SERI/TP-31-193

THE EFFECTS OF PHOTO-INDUCED OPTICAL DEGRADATION OF TYPICAL PLASTIC GLAZING MATERIALS UPON FLAT-PLATE SOLAR ENERGY COLLECTION EFFICIENCY

GARY JORGENSEN

TO BE PRESENTED AT SOLAR GLAZING:
1979 TOPICAL CONFERENCE SPONSORED BY THE
MID-ATLANTIC SOLAR ENERGY ASSOCIATION

STOCKTON STATE COLLEGE
POMONA, NEW JERSEY

JUNE 22-23, 1979

Solar Energy Research Institute

1536 Cole Boulevard
Golden, Colorado 80401

A Division of Midwest Research Institute

Prepared for the
U.S. Department of Energy
Contract No. EG-77-C-01-4042

NOTICE

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Abstract

The effect of photo-induced optical degradation of plastic glazings upon the thermal performance of flat-plate solar energy collection systems was investigated. Computer simulations of singly and doubly glazed collectors having cover plates comprised of various commercially available transparent materials were made for one-week time periods using Phoenix, Arizona, insolation and meteorological data. Optical degradation was modeled by systematically decreasing the specified values of solar transmittances of the plastic cover plates under consideration. Energy collection efficiencies corresponding to each decrement of transmittance were normalized to that of nondegraded glass to allow comparisons both with a standard and among the different plastics. This provides a measure of the relative usefulness of various candidate polymeric glazing materials when realistic rates of optical degradation are known.

Introduction

Glazings for flat-plate solar collectors are generally either glass or plastic materials. Glass has proven to be an effective cover plate material, exhibiting extended service lifetime and high solar transmittance while remaining essentially opaque to thermal reradiation. Plastics, which are cost competitive with glass, are lightweight and pliable. In general, plastics have higher solar transmittances than commercial window glass but they also transmit a greater amount of reradiated thermal energy from the collector unless their thickness is sufficient to absorb the emitted infrared effectivity. Perhaps the greatest shortcoming of the use of plastics for flat-plate solar energy collection systems is their poor weathering qualities. While both glass and plastics absorb solar ultraviolet radiation, glass is very resistant to photo-induced degradation. However, chemical reactions which result in deterioration of mechanical and optical properties can be readily induced in plastics by UV photons.

Various plastics experience differing degrees of degradation. For example, a sample of Plexiglas (an acrylic), exposed to solar radiation for 17.7 years in Albuquerque, New Mexico, was found to have lost only 10% of its original optical transmittance [1]. Mylar (a polyester), on the other hand, undergoes extreme ultraviolet degradation. Following an accelerated exposure equivalent to 1.33 years of sunlight, a Mylar specimen exhibited roughly 55% transmission loss in the visible spectrum [2]. A qualitative survey of the resistance to photo-degradation of the various plastics studied is given in Table 1. The effect of optical degradation of various glazing materials upon flat-plate system solar energy collection efficiency is examined in this paper. Such information indicates expected thermal performance, which can be correlated with measurable optical degradation rates.

Method

Modified flat plate simulation software [6,7] was used in conjunction with TRNSYS [8] to study the effect of photodegradation upon solar energy collection efficiency of flat-plate systems. Photodegradation was modeled by decreasing the solar transmittance of the cover plates. Single- and double-glazed systems were simulated for an environment homologous to Phoenix, Arizona, for one-week time periods in both June and December. The analysis can be extended easily to an annual basis. Preliminary yearly simulations were in close agreement with the weekly predictions. Since the results were intended to reveal general trends, the one-week simulations were considered to be satisfactory.

The system modeled was a stand-alone flat-plate solar collector characterized by the physical parameters given in Table 2. A closed tube-liquid (water) collector with an area of 6.5 m^2 was chosen. The absorber was aluminum with nonselective absorptance. Copper fluid tubes were assumed to be solder-bonded to the fin at 15-cm spacings. All plate gap distances (cover-cover, cover-absorber) were 1.9 cm. The collector was south-facing with a tilt angle fixed at 43.°43 (latitude of Phoenix + 10°).

For test purposes, a constant inlet fluid temperature was assumed to be provided by a water storage unit controlled by a temperature regulator as shown in Figure 1. Single- and double-glazed collectors were investigated using appropriate [9] inlet temperatures of 50°C and 75°C respectively. The materials chosen for study were glass (float or tempered), fiberglass reinforced polyester (Sunlite), acrylic (Plexiglas), polycarbonate (Lexan), polytetrafluoroethylene (Teflon), polyvinyl fluoride (Tedlar), polyester (Mylar), polyvinylidene fluoride (Kynar), and polyethylene (Marlex). Most of the thermal and optical data were obtained from information compiled by Ratzel and Bannerot [3] as recorded in Table 3. Materials were distinguished by refractive index, solar and infrared transmittance (at normal incidence), and thermal capacity (calculated as the product of the thickness, density, and specific heat of the covers). The long-wave transmittance (τ_{IR}) of Kynar and Marlex were obtained by numerical integration of infrared spectrograms [5,10]. This technique was carried out for various temperatures (Figure 2), and values of τ_{IR} were selected at temperatures near collector operating conditions of interest. As can be seen, the infrared transmittance for Marlex is relatively constant at about 0.81 between 0 and 200°C. Kynar exhibits a steady increase of τ_{IR} with increasing temperature; between 50°C and 100°C an average value of 0.23 was used.

Results

Ten computer runs were made for each material. Five values of decreasing solar transmittance were chosen (ranging between the maximum nondegraded value and 25% transmittance) to represent the effects of exposure to solar ultraviolet radiation. Each set of five transmittances was modeled during

both summer and winter ambient weather conditions. Results from the simulations were daily and weekly summaries of incident sunlight, useable collected energy, and the associated system efficiencies. Also available on an hourly basis were the upward heat loss coefficient, plate temperature, and outlet temperature. An example of the daily flux profile of insolation and collected solar energy as a function of optical transmittance is presented in graphical form in Figures 3a and 3b. Overall flat-plate energy collection efficiencies (ϵ) are also tabulated in these figures.

The resultant weekly efficiencies for single glazings of the materials studied are given in Table 4 as a function of transmittance for both June and December. Since the computed efficiencies were configuration-specific (dependent upon the values of the parameters and inlet temperatures used), all efficiencies were normalized to a standard defined to be nondegraded glass. These relative efficiencies allowed comparisons among the various plastics. Percentage degradation was calculated as the decreased solar transmittance used, divided by the maximum (nondegraded) value for each material. Changes in infrared transmittance were not modeled. The variation of relative efficiency versus percentage degradation is graphically displayed in Figures 4a-4h. Solid lines represent the results for June and dashed lines the December results.

As seen in Figures 4a through 4c, the collectors covered with Plexiglas, Lexan, and Sunlite initially perform nearly as well as, or, in some cases, better than glass. This is due to the high solar transmittance (compared to that of glass) coupled with low thermal transmittance. Collectors with Teflon, Tedlar, Mylar, and Kynar all have an initial relative efficiency of about 80% as shown in Figures 4e through 4h. Although the solar transmittance is significantly greater than glass for these materials, the infrared transmittance is also much higher, resulting in greater heat losses and lower efficiencies. For example, the average upward heat loss coefficients for Tedlar were 13.55 (June) and 11.11 (December) $W/m^2-°K$ as compared to 6.76 (June) and 6.69 (December) $W/m^2-°K$ for glass. This behavior is most striking in the case of Marlex, which has an extremely high infrared transmittance. Figure 4d clearly shows the undesirable performance of this plastic as a single glazing flat-plate collector cover material. The strong dynamic dependence of collection efficiency upon solar transmittance is well illustrated (Figures 4a through 4h) by the marked decline of relative efficiency with increasing degradation.

Collectors having two cover plates were also investigated for several materials. Tedlar and Marlex were chosen as typical and atypical plastic cover plate candidates based on the single glazing simulations. In each case the plastic was assumed to be the innermost cover with the outer cover being glass. The standard configuration was a double glass cover collector. Direct comparisons between the one- and two-cover plate results were not possible because of the different inlet temperatures used. This was a consequence of the elevated operating temperature normally associated with multiglazed flat-plat collectors.

Results of the two-cover runs are presented in Table 5. The solar transmittances listed are for the plastic glazings only; the glass covers were assumed to be nondegraded. All other parameters were as defined for the single cover case. A significantly high relative efficiency is obtained when the thermal radiation transmitted by the inner cover of Tedlar is retained by an outer plate of glass (which is opaque to infrared emission). A system employing nondegraded Tedlar as a replacement for an inner cover of glass is found to perform 95% as well as the reference configuration.

Although glass absorbs in the ultraviolet, most of the incident radiation is transmitted. Consequently, an outer plate of glass does not provide complete protection from these rays for the inner plastic glazing and photodegradation can still occur. The effects of such optical degradation are displayed in Figure 5. A notable drop in relative (to the glass-glass collector) efficiency occurs as the plastic degrades.

Figure 5 also shows similar results for a glass-Marlex system. Once again the outer plate of glass compensated for the poor thermal transmittance properties of the plastic. Seasonal variation of relative efficiencies are a consequence of lower ambient winter temperatures and incident solar radiation. The average values of these quantities during daytime hours were:

Month	Insolation (W/m^2)	Dry Bulb Temperature (°C)
June	751	38.4
December	394	14.9

These factors controlled the outlet temperatures available (T_{out}) from the solar collector. Whenever conditions existed such that:

$$T_{out} \leq T_{in} + (\dot{Q}_c + \dot{Q}_p)/\dot{m}\, C_p$$

where:

T_{in} = inlet temperature (°C)
$\dot{Q}_c$ = thermal capacity factor (W)
$\dot{Q}_p$ = pump power (W)
$\dot{m}$ = flow rate (kg/sec)
$\dot{C}_p$ = specific heat of fluid (J/°K -kg)

the system did not operate and no useable solar energy was collected. This situation occurred more frequently during the winter than during the summer. Collectors with plastic cover plates were more sensitive to this effect because their increased heat losses (due to thermal transmission) resulted in lower outlet temperatures relative to the reference systems.

Conclusions

These results allow an evaluation of a number of candidate plastic cover plate materials based upon the decline of system collection efficiency as a function of photo-induced optical degradation. Optimum utilization of the data requires a knowledge of the prevalence and rate of optical degradation experienced by plastics during real-world service conditions. The most optimistic estimate of thermal efficiency for the collection systems considered is the nondegraded state. This corresponds to plastics having favorable weathering characteristics or whose UV-stability can be significantly improved with research. In this case, for single glazing systems (Figures 4a-4h), acrylic (Plexiglas), polycarbonate (Lexan), and fiber reinforced polyester (Sunlite) cover plates perform nearly as well as glass. Polytetrafluoroethylene (Teflon), polyvinyl fluoride (Tedlar), polyester (Mylar), and polyvinylidene fluoride (Kynar) all exhibit 80% efficiency relative to glass. These plastics experience a slope dependence of roughly -1.0 for relative efficiency versus optical degradation; a 10% transmittance drop results in a 10% efficiency loss relative to nondegraded glass.

Polyethylene (Marlex) is seen to be unacceptable as a single glazing cover system. When used in conjunction with an outer cover of glass for a double glazing application, however, a more encouraging result is found (Figure 5). A glass/Marlex cover plate system can perform with an efficiency up to 80% relative to a glass/glass arrangement. Furthermore, the sensitivity of relative efficiency to decline in degradation is less than that of the single glazing case. A 10% optical degradation produces only a 5% decrease in relative efficiency. These results point to the importance of the specific use of individual components of flat-plate systems.

A cover plate configuration of inner plastic and outer glass glazings suggests another solution to the plastic UV-degradation problem. Solar ultraviolet radiation arrives at the earth's surface in the wavelength band between 0.3-0.4μ and represents only 6% of the total incident intensity. Commercial soda lime glass of 3-mm thickness has a transmittance in this region of roughly 80% (UV extinction coefficient of 0.047/mm). If the UV opacity of the outer glass cover can be increased sufficiently while maintaining a high optical transmittance, the glass can function as an effective UV screen for the inner plastic glazing and still allow high energy collection.

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TABLE 1

RESISTANCE OF PLASTICS TO PHOTO-DEGRADATION

Material	Resistance Rating*	Reference
Fiberglass Reinforced Polyester (Sunlite)	Fair-Good	[3]
Acrylic (Plexiglas)	Excellent	[1,3,4]
Polycarbonate (Lexan)	Fair-Good	[3,4]
Polytetrafluoroethylene (Teflon)	Excellent	[3,4]
Polyvinyl Fluoride (Tedlar)	Good-Excellent	[3]
Polyester (Mylar)	Poor	[2,3]
Polyvinylidene Fluoride (Kynar)	Excellent	[5]
Polyethylene (Marlex)	Poor	[4]

*Resistance is a subjective consensus of various references based on relative comparisons among the glazings under consideration.

TABLE 2

FLAT-PLATE COLLECTOR PARAMETERS

Parameters	Value Used
Collector type	Closed tube
Collector area	6.5 m^2
Collector tilt angle	43°.43 (Latitude of Phoenix + 10°)
Collector azimuth	0°.0 (South)
Fluid flow rate	0.09035 kg/sec
Specific heat of fluid	4186.0 J/°K-kg (H_2O)
Pump power	186.6 W
Ground emittance	0.95
Short-wave absorptance of collector plate	0.95
Long-wave absorptance of cover plate	0.95
Thermal capacity of fluid and tubes	0.379 W-hr/°K-m^2 (copper tubes + H_2O)
Thermal capacity of collector plate	0.433 W-hr/°K-m^2 (aluminum)
Thermal capacity of back insulation	1.400 W-hr/°K-m^2
U-value of back insulation	0.300 W/°K-m^2
Tube spacing	0.150 m
Tube-fin bond width	0.020 m
Tube inner diameter	0.020 m
Tube wall thickness	0.001 m
Fin thickness	6.35 x 10^{-4} m
Bond conduction	1130.0 W/°K-m^2
Tube wall conductivity	392.8 W/°K-m (copper)
Fin material conductivity	221.5 W/°K-m (aluminum)
Tube wall to fluid heat transfer coefficient	1500.0 W/°K-m (forced circulation)

TABLE 4

SINGLE GLAZING
(T_{IN} - 50°C)

Material	Normal Incident Solar Transmittance (τ)	% Degradation of τ	Efficiency (June)	% Efficiency Relative to Glass	Efficiency (December)	% Efficency Relative to Glass
Glass	0.84	0.0	0.475	100.0	0.294	100.0
	0.80	4.8	0.456	96.0	0.278	94.6
	0.75	10.7	0.433	91.2	0.259	88.1
	0.50	40.5	0.308	64.8	0.160	54.4
	0.25	70.2	0.133	28.0	0.068	23.1
Fiberglass	0.87	0.0	0.452	95.2	0.280	95.2
Reinforced	0.80	8.0	0.420	88.4	0.253	86.1
Polyester	0.75	13.8	0.398	83.8	0.233	79.3
(Sunlite)	0.50	42.5	0.280	58.9	0.136	46.3
	0.25	71.3	0.128	26.9	0.051	17.3
Acrylic	0.90	0.0	0.503	105.9	0.320	108.8
(Plexiglas)	0.85	5.6	0.480	101.1	0.299	101.7
	0.75	16.7	0.434	91.4	0.259	88.1
	0.50	44.4	0.307	64.6	0.160	54.4
	0.25	72.2	0.131	27.6	0.069	23.5
Polycarbonate	0.84	0.0	0.474	99.8	0.293	99.7
(Lexan)	0.80	4.8	0.455	95.8	0.277	94.2
	0.75	10.7	0.433	91.2	0.258	87.8
	0.50	40.5	0.310	65.3	0.160	54.4
	0.25	70.2	0.136	28.6	0.068	23.1
Polytetrafluo-	0.96	0.0	0.392	82.5	0.241	82.0
roethylene	0.85	11.5	0.341	71.8	0.199	67.7
(Teflon)	0.75	21.9	0.293	61.7	0.161	54.8
	0.50	47.9	0.173	36.4	0.075	25.5
	0.25	74.0	0.072	15.2	0.006	2.0
Polyvinyl	0.92	0.0	0.399	84.0	0.244	83.0
Fluoride	0.85	7.6	0.366	77.1	0.217	73.8
(Tedlar)	0.75	18.5	0.319	67.2	0.178	60.5
	0.50	45.7	0.202	42.5	0.091	31.0
	0.25	72.8	0.095	20.0	0.041	4.8

TABLE 4 (con't)

SINGLE GLAZING
(T_{IN} - 50°C)

Material	Normal Incident Solar Transmittance (τ)	% Degradation of (τ)	Efficiency (June)	% Efficiency Relative to Glass	Efficiency (December)	% Efficency Relative to Glass
Polyester	0.87	0.0	0.390	82.1	0.234	79.6
(Mylar)	0.80	8.0	0.358	75.4	0.207	70.4
	0.75	13.8	0.334	70.3	0.188	63.9
	0.50	42.5	0.219	46.1	0.099	33.7
	0.25	71.3	0.108	22.7	0.021	7.1
Polyvinylidene	0.93	0.0	0.392	82.5	0.239	81.3
Fluoride	0.85	8.6	0.354	74.5	0.208	70.7
(Kynar)	0.75	19.4	0.307	64.6	0.170	57.8
	0.50	46.2	0.189	39.8	0.083	28.2
	0.25	73.1	0.085	17.9	0.009	3.1
Polyethylene	0.92	0.0	0.117	24.6	0.060	20.4
(Marlex)	0.85	7.6	0.004	0.8	0.039	13.3
	0.75	18.5	0.000	0.0	0.011	3.7
	0.50	45.7	0.000	0.0	0.000	0.0
	0.25	72.8	0.000	0.0	0.000	0.0

TABLE 3

THERMAL AND OPTICAL PROPERTIES OF COVER PLATE MATERIALS

Material	Index of Refraction	Normal Incident Short-wave Transmittance (λ=0.4-2.5μ)	Normal Incident Long-wave Transmittance (λ=2.5-40μ)	Thickness* (m)	Density (kg/m^3)	Specific Heat (J/°K-kg)	Thermal** Capacity (W-hr/°K-m^2)	References
Glass	1.518	0.840	0.020	3.175×10^{-3}	2.489×10^3	0.754×10^3	1.659	[3]
Fiberglass Reinforced Polyester (Sunlite)	1.540	0.870	0.076	6.350×10^{-4}	1.399×10^3	1.465×10^3	0.361	[3]
Acrylic (Plexiglas)	1.490	0.900	0.020	3.175×10^{-3}	1.189×10^3	1.465×10^3	1.534	[3]
Polycarbonate (Lexan)	1.586	0.840	0.020	3.175×10^{-3}	1.199×10^3	1.193×10^3	1.260	[3]
Polytetrafluoroethylene (Teflon)	1.343	0.960	0.256	5.080×10^{-5}	2.148×10^3	1.172×10^3	0.036	[3,11]
Polyvinyl Fluoride (Tedlar)	1.460	0.920	0.207	$1.016 \times 10_{-4}$	1.379×10^3	1.256×10^3	0.049	[3]
Polyester (Mylar)	1.640	0.870	0.178	1.270×10^{-4}	1.394×10^3	1.046×10^3	0.051	[3]
Polyvinylidene Fluoride (Kynar)	1.413	0.930	0.230	1.016×10^{-4}	1.770×10^3	1.256×10^3	0.063	[5], Fig. 2
Polyethylene (Marlex)	1.500	0.920	0.810	1.016×10^{-4}	0.910×10^3	2.302×10^3	0.059	[10,11], Fig. 2

* These values correspond to the thickness associated with the stated transmittances. They were used in the simulations to compute thermal capacity and are representative of commercially available film thicknesses.

**Thermal capacity = (Thickness) (Density) (Specific heat)

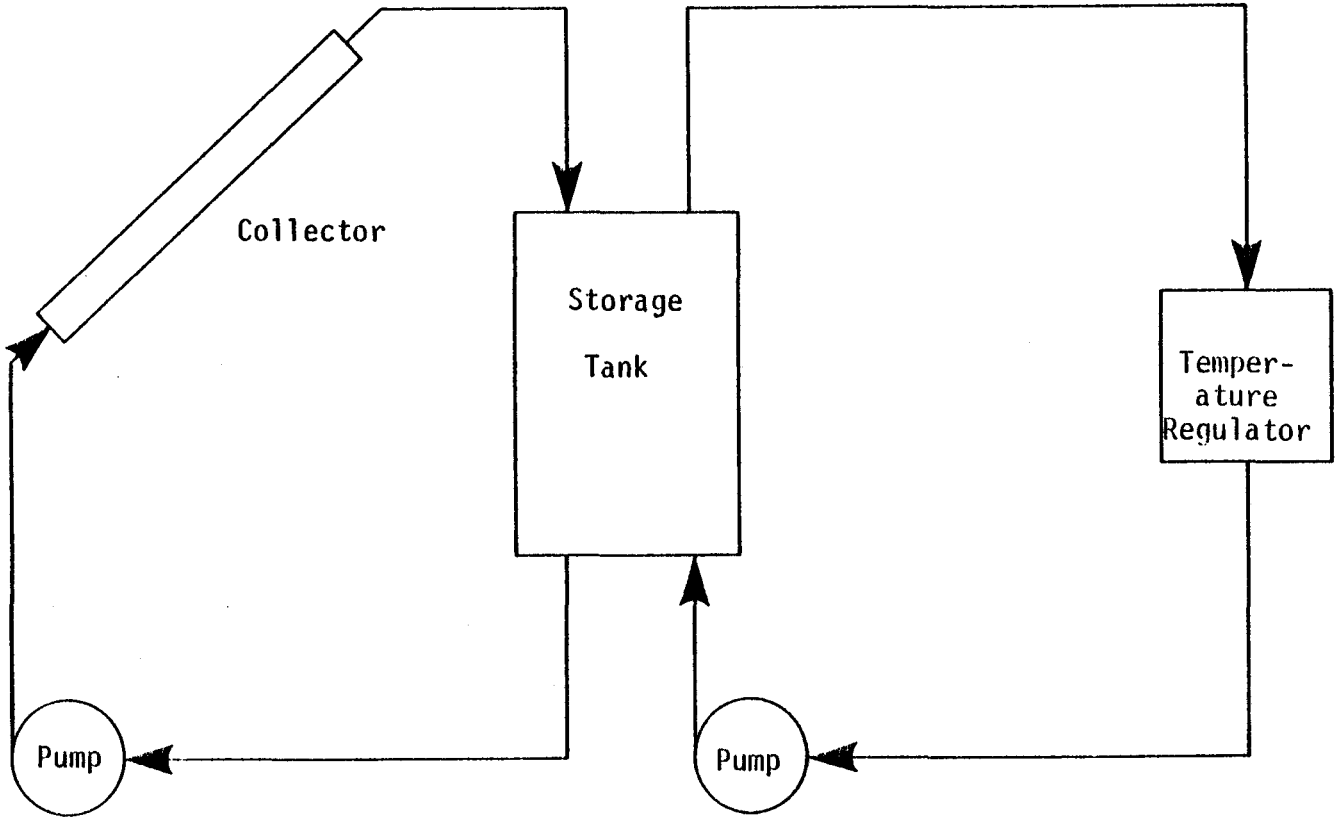


Figure 1. SYSTEM COMPONENT CONFIGURATION

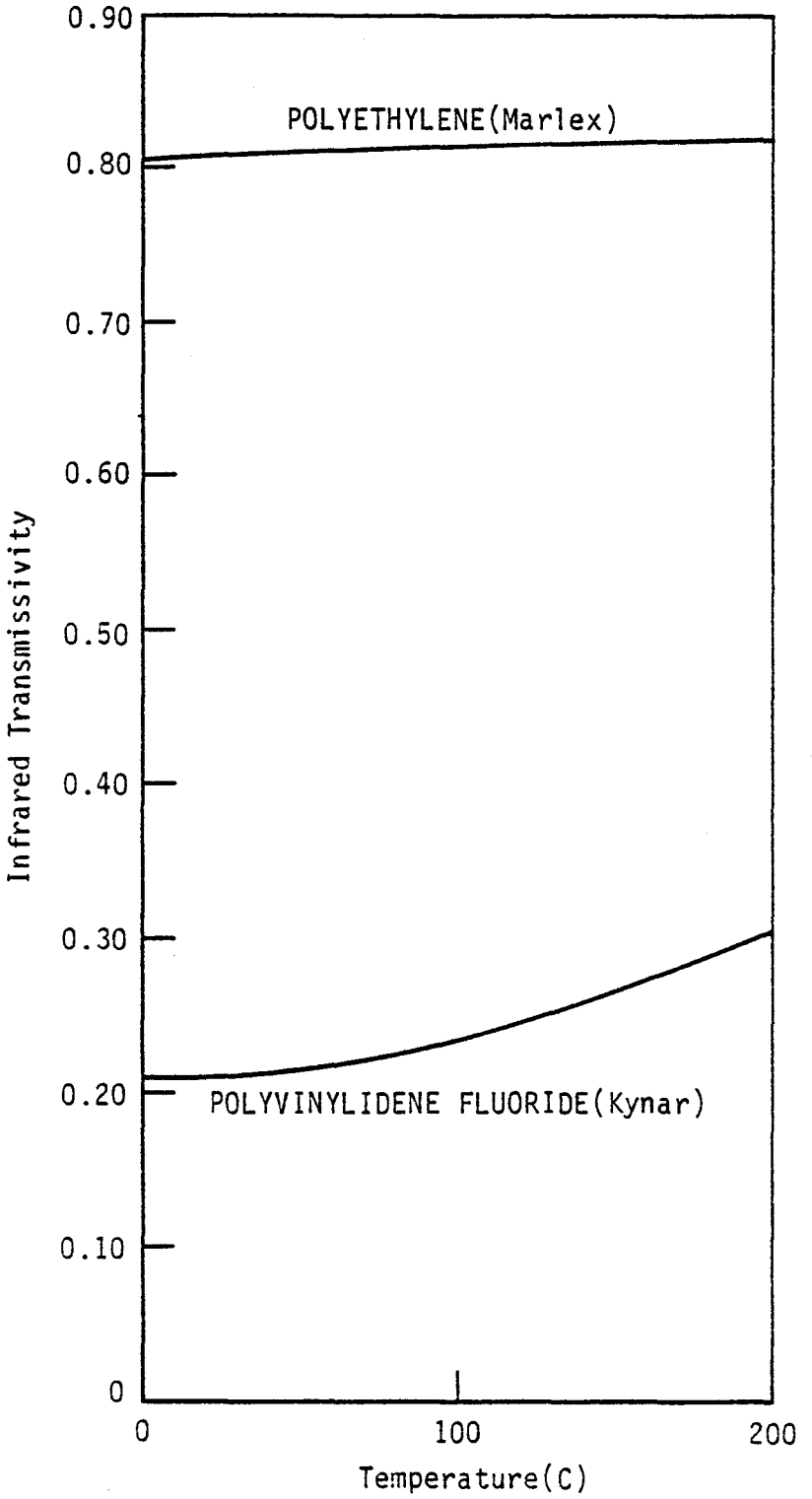


Figure 2. TEMPERATURE DEPENDENCE OF INFRARED TRANSMITTANCE OF SELECTED PLASTICS

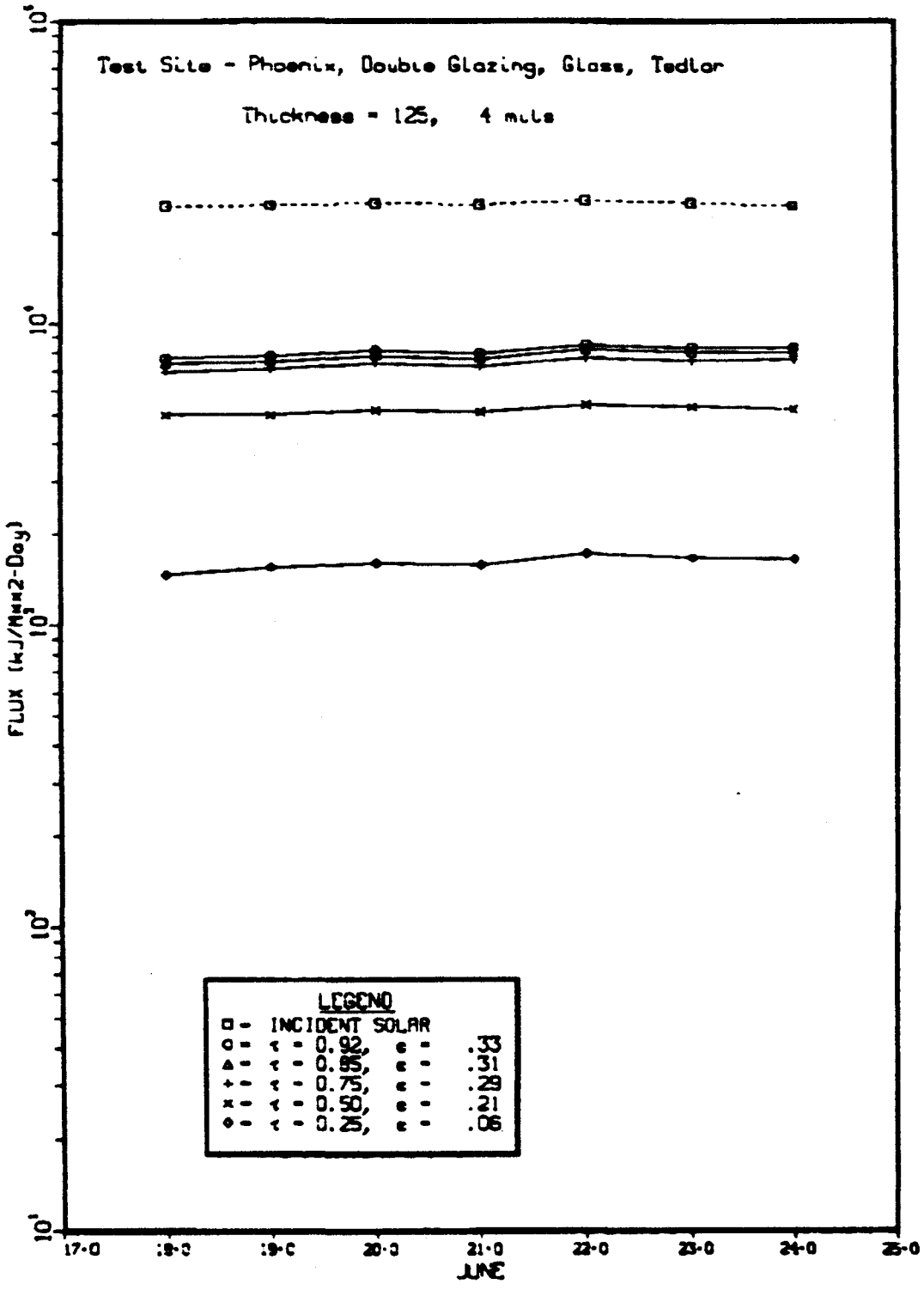


Figure 3a. SOLAR AND USABLE ENERGY FLUX VS. TIME

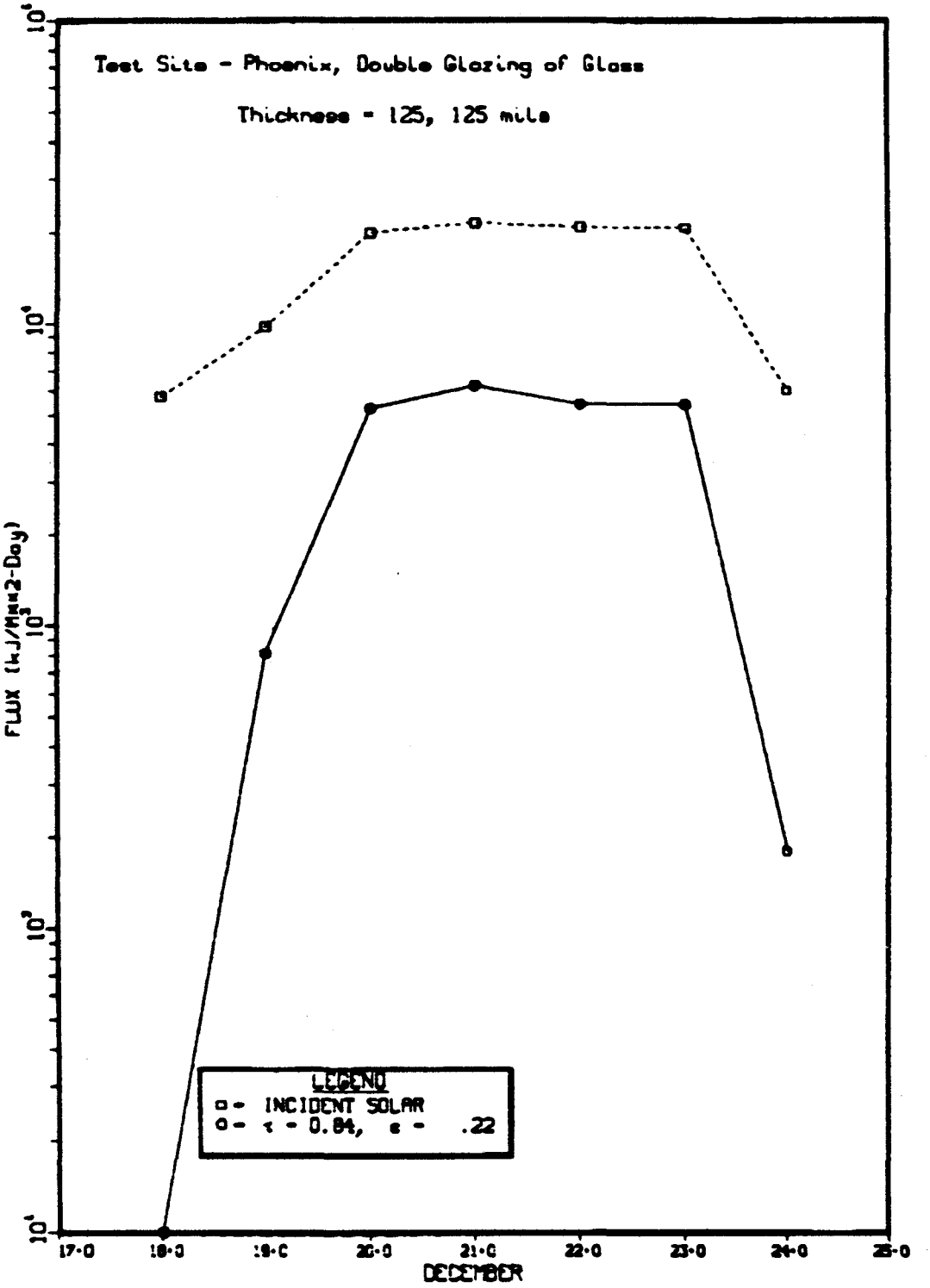
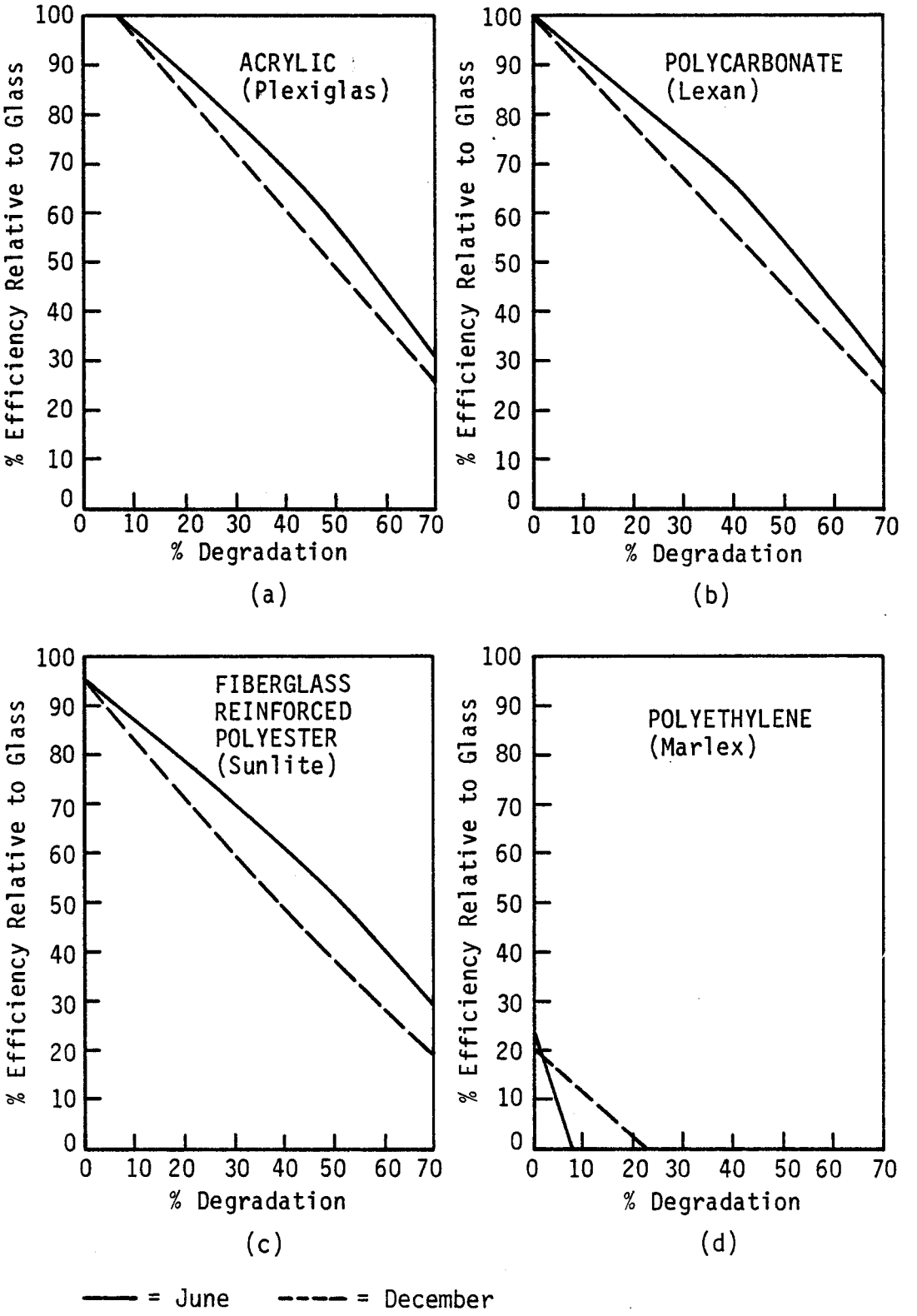
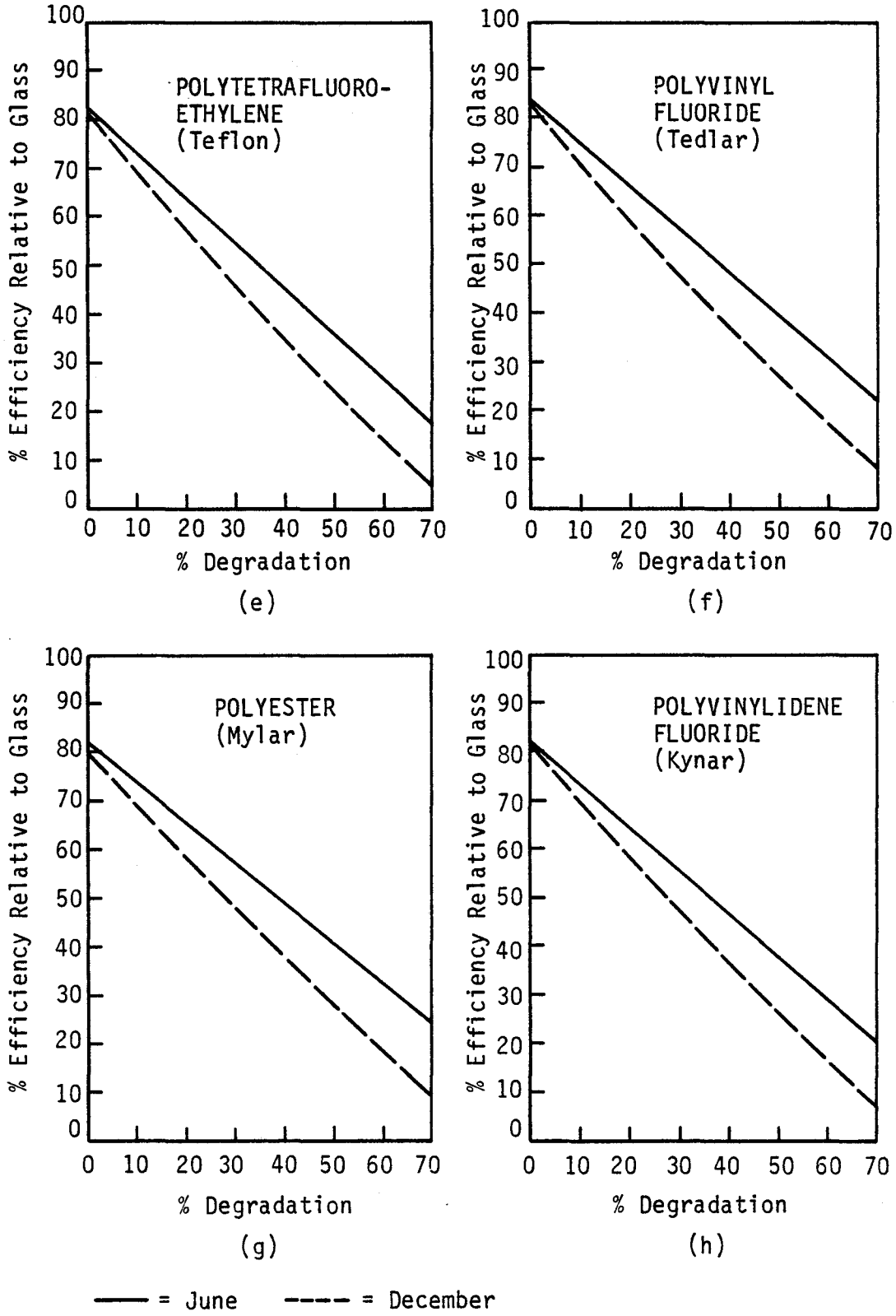


Figure 3b. SOLAR AND USABLE ENERGY FLUX VS. TIME



Figures 4a-d. EFFECT OF OPTICAL DEGRADATION ON EFFICIENCY FOR SINGLE GLAZINGS OF PLASTICS



Figures 4e-h. EFFECT OF OPTICAL DEGRADATION ON EFFICIENCY FOR SINGLE GLAZINGS OF PLASTICS

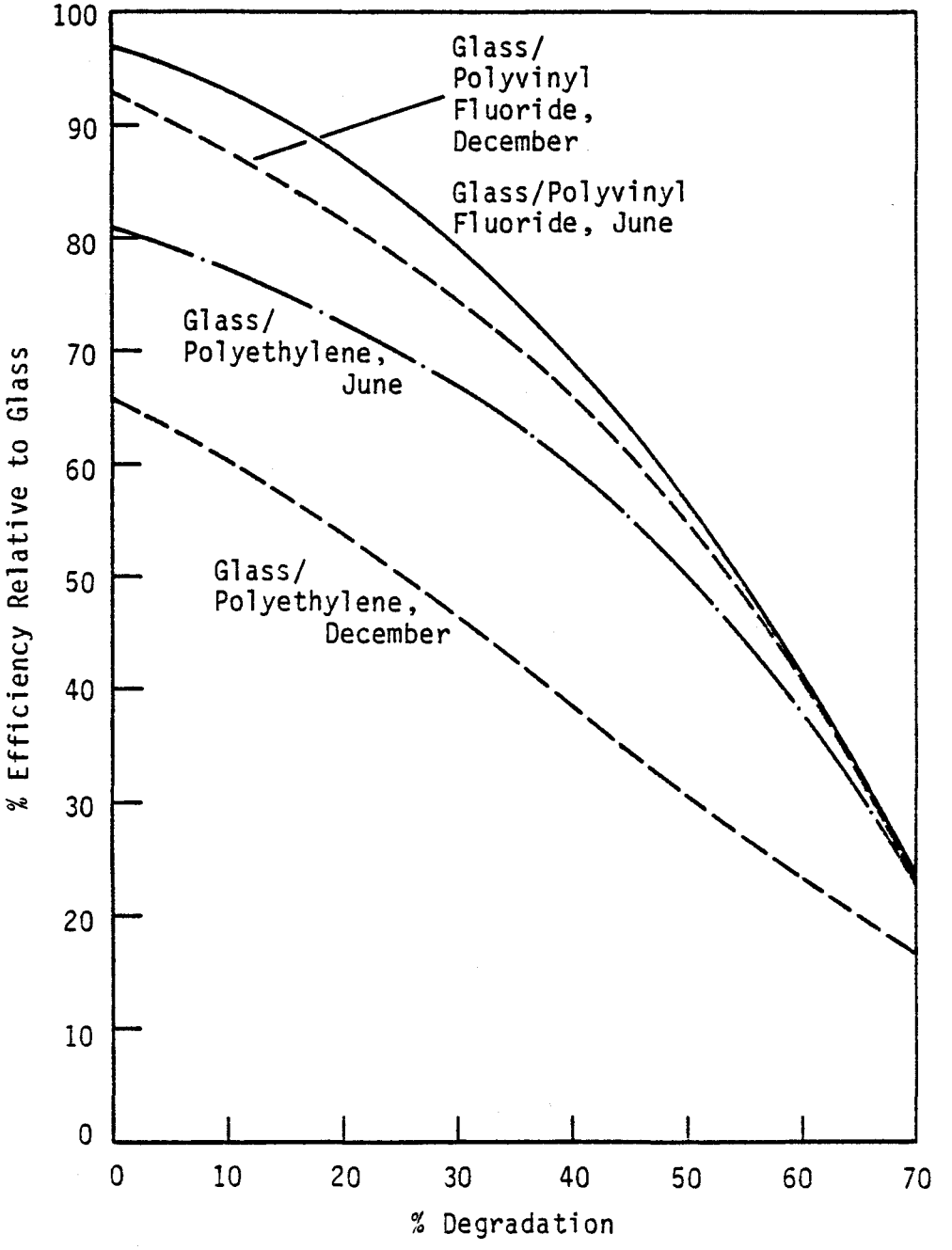


Figure 5. EFFECT OF OPTICAL DEGRADATION ON EFFICIENCY FOR DOUBLE GLAZING OF GLASS/PLASTICS

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