LBL-13374
Preprint

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

ENERGY & ENVIRONMENT
DIVISION

Submitted to Solar Energy Materials

INFRARED PROPERTIES OF POLYETHYLENE TEREPHTHALATE FILMS

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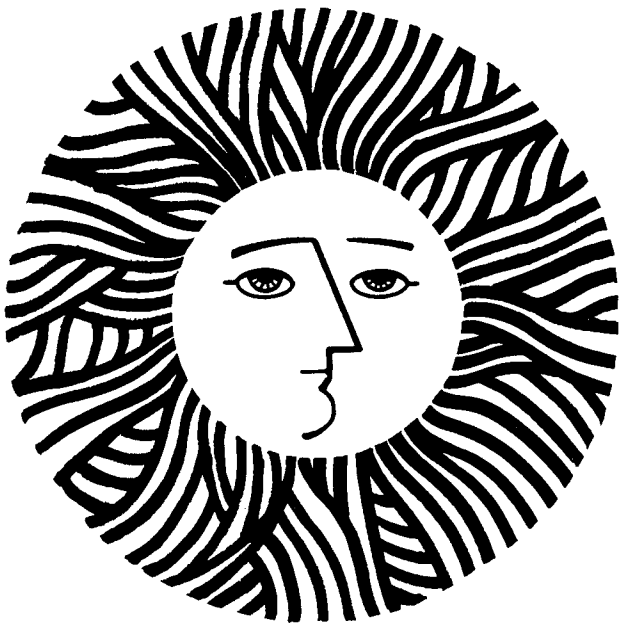
October 1981



Prepared for the U.S. Department of Energy under Contract W-7405-ENG-48

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LBL-13374
EEB-W-81-21
W-105

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ABSTRACT

The infrared radiation properties of polyethylene terephthalate films are calculated from the optical constants. Hemispherical total transmittance and emittance are given as functions of thickness. The difference between these properties and those of glass will significantly affect the thermal conductance of windows or solar collector covers.

The work described in this paper was funded by the Assistant Secretary for Conservation and Renewable Energy, Office of Buildings and Community Systems, Buildings Division of the U.S. Department of Energy under Contract No. W-7405-ENG-48.

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The infrared radiation properties of polyethylene terephthalate films are calculated from the optical constants. Hemispherical total transmittance and emittance are given as functions of thickness. The difference between these properties and those of glass will significantly affect the thermal conductance of windows or solar collector covers.

Introduction

Polyethylene terephthalate (PET) films are used for making storm windows and for replacing glass panes in triple- and quadruple-glazed windows [1]. These films also serve as substrates for coatings which reflect or antireflect solar energy and which reflect thermal radiation. In this paper, we present those radiation properties needed to calculate heat transfer through windows that incorporate PET films.

Additives designed to improve weathering, as well as differences among manufacturing processes, affect the solar optical properties of PET films. However, normal-transmittance spectra in the far infrared show little difference between products of different manufacturers and between weatherable and non-weatherable products from the same manufacturer. Thus, we assume that our results apply to all varieties of PET.

The thickness of PET films used in solar collectors or windows ranges from about 0.02 to 0.2 mm. Thinner films are too fragile, while thicker films have too little solar transmittance. Both transmittance and emittance are needed to characterize such films in the infrared, in contrast to window glass which is thick enough to be opaque. The hemispherical total emittance of soda-lime glass is about 0.84 at room temperature [2], and is independent of thickness.

Theory

For the following calculations, we assume the material to be specularly reflecting, because observed surface defects were much smaller than far-infrared wavelengths [3]. In addition, we assume the films to be homogeneous and isotropic. Due to stretching in the manufacturing process, PET films exhibit birefringence [3,4,5], but assuming isotropy will not introduce large errors in hemispherically averaged quantities.

Plastics, compared to other solids, contain a large number of resonances in the far-infrared spectrum. This complexity is treated by using band-averaged optical constants (n, k) determined from transmittance measurements on two samples of different thicknesses [6].

Although PET is non-metallic, the extinction coefficient, k, can be large enough near a resonance to violate the condition $(n-1)^2 \gg k^2$, where n is the index of refraction. However, the spectral reflectance near these resonances contributes so little to the average that the ideal-dielectric approximation is valid for determining total

properties. Then, a single boundary between sample and air reflects a fraction r of normally incident energy:

$$r = \left[\frac{n - n_a}{n + n_a}\right]^2 \tag{1}$$

where the index of refraction of air, n_a, is 1. For non-normal incidence, depending on polarization, replace n_a by either $n_a\cos\theta$ or $n_a/\cos\theta$, where θ is the angle of incidence. Similarly, replace n by either $n\cos\phi$ or $n/\cos\phi$, where ϕ is the angle of refraction given by

$$\cos\phi = \left[1 - \frac{\sin^2\theta}{n^2}\right]^{1/2}. \tag{2}$$

A film of thickness d transmits a fraction of energy t at wavelength λ on a single transit within the material:

$$t = \exp\left[-\frac{4\pi kd}{\lambda\cos\phi}\right]. \tag{3}$$

Counting all multiple reflections and summing the resulting infinite series gives the directional spectral transmittance, $T(\theta,\lambda)$, and directional spectral reflectance, $R(\theta,\lambda)$, of the film:

$$T(\theta,\lambda) = \frac{(1-r)^2 t}{1 - r^2t^2}, \tag{4}$$

and

$$R(\theta,\lambda) = r + \frac{(1-r)^2 rt^2}{1 - r^2t^2}. \tag{5}$$

The emittance is given by

$$E(\theta,\lambda) = 1 - T(\theta,\lambda) - R(\theta,\lambda), \tag{6}$$

viewing θ as the angle of emission.

Directional total properties are found by averaging the spectral properties, weighted by the blackbody emissive power, $P(\lambda)$, at each wavelength. For example, the directional total transmittance is

$$T(\theta) = \frac{\int_0^\infty T(\theta,\lambda)\ P(\lambda)\ d\lambda}{\int_0^\infty P(\lambda)\ d\lambda}. \qquad (7)$$

The optical constants from Ref. 6 range from 4.0 to 100.0 μm. These wavelengths are acceptable limits of integration because they encompass 98% of the energy emitted by a blackbody at room temperature (293 K).

Hemispherical properties are obtained from directional properties by equations of the form

$$T_h = 2 \int_0^{\pi/2} T(\theta)\ \cos\theta\ \sin\theta\ d\theta. \qquad (8)$$

Results

Figure 1 shows the directional total emittance, $E(\theta)$, of two PET films having different thicknesses and of a sheet of window glass that is optically thick (3mm). Notice that the emittance curves of the PET films are not semicircular. This non-Lambertian behavior is due to the partial transmittance of the film--as θ increases, emission increases due to the longer path through the material. At high θ, surface reflectance rapidly approaches unity and emittance vanishes. The emittance of the glass plate does not depend on θ because the opacity of the material limits the amount of radiation reaching the surface.

Such details of directional behavior usually are not needed for calculating heat transfer through windows. Only the hemispherical

average enters these calculations. Figure 2 shows the effect of thickness on the hemispherical total properties of a PET film at room temperature (293 K). As the thickness increases, T_h decays to zero and R_h approaches the single interface value, r. Least-squares fits of simple exponential forms provide formulas for T_h and E_h as functions of thickness (in mm):

$$T(d) = 0.720 \exp(-14.2d + 11.1d^2) \tag{9}$$

and

$$E(d) = 0.846 - 0.811 \exp(-15.0d + 18.0d^2). \tag{10}$$

Discussion

A PET film 0.1mm thick and a sheet of double-strength clear glass 3mm thick transmit about the same fraction of solar energy. However, from (9) and (10) we find that T_h=0.19 and E_h=0.63 for the PET, while for glass, $T_h \approx 0$ and E_h=0.84. Consider two windows made from these materials: a triple-pane glass window (g-g-g), and a similar window in which a PET film replaces the middle pane (g-p-g). When the spacing between layers in both windows is the same, the heat-transfer rate is higher for the g-p-g window because of the partial transparency of the PET. Figure 3a illustrates this effect in terms of thermal conductance, or U-value, calculated for typical winter conditions [7]; as the gap spacing decreases, the conductive and convective heat transfer increases, increasing the overall U-value and short-circuiting the mechanism of radiative transfer, which equalizes the U-values of the two windows.

Freedom to set the spacing between layers is limited by the range of outside dimension (OD) available from most manufacturers of

multiglazed window units. The thickness of a glass pane can reduce the available air space of a fixed-OD window by enough to significantly affect the U-value, but the thickness of the PET film is negligible. Figure 3b shows that for small OD the g-p-g window has a lower U-value than the g-g-g window despite the infrared transmittance of PET. As the OD increases, the individual gaps become large compared to the thickness of the glass, allowing the U-value of triple glass to fall below that of the window having the PET film.

A low-emittance coating applied to either glass or PET supresses radiative heat transfer [8]. The transparency of the PET film enhances the "heat mirror" effect because the emittance of the uncoated side is also lowered. Antireflection coatings for the solar spectrum, however, have little effect on the far-infrared properties of PET.

Acknowledgement

The work described in this paper was funded by the Assistant Secretary for Conservation and Renewable Energy, Office of Buildings and Community Systems, Buildings Division of the U.S. Department of Energy under Contract No. W-7405-ENG-48.

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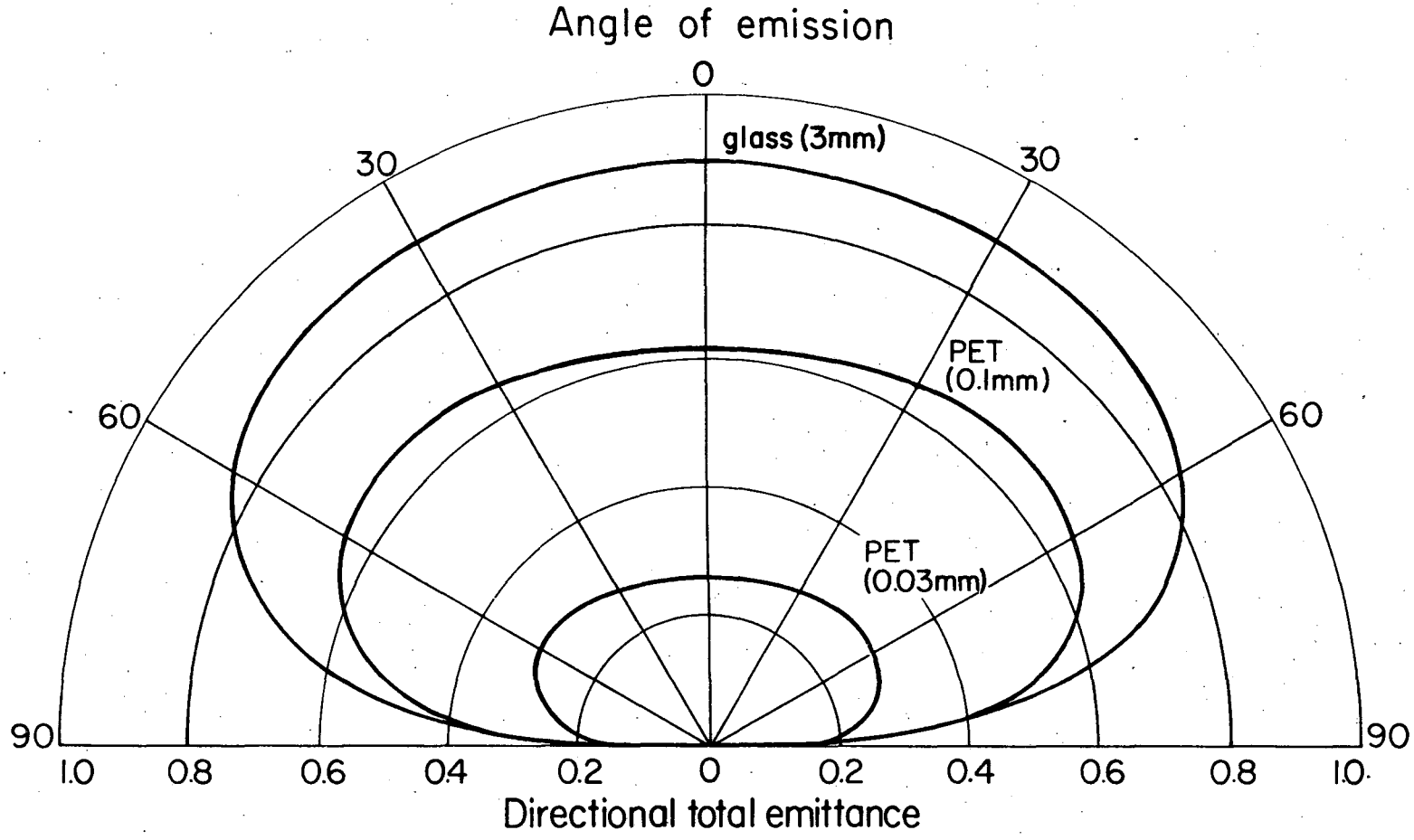

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Figure 1. Directional total emittance of window glass (3mm) and PET films (0.1 and 0.03mm) at 293° K. The horizontal axis represents the surface of the material; the angle of emission is measured from the normal to this surface.

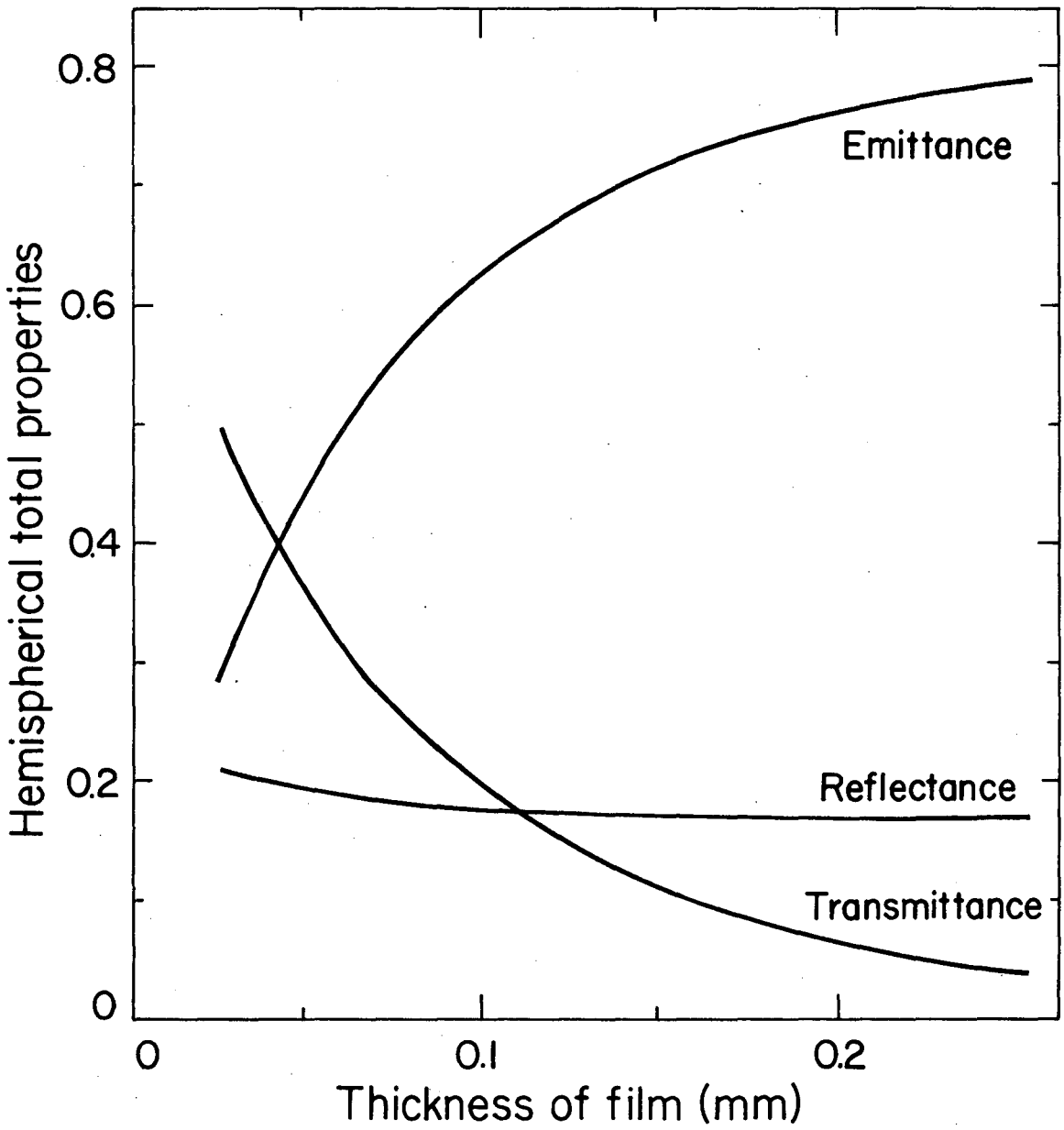

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Figure 2. Hemispherical total transmittance, reflectance, and emittance of PET films vs. thickness of film at 293 K.

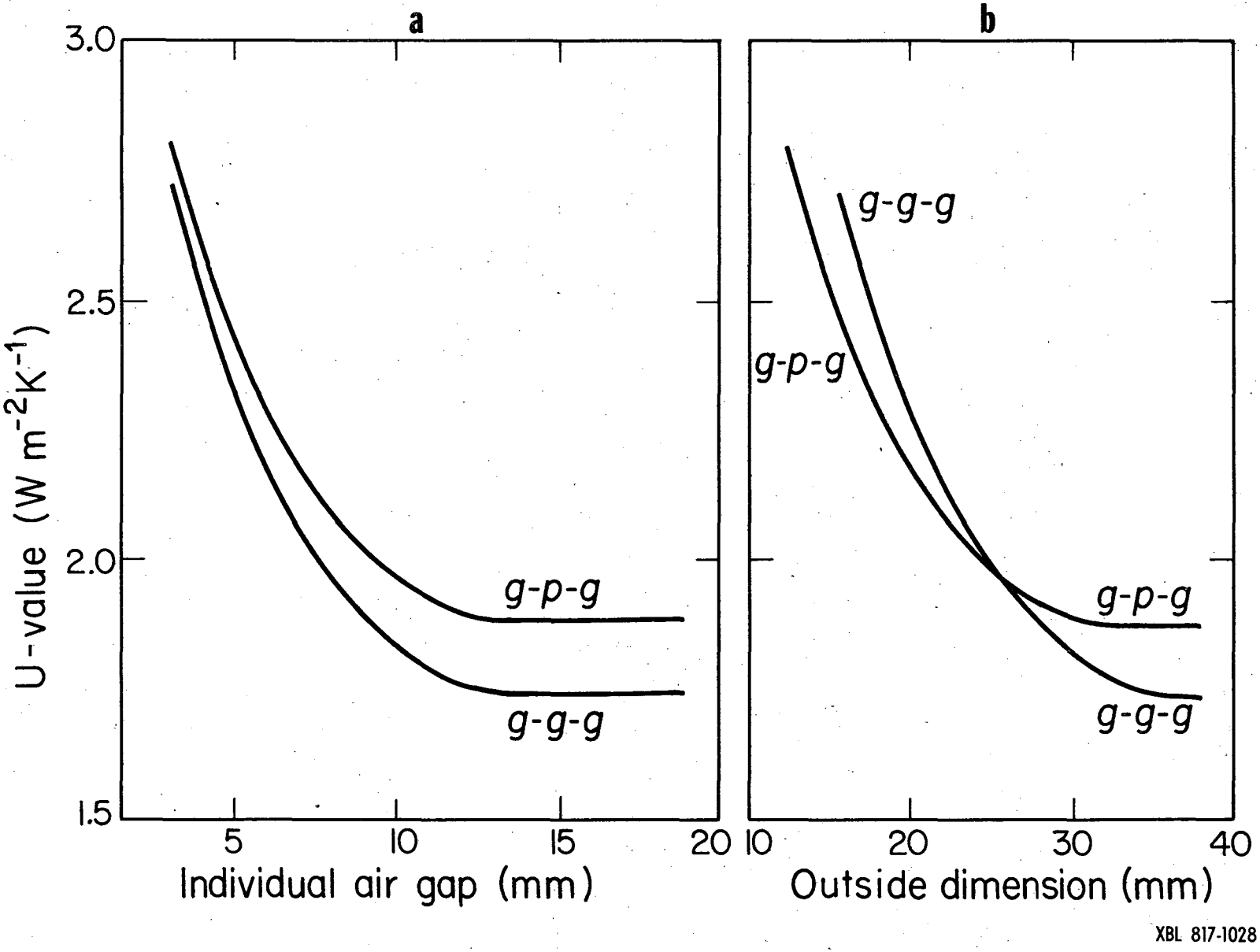

Figure 3. Comparison between the U-values of triple-layer windows for (a) freely adjustable air gaps and (b) fixed outside dimension (g=3mm clear glass; p=0.1mm clear PET).

This report was done with support from the Department of Energy. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the Department of Energy.

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