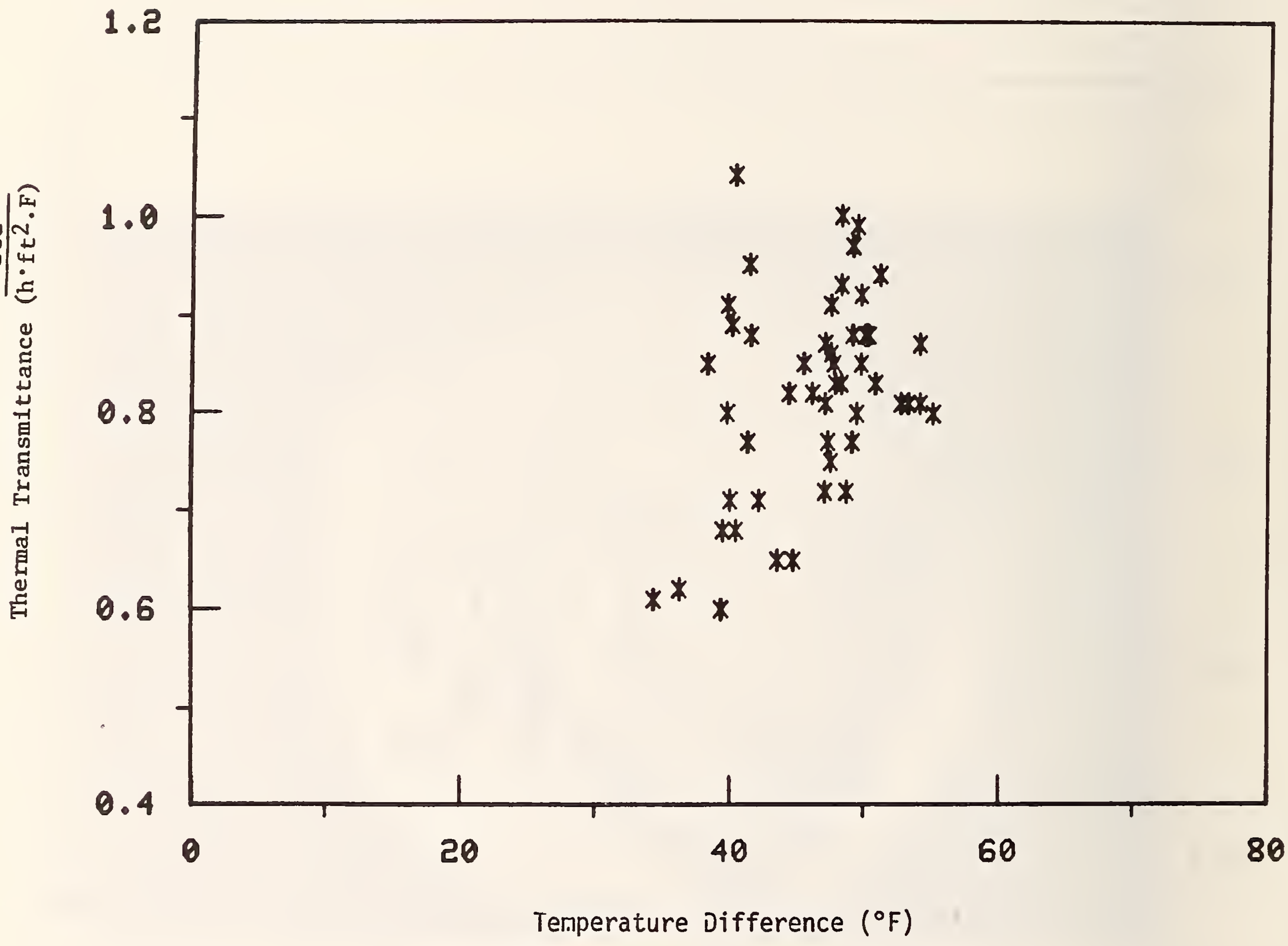

Figure 8b Measured thermal transmittance (U-value) as a function of inside-to-outside air temperature difference for film B

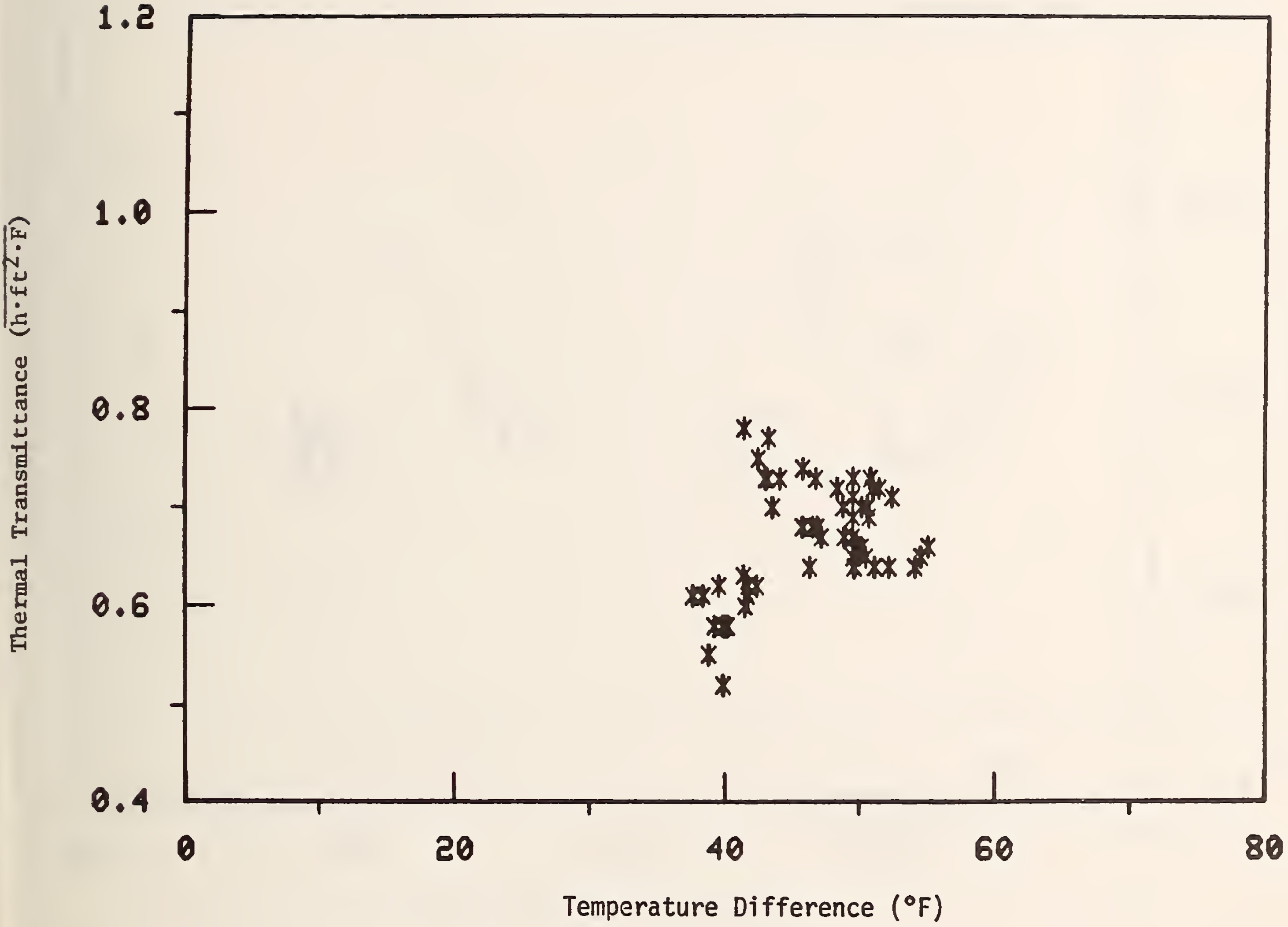

Figure 8c Measured thermal transmittance (U-value) as a function of inside-to-outside air temperature difference for film C

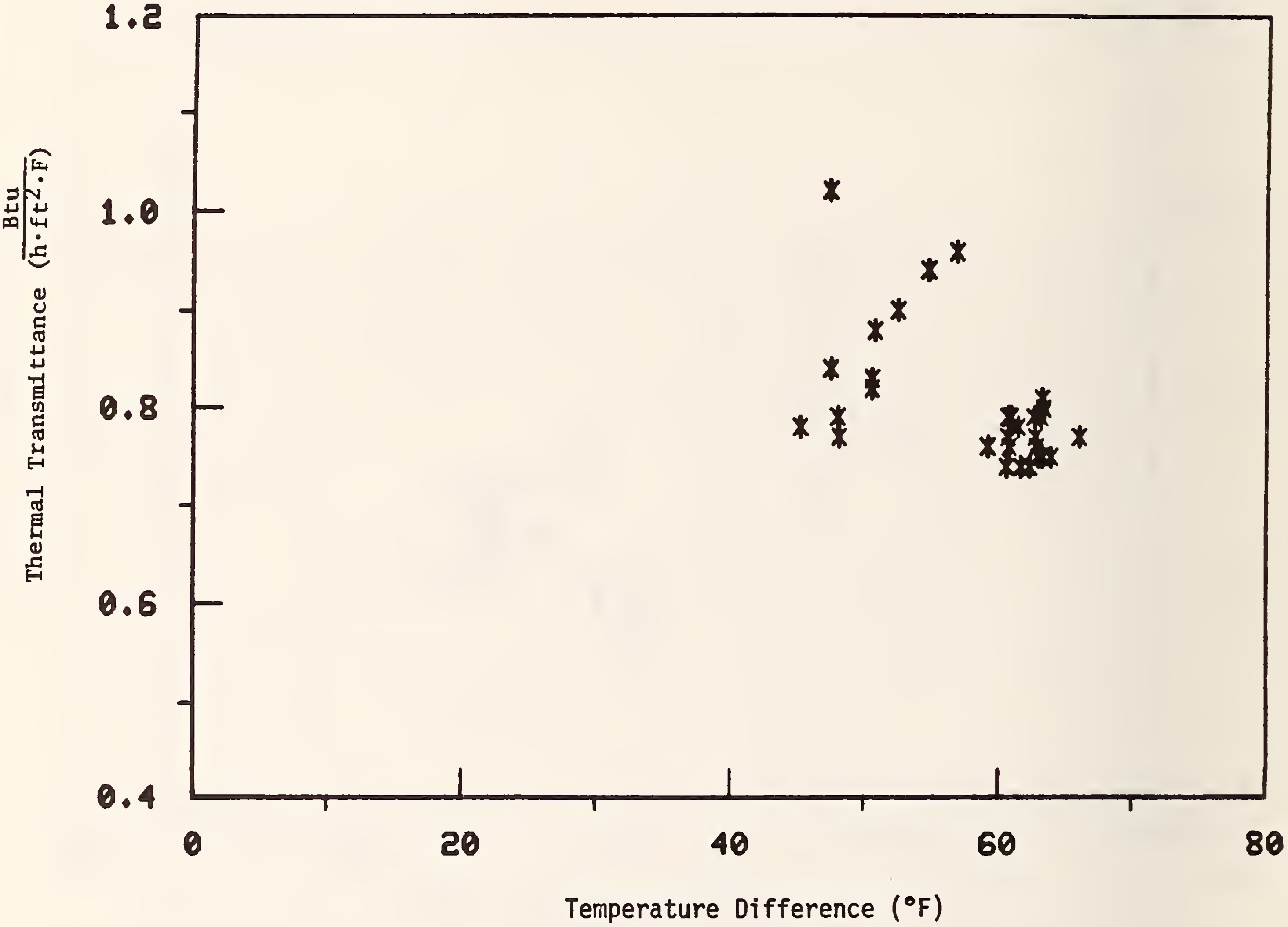

Figure 8d Measured thermal transmittance (U-value) as a function of inside-to-outside air temperature difference for film D

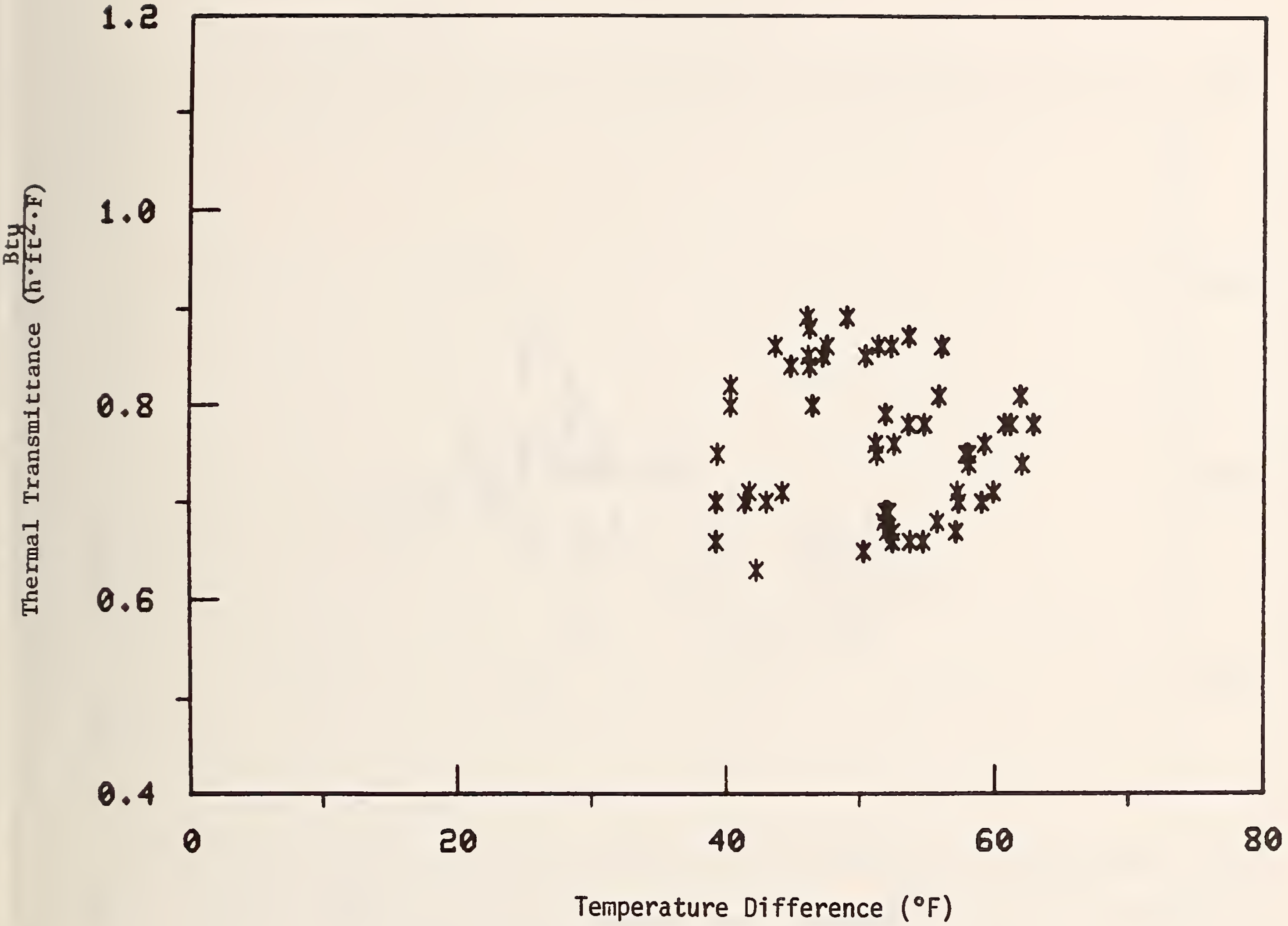

Figure 8e Measured thermal transmittance (U-value) as a function of inside-to-outside air temperature difference for film E

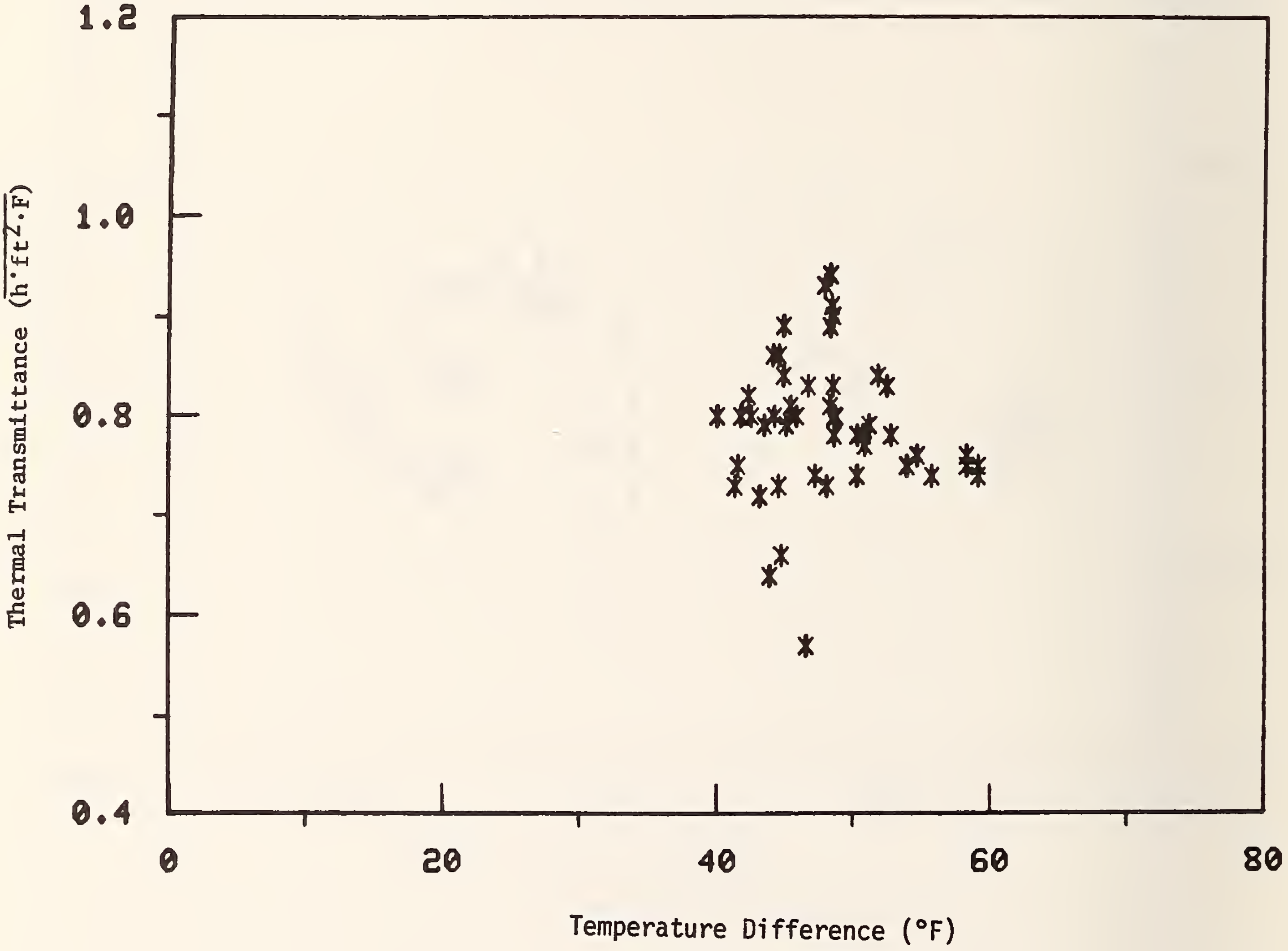

Figure 8f Measured thermal transmittance (U-value) as a function of inside-to-outside air temperature difference for film F

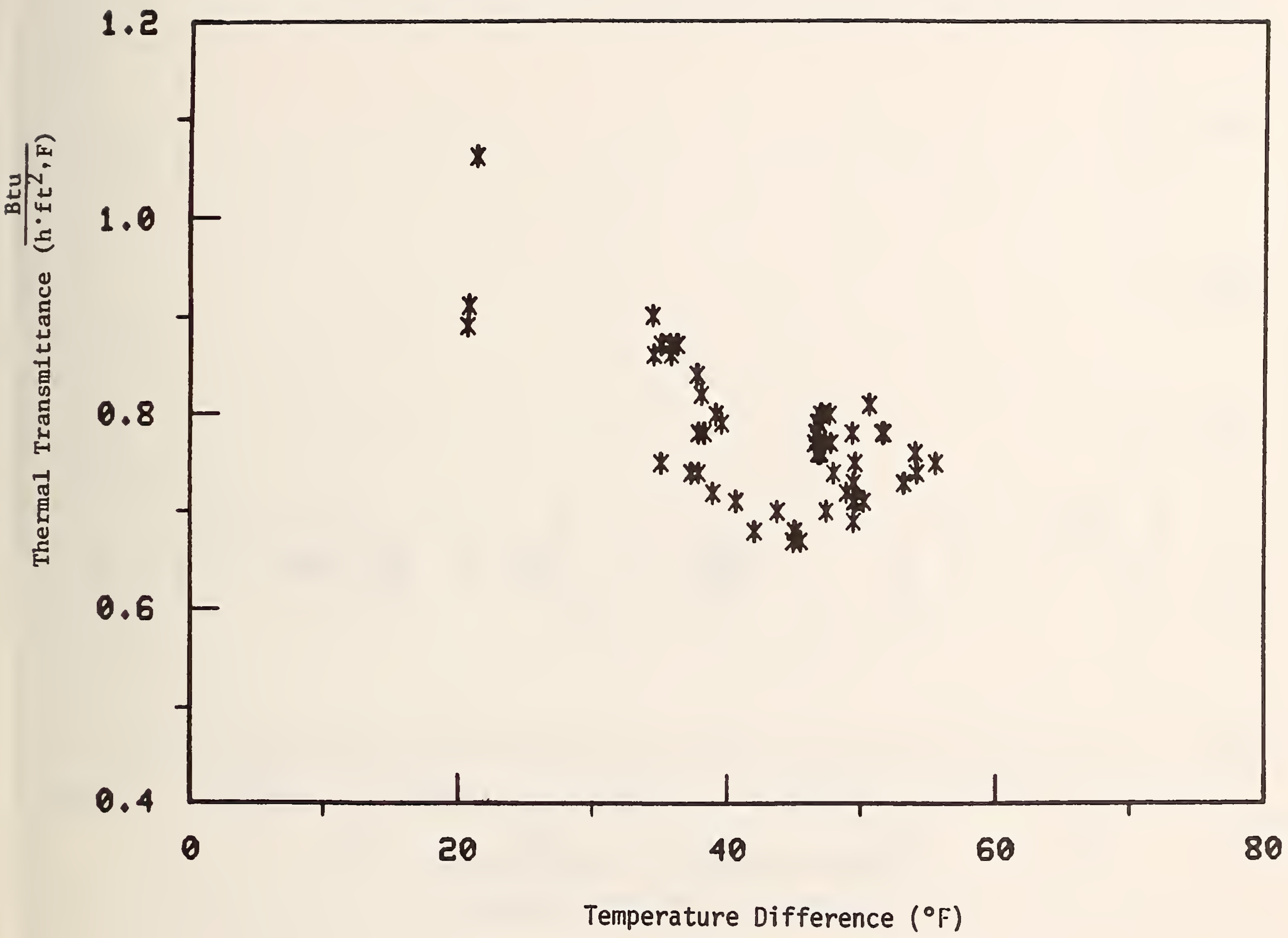

Figure 8g Measured thermal transmittance (U-value) as a function of inside-to-outside air temperature difference for clear glass

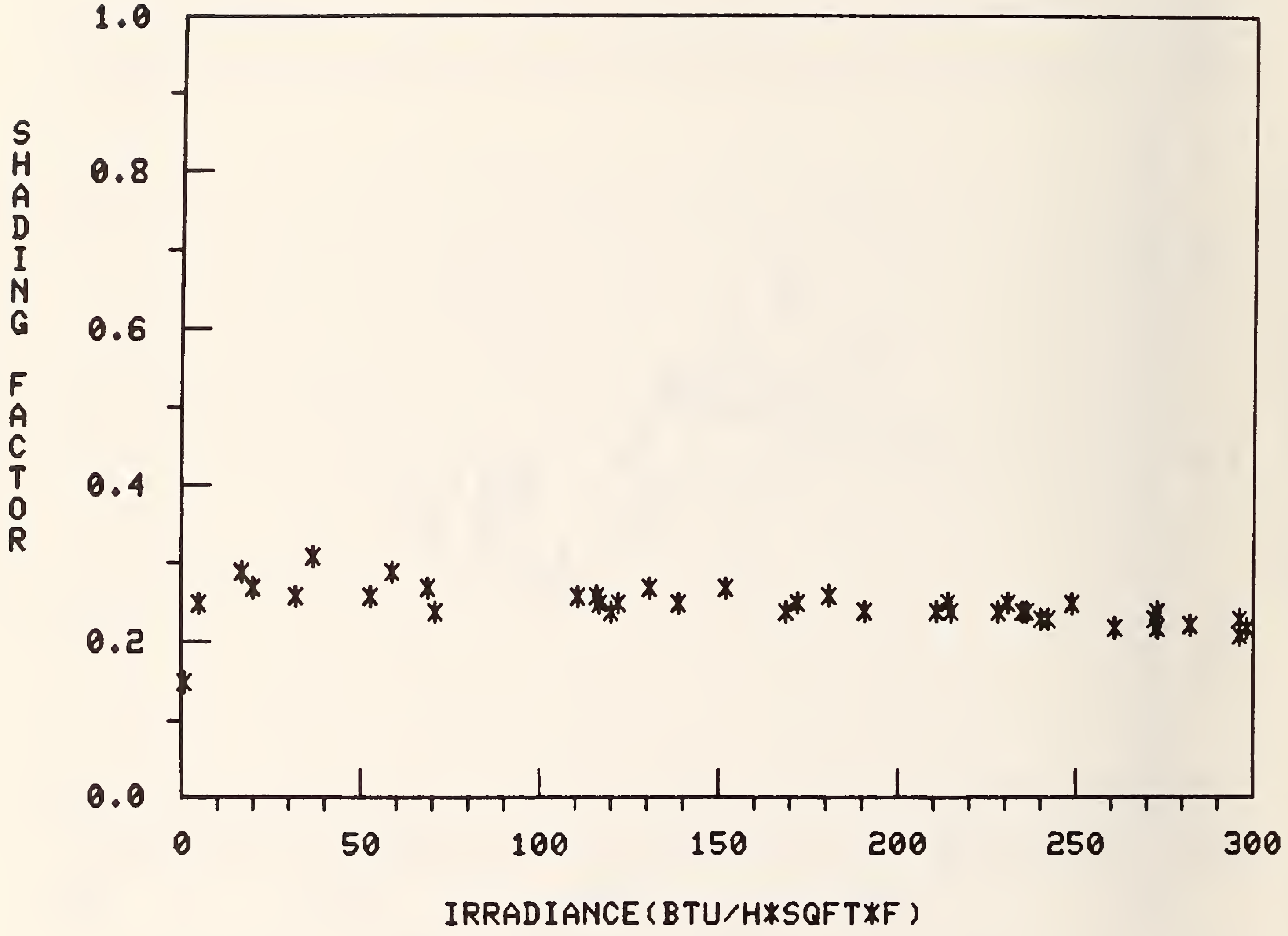

Figure 9a Measured shading factor as a function of level of incident irradiance for film A

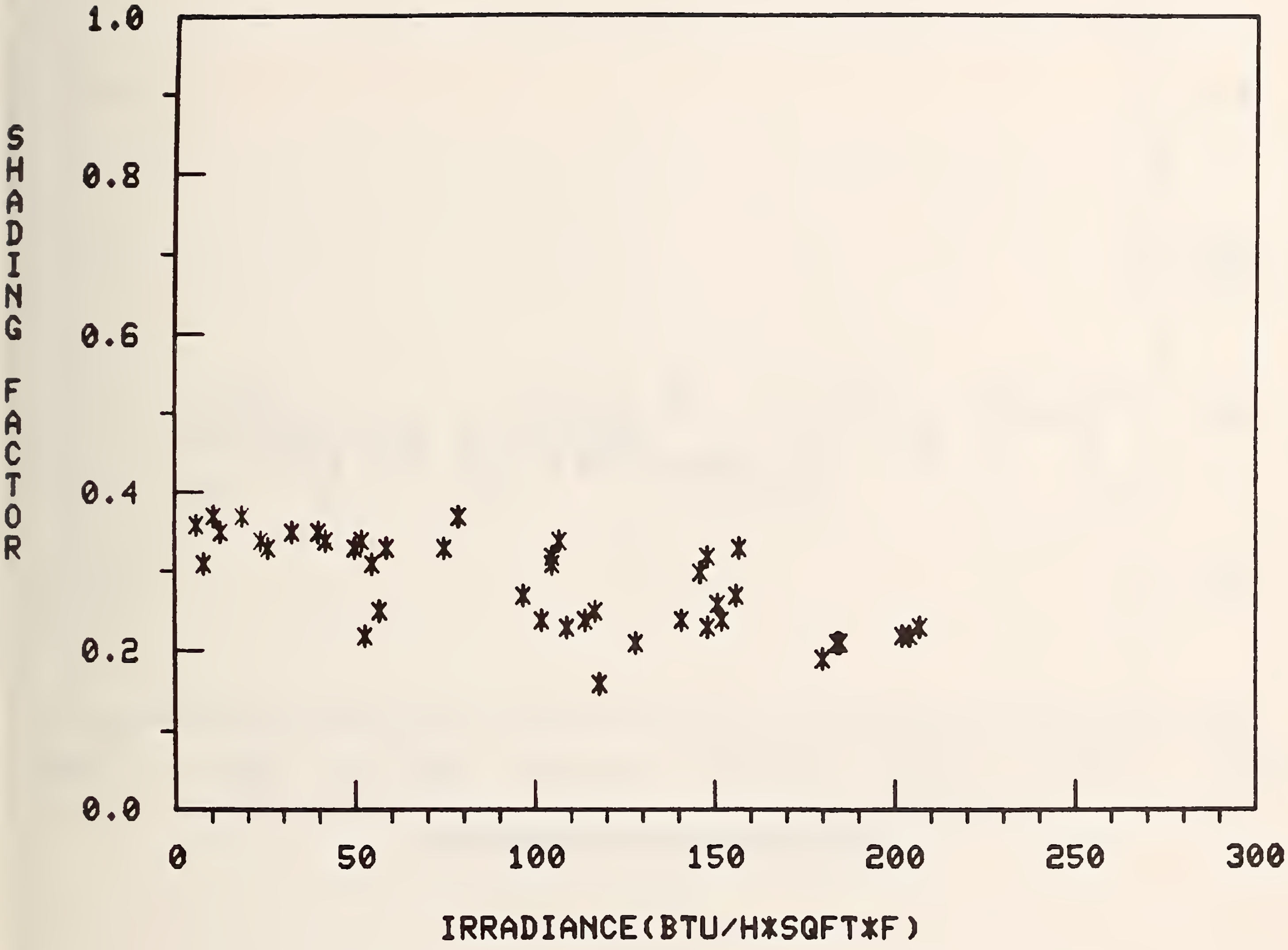

Figure 9b Measured shading factor as a function of level of incident irradiance for film B

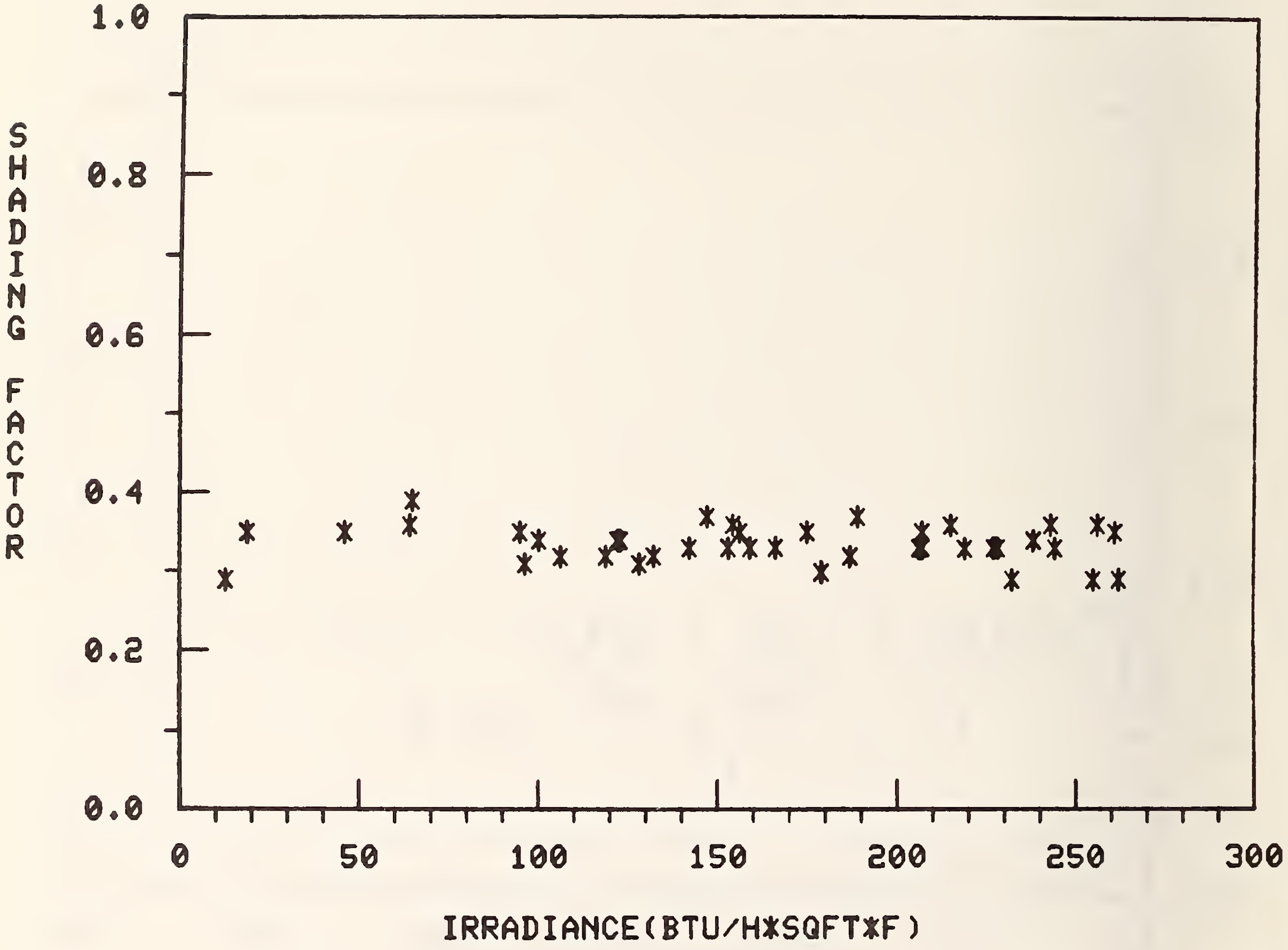

Figure 9c Measured shading factor as a function of level of incident irradiance for film C

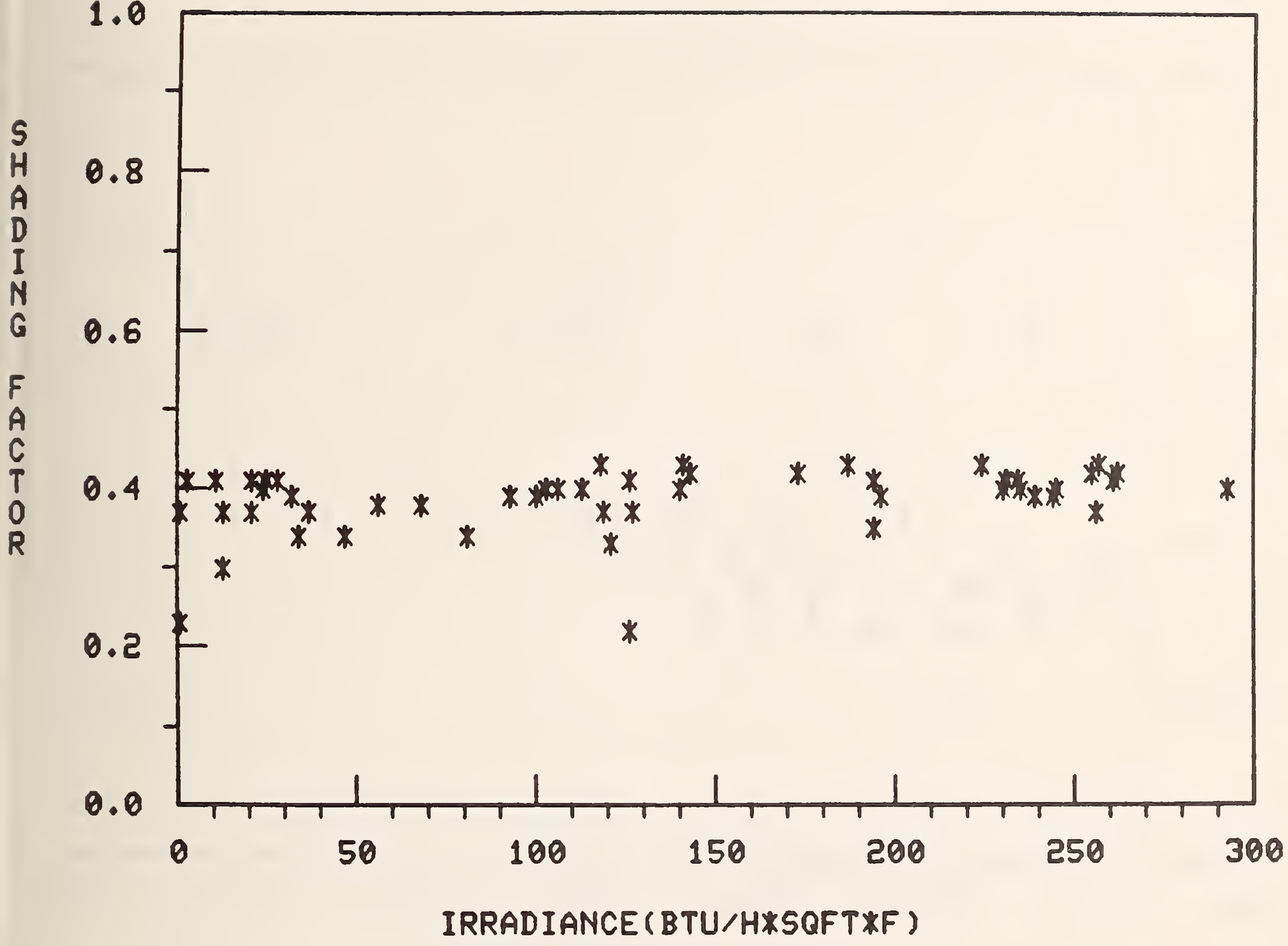

Figure 9d Measured shading factor as a function of level of incident irradiance for film D

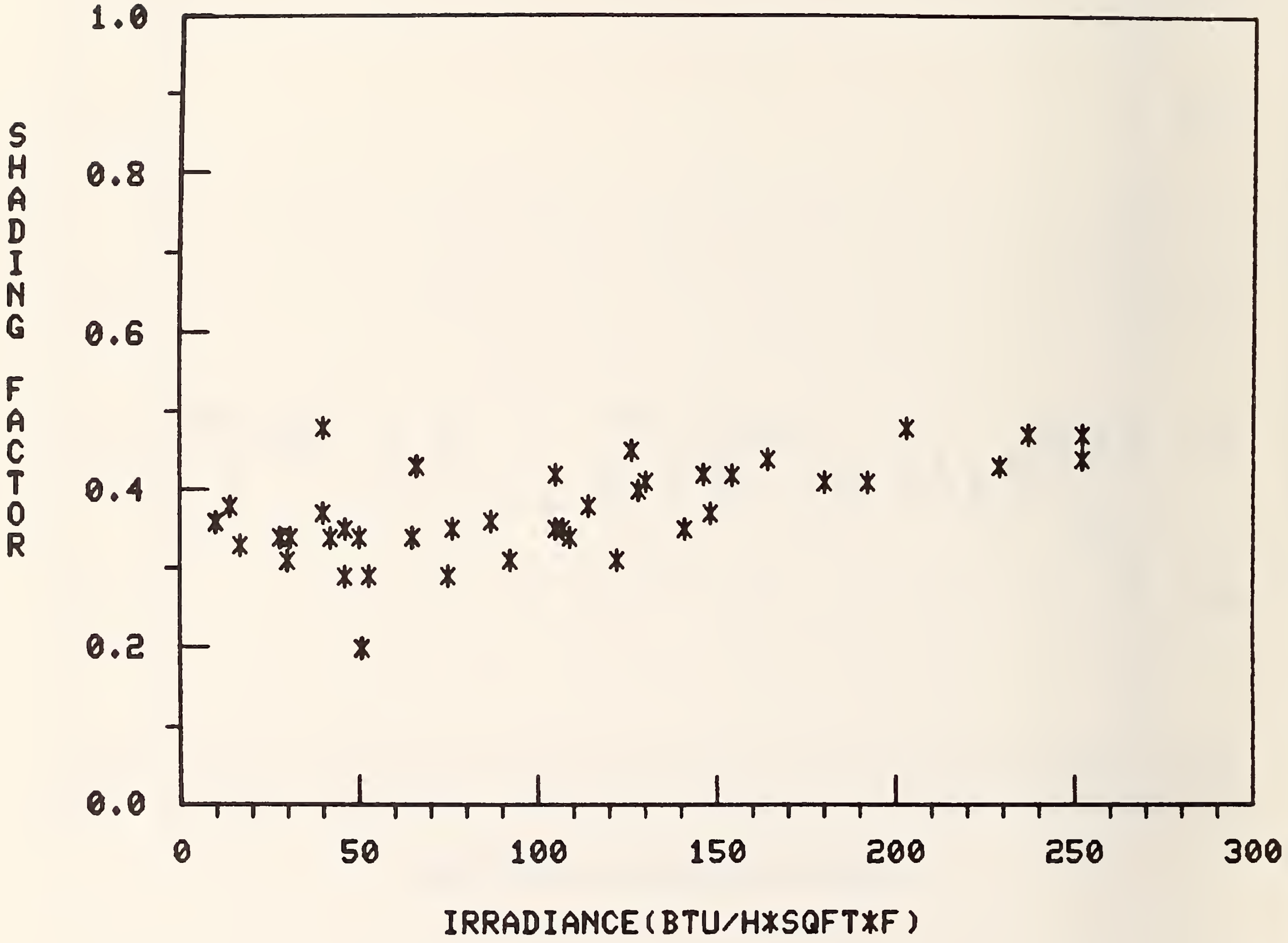

Figure 9e Measured shading factor as a function of level of incident irradiance for film E

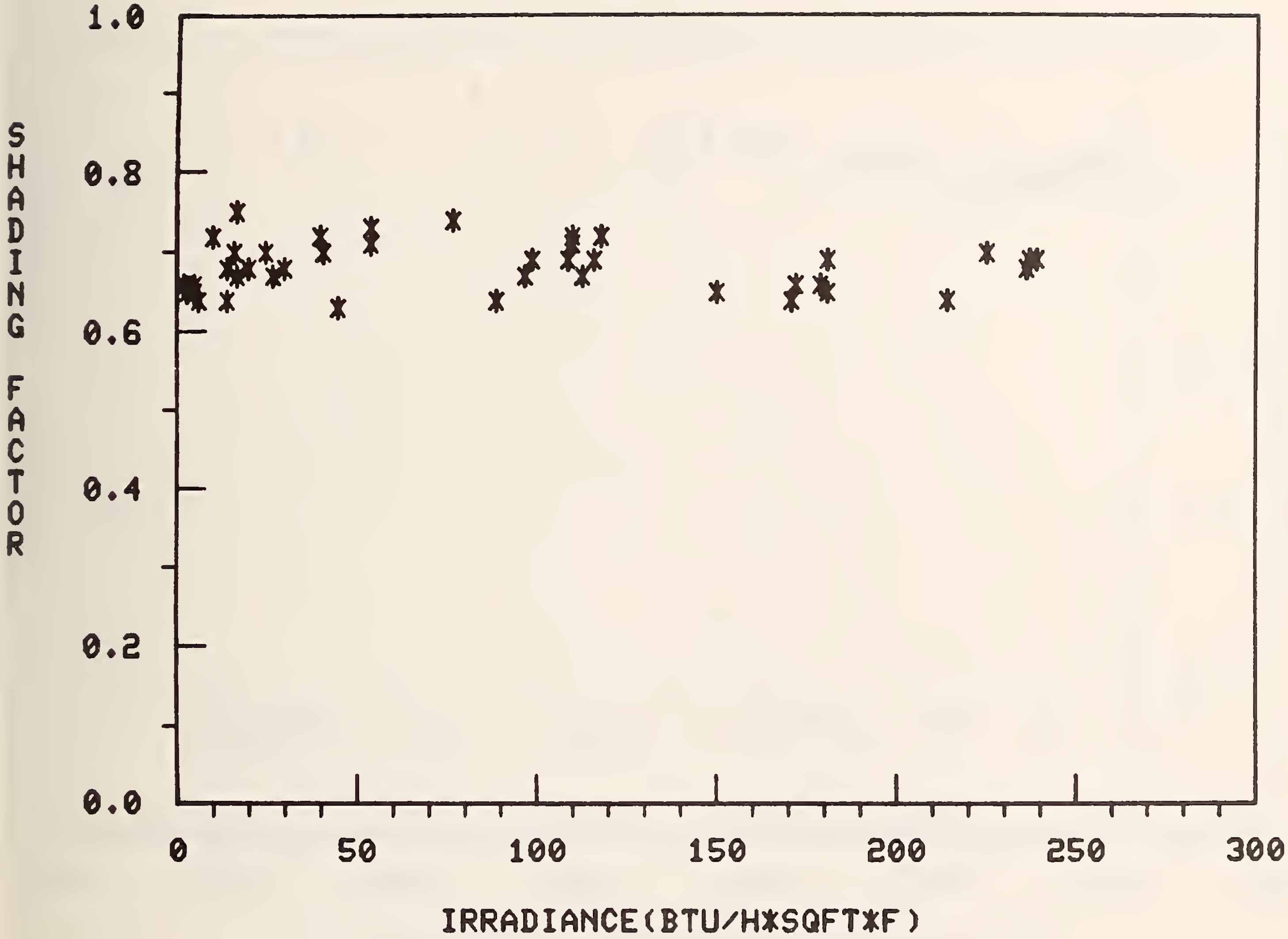

Figure 9f Measured shading factor as a function of level of incident irradiance for film F

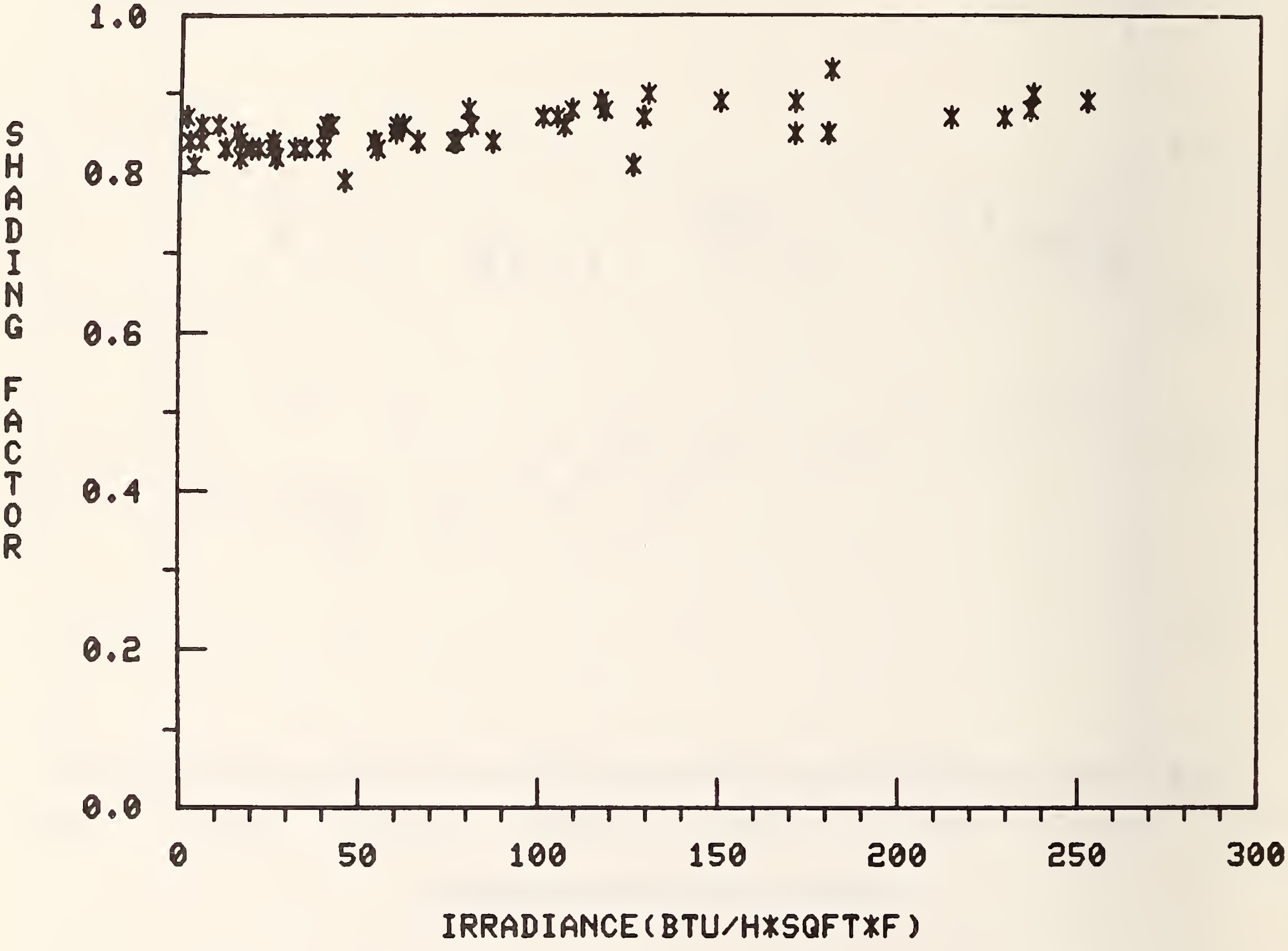

Figure 9g Measured shading factor as a function of level of incident irradiance for clear glass

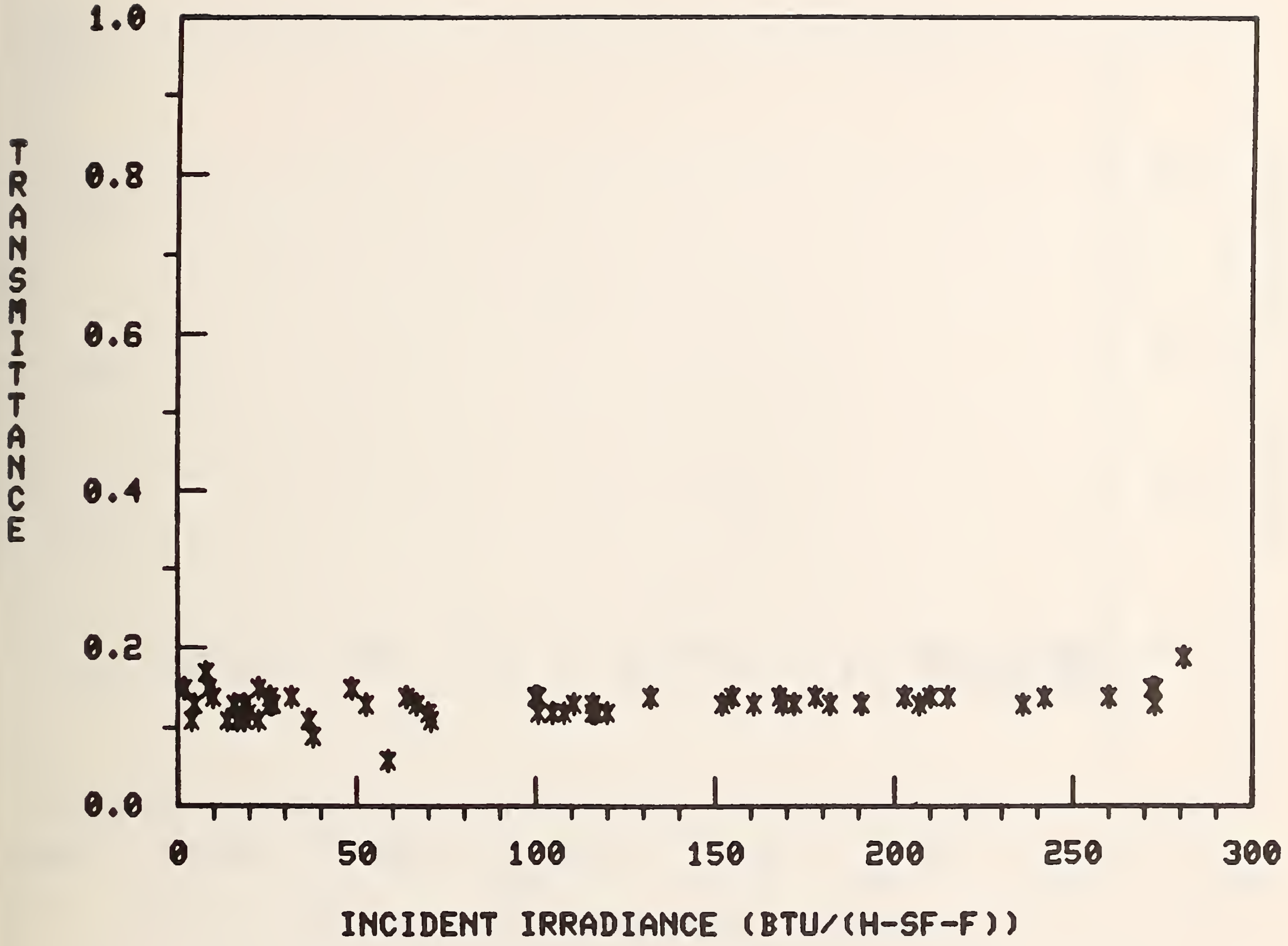

Figure 10a Measured solar transmittance as a function of level of incident irradiance for film A

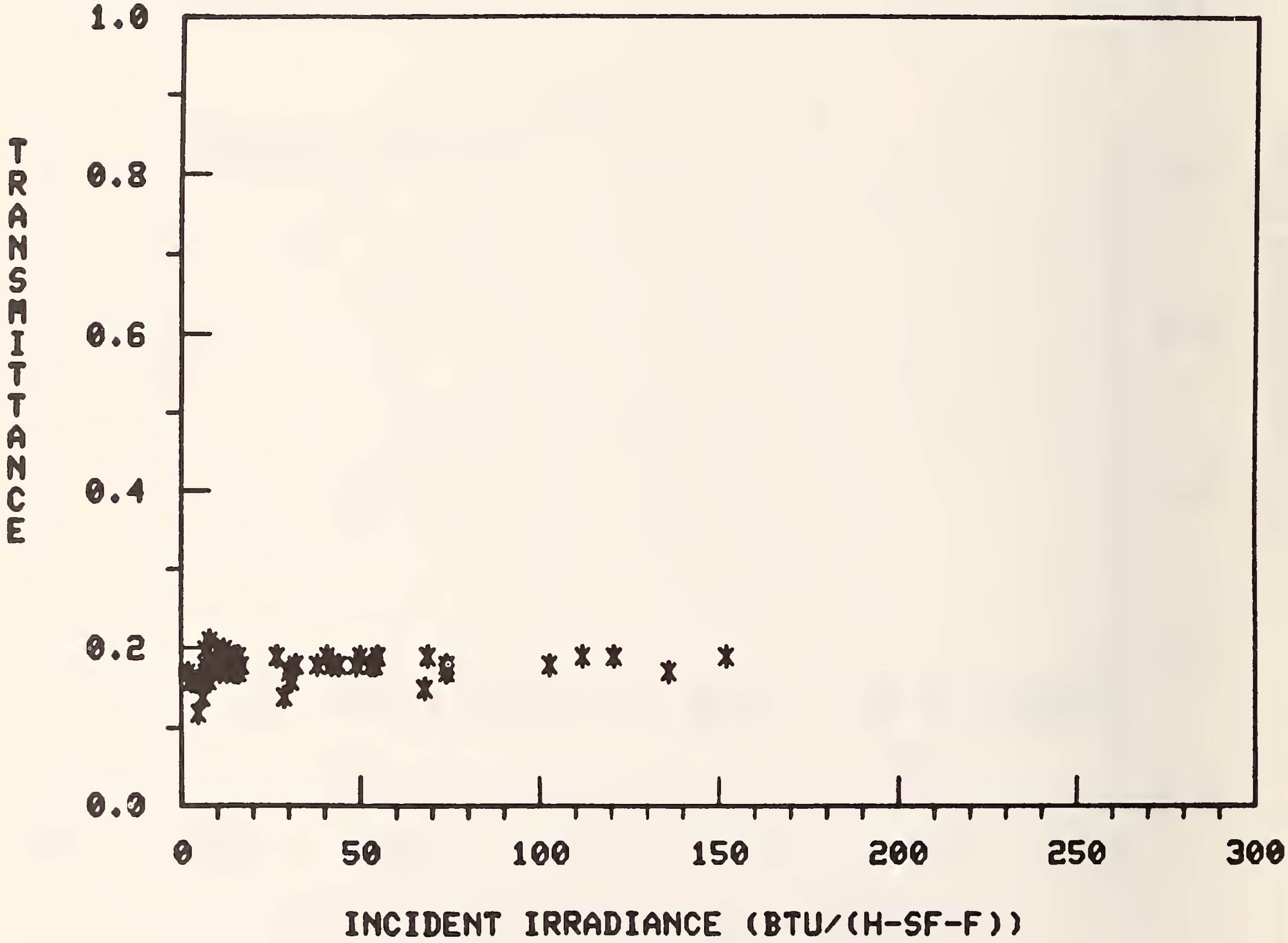

Figure 10b Measured solar transmittance as a function of level of incident irradiance for film B

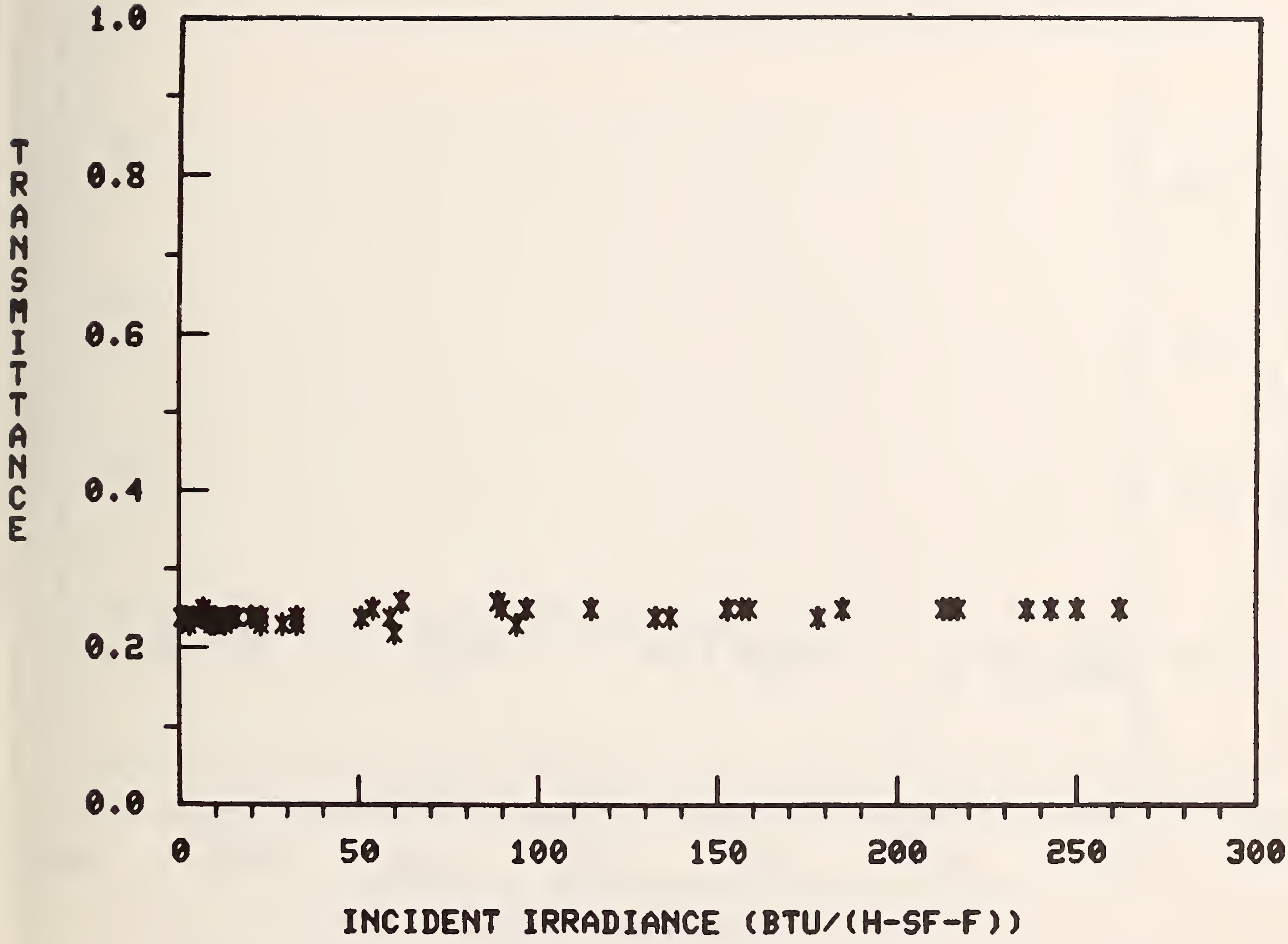

Figure 10c Measured solar transmittance as a function of level of incident irradiance for film C

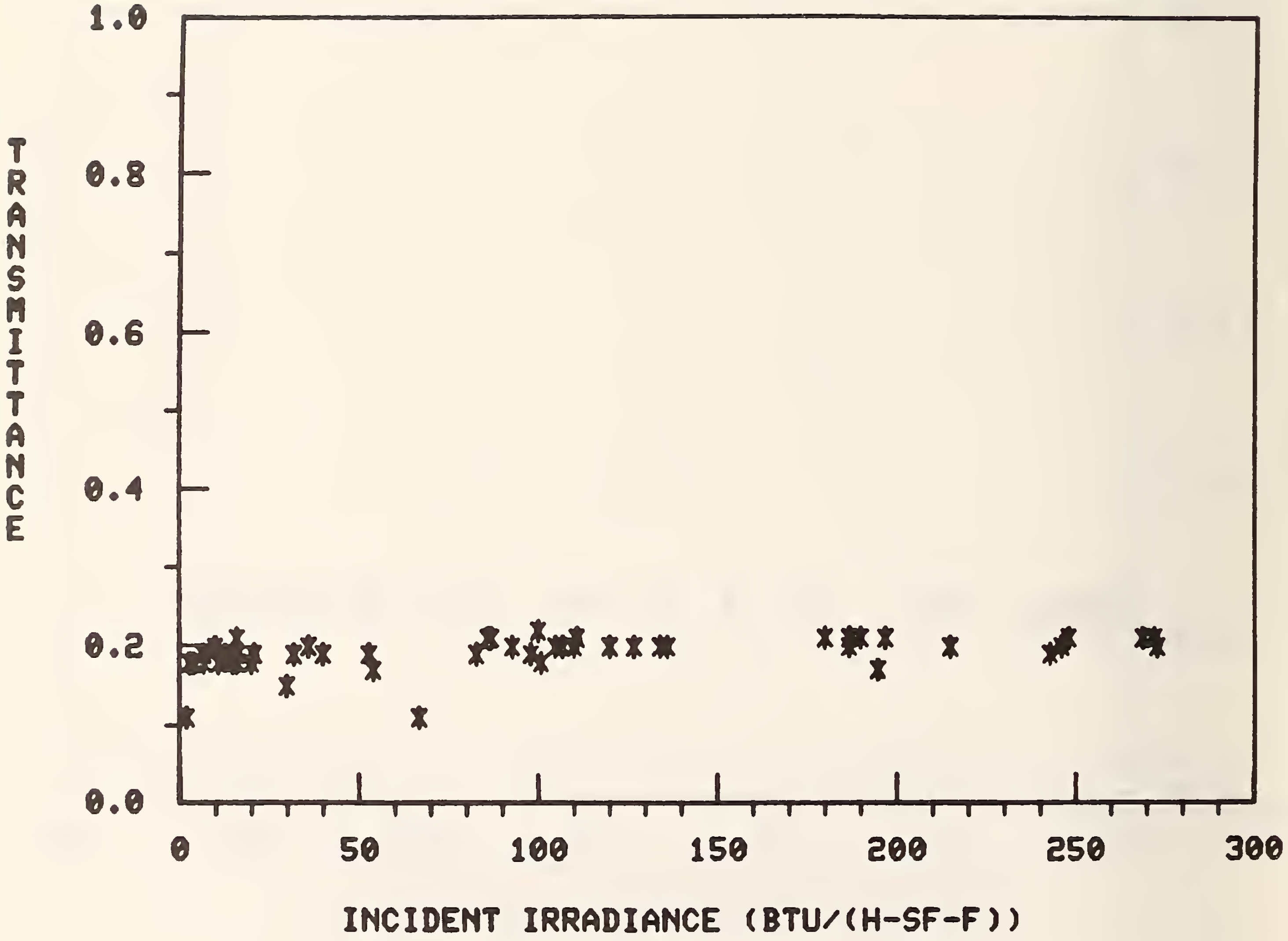

Figure 10d Measured solar transmittance as a function of level of incident irradiance for film D

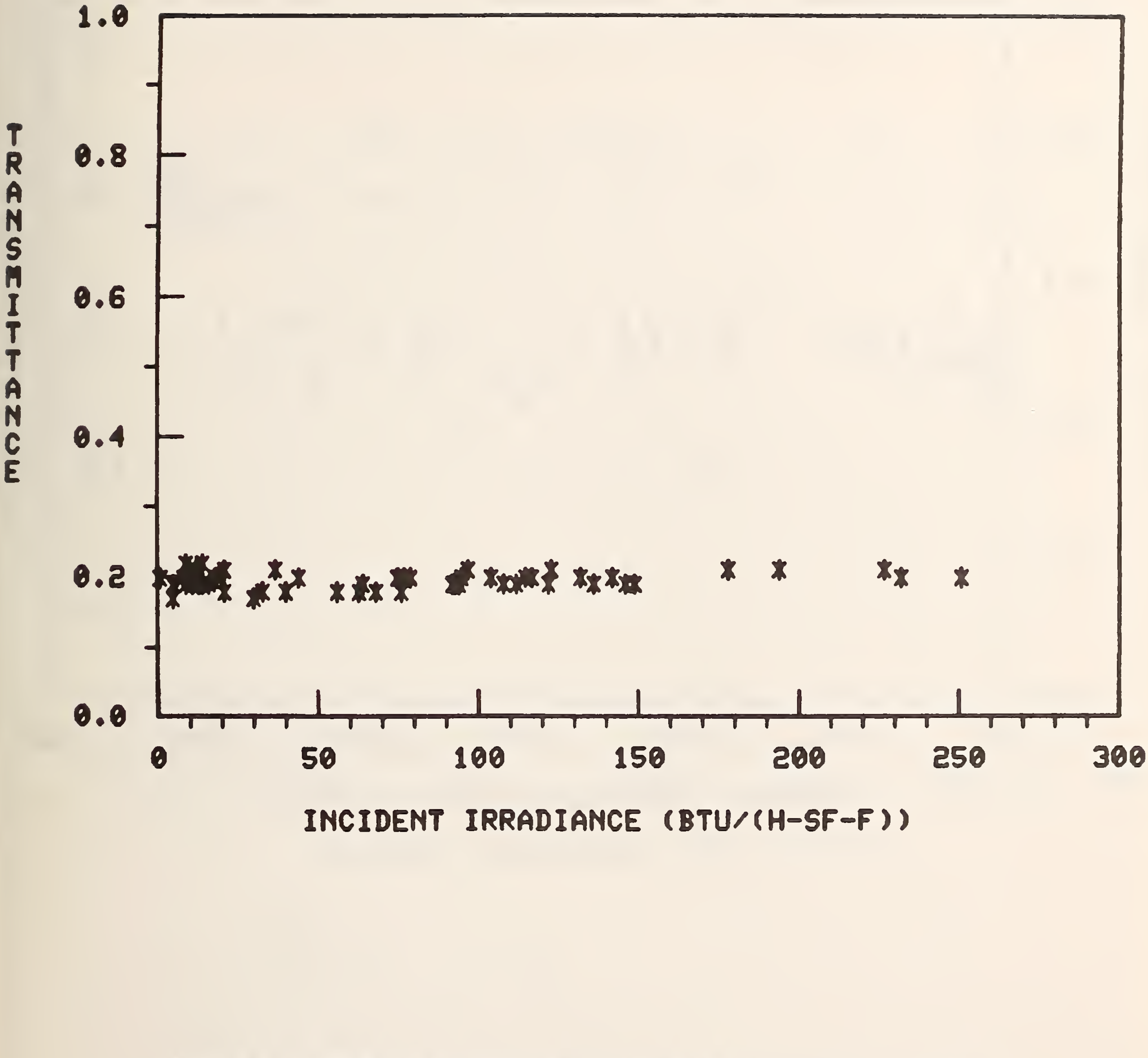

Figure 10e Measured solar transmittance as a function of level of incident irradiance for film E

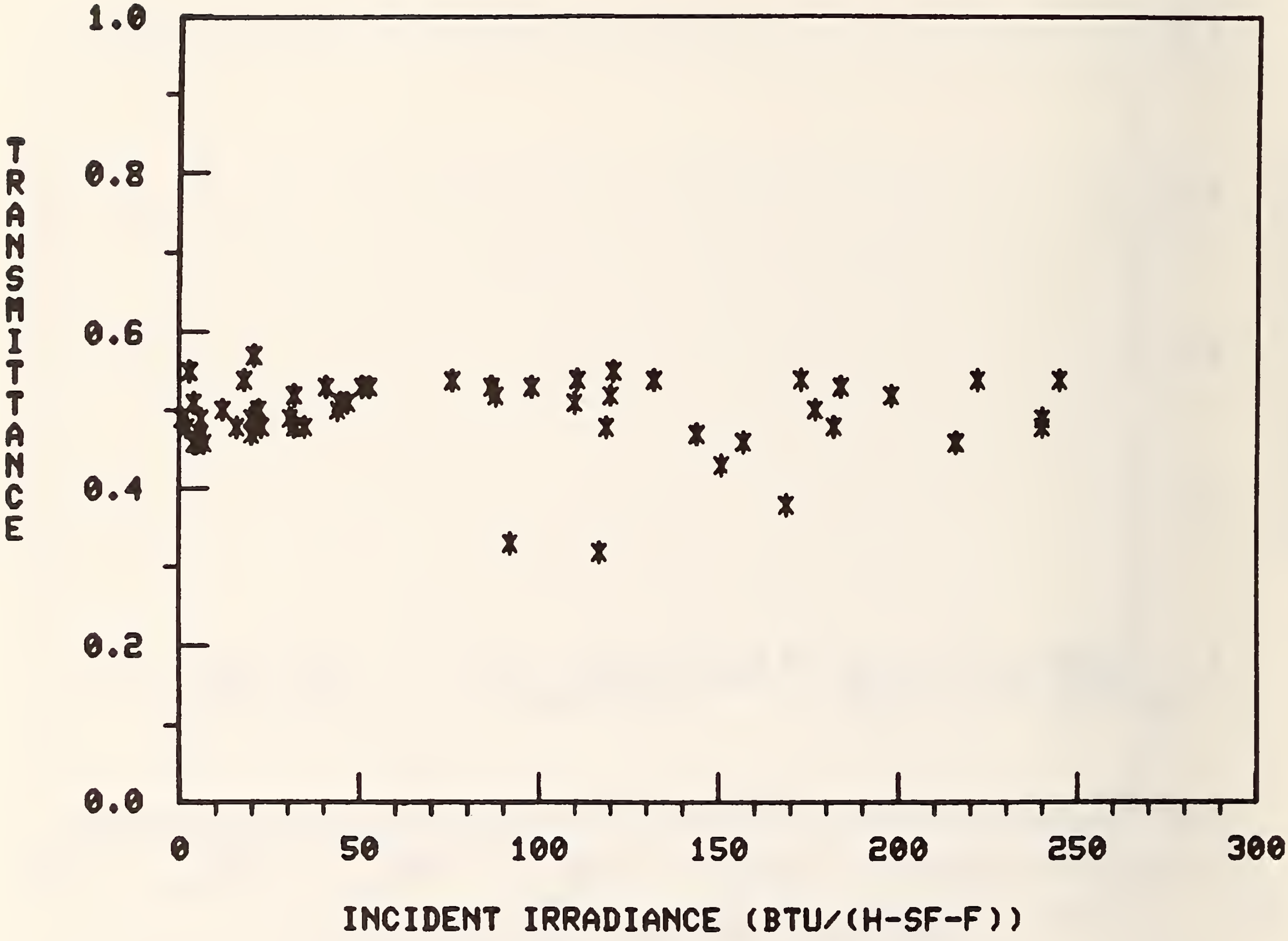

Figure 10f Measured solar transmittance as a function of level of incident irradiance for film F

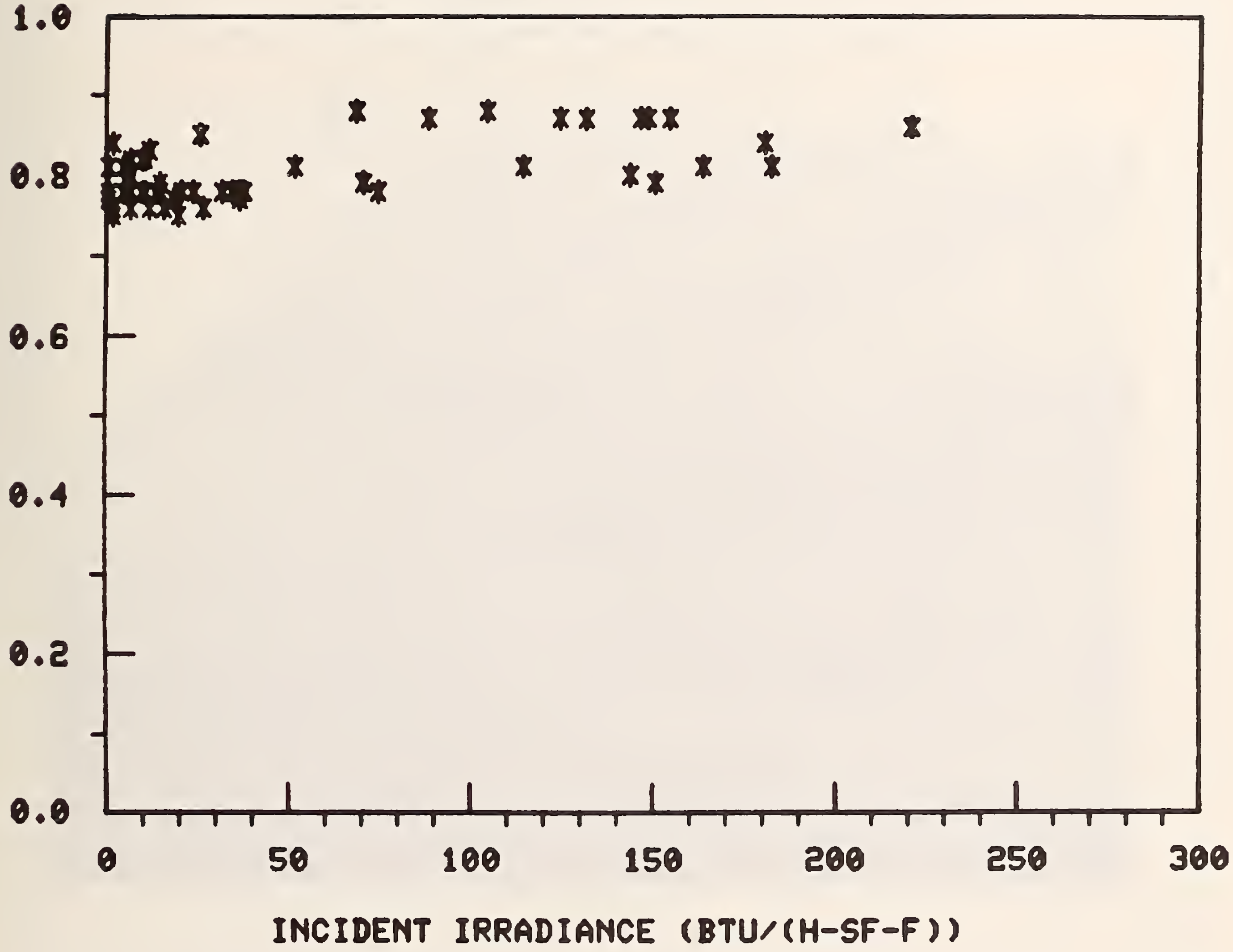

Figure 10g Measured solar transmittance as a function of level of incident irradiance for clear glass

Figure 11 Photograph of study building

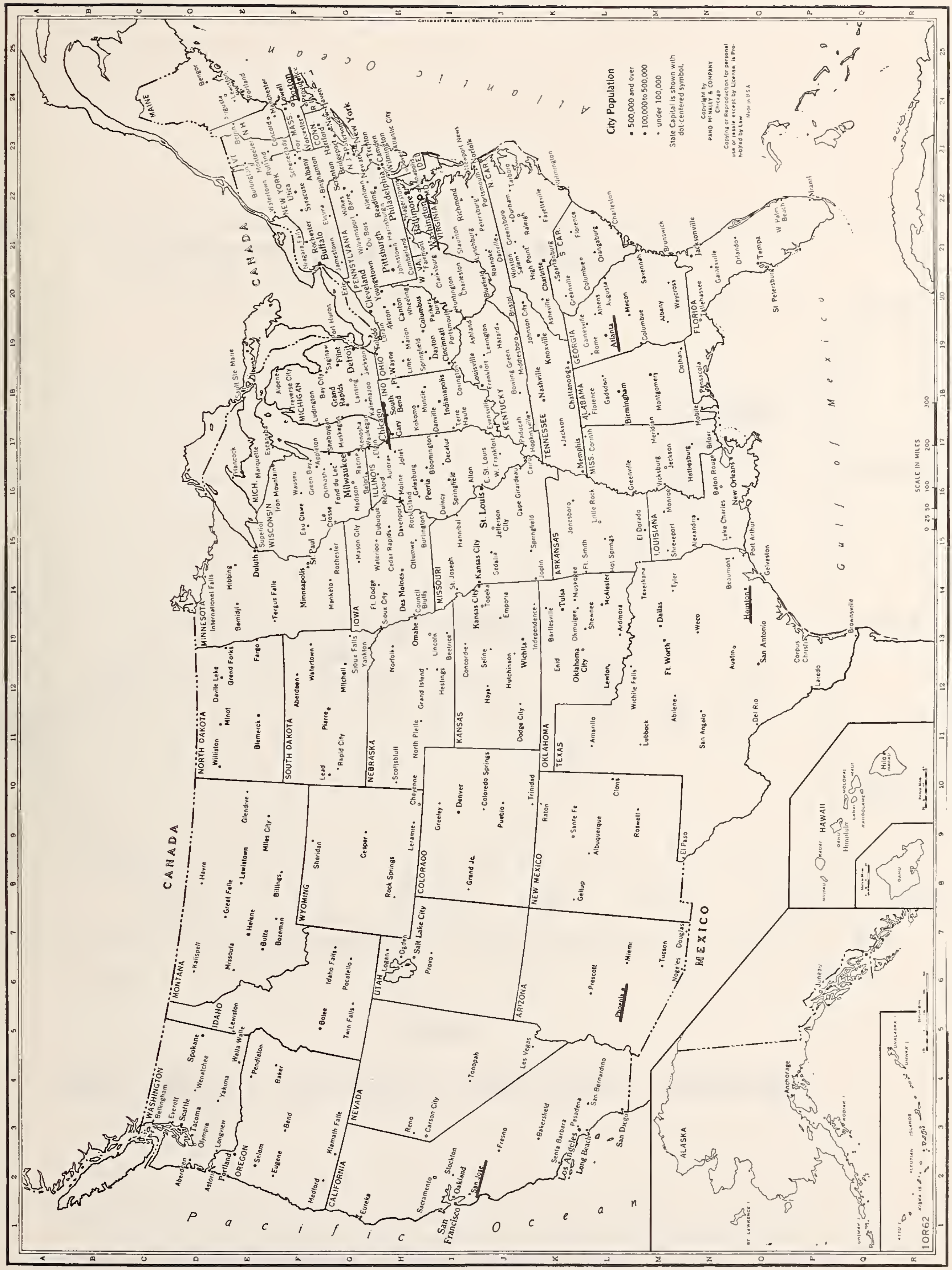

Figure 12. Map showing locations of climatic regions

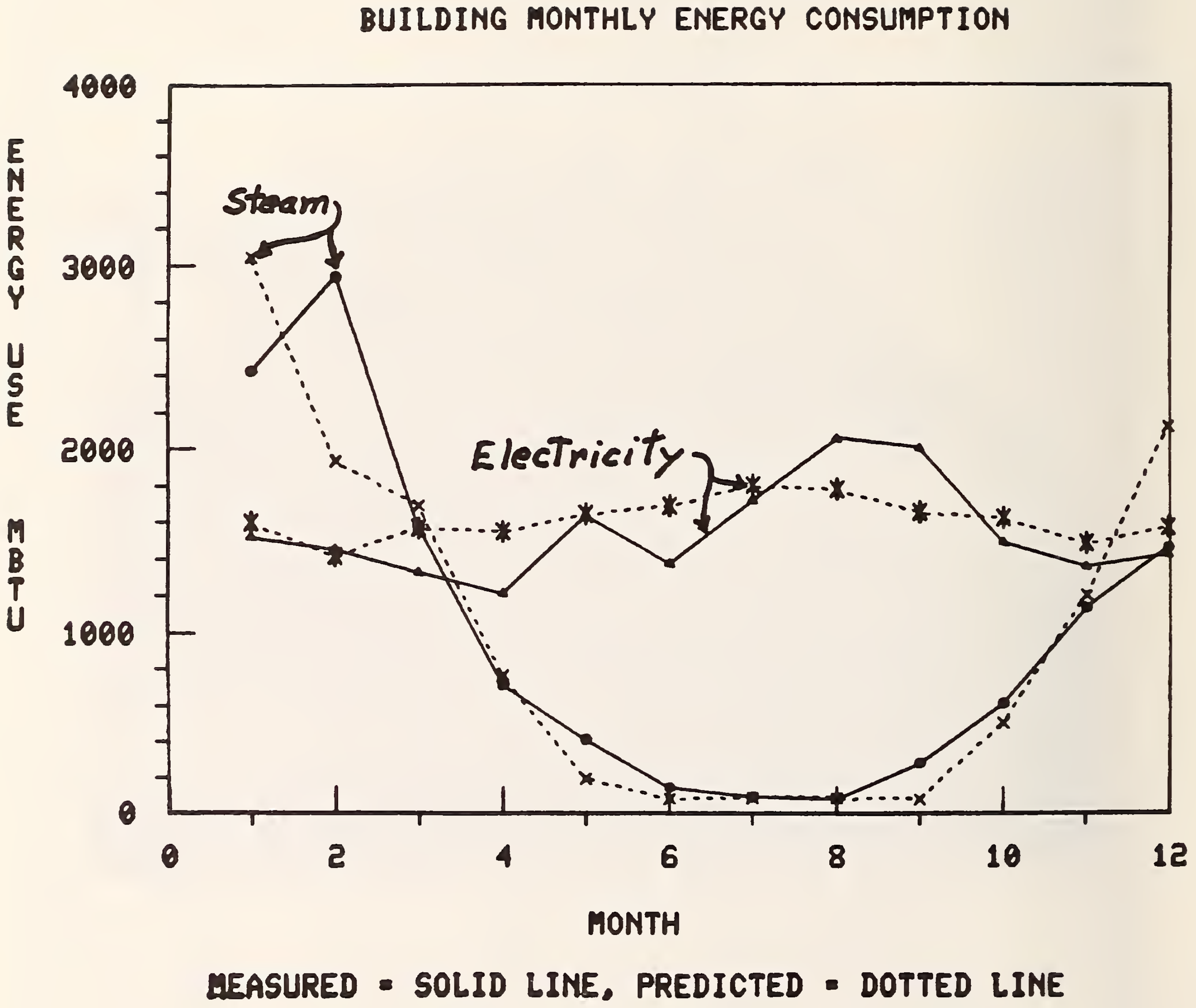

Figure 13 Monthly energy consumptions for actual and simulated building

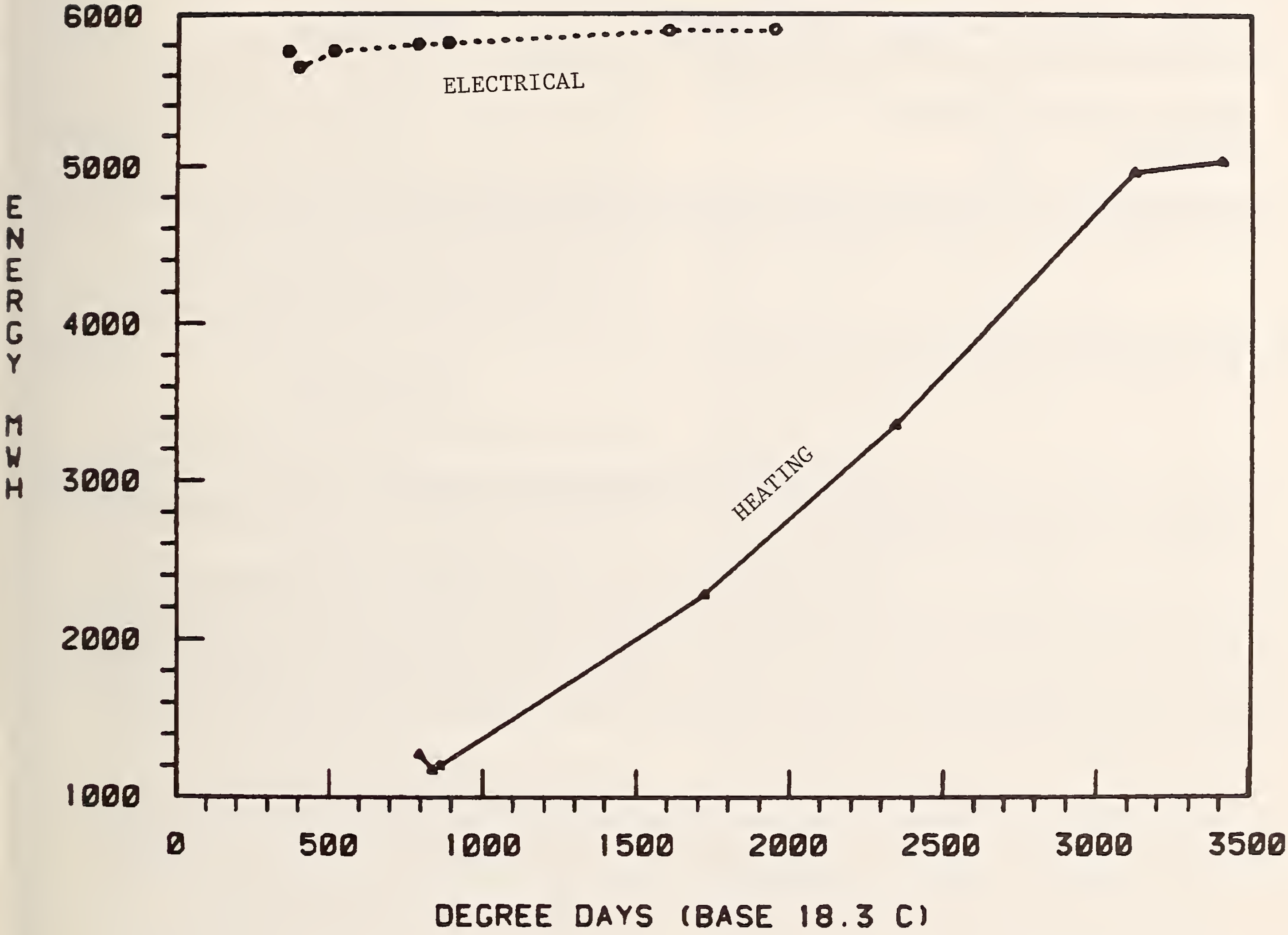

Figure 14 Annual heating and electrical consumptions for simulated building with clear glass as a function of heating and cooling degree days, respectively

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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)*

The impact of solar window film utilization on building HVAC system loads, energy consumption and costs, is examined for a typical office building. The evaluation includes characterization and measurement of important film properties, performance of single-glazing window systems with and without film, simulation of annual building energy performance using the DOE-2 computer program, and a life-cycle cost analysis. Six window film options are compared to clear glass performance for seven climatic regions throughout the United States.

Guidelines are developed for effective solar film utilization in office buildings, in terms of energy performance and cost-effectiveness. Results indicate that solar films can be effective in reducing building energy requirements and costs in areas with high cooling loads, with less savings expected in areas with lower cooling loads and higher heating loads, and no savings in regions with high heating loads.

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

building energy analysis; cooling loads; heating loads; solar film; solar heat gain; window management

13. AVAILABILITY

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