Advanced Low-Emissivity Glazings

S. Nadel, BOC Coating Technology, Fairfield, CA

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ABSTRACT
This paper discusses current trends in advanced low-emissivity glazings, comparing product requirements and trends in Europe and North America driven by residential and commercial architectural requirements. A brief description of the sputtering process and associated vacuum deposition equipment is given. Low-emissivity glazings which combine solar control with thermal insulation and high visible transmission are now available. The relative performance of these different products will be discussed. Advanced low-emissivity glazings under development utilizing high index materials are presented.

INTRODUCTION

Architectural glazings utilize thin film materials to control the flow of visible and solar energy through the glazing. The use of large scale sputter deposition of thin films for architectural glazings was pioneered nearly twenty years ago. With the development of the planar magnetron sputtering cathode in the early 1970's, the large scale deposition of architectural glazings became commercially feasible. The introduction of large scale sputter deposition created the capability to deposit a wide variety of thin film materials, enabling the creation of coatings with flexible variation in appearance and thermal performance.

Figure 1 shows a schematic representation of the sputtering process using a planar magnetron cathode. The key innovation which made sputter deposition an economical process was the use of magnetic fields to confine the plasma of backfill gas ions and electrons near the surface of the target. The basic patents on the planar magnetron cathode were issued to BOC in the early 1970's.

The planar magnetron was extremely successful in enabling the deposition of metal films and many useful reactive compounds. However the planar geometry of the magnetron cathode resulted in some significant processing limitations, especially for reactive deposition of heavily insulating materials. Since the erosion zone is localized in a ring pattern, areas outside of the ring are not sputtered. These areas can build up insulating reacted compounds, when target materials are sputtered in nitrogen or oxygen. Most of these oxide compounds are non-conductive, therefore they can build up

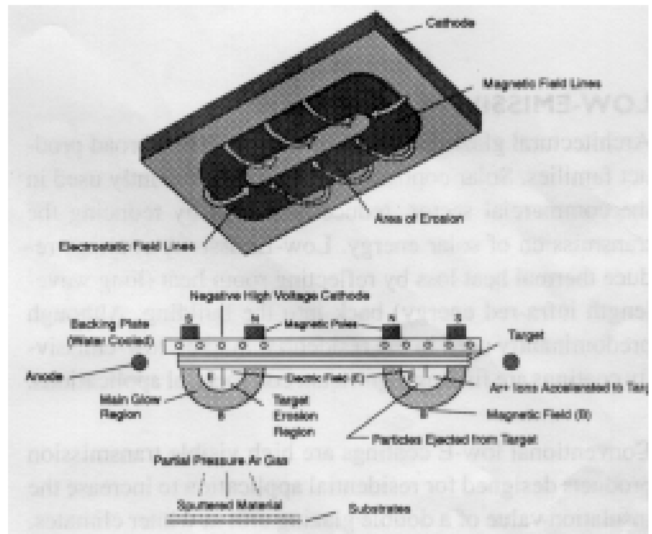

Figure 1 - Planar Magnetron

an electric charge from the plasma until the point at which the material breaks down with a destructive arc. This process has kept sputtering from being applied to very insulating materials such as silicon oxide or nitride, which have desirable optical or durability properties.

In 1989, BOC Coating Technology introduced a new magnetron cathode geometry, the rotating cylindrical magnetron cathode, or C-MAG® cathode. The rotating geometry ensures that all surfaces of the target material are sputtered, eliminating the ability for reactive layers to build up on the cathode. Figure 2 shows a schematic of the C-MAG cathode configuration. Currently, the common configuration for this source is to use two rotating tubes in the place previously occupied by a single planar magnetron.

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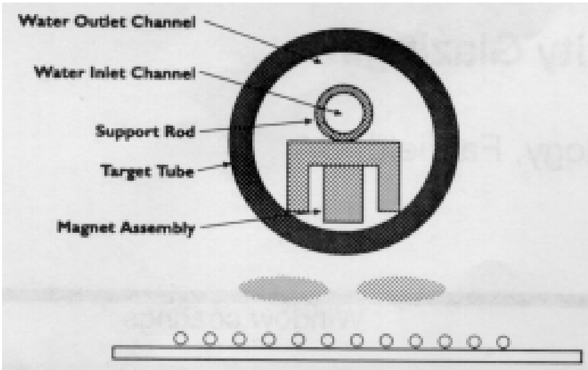

Figure 2-C-MAG Rotatable Cathode Cross Section

LOW-EMISSIVITY COATINGS

Architectural glazings can be divided into two broad product families. Solar control coatings, predominantly used in the commercial sector, reduce heat load by reducing the transmission of solar energy. Low-Emissivity coatings reduce thermal heat loss by reflecting room heat (long wavelength infra-red energy) back into the building. Although predominantly used in the residential market, low-emissivity coatings are finding significant commercial applications.

Conventional low-E coatings are high visible transmission products designed for residential application to increase the insulation value of a double glazing unit in winter climates. These coatings utilize a thin layer of silver, dereflected by transparent oxide layers, to reflect infra-red energy while maintaining a high visible transparency. In addition, a thin sacrificial metal layer is deposited between the silver and top metal oxide layer to protect the silver. The region of the infra-red from 5 to 50 microns in wavelength, is the region in which a heated room will radiate thermal energy. In this region, a typical low-emissivity coating will reflect from 85-95% of the thermal energy back into the room.

For reduction of heat loss, the low-E coating is typically glazed on the #3 surface of the insulated glass unit (with the number 1 surface being the outside surface of the lite facing out of the building). However, the ability to reflect infra-red energy can be adapted to the commercial solar control market, to provide products that combine higher visible transmission and lower reflectances with lower shading coefficients. In a solar control driven application, such as in commercial architectural use, the low-E can be glazed on the number 2 surface. This position takes maximum advantage of the low-E reflectance of the infra-red portion of the solar spectrum.

In cold dominated climates, such as Canada and Northern Europe, energy conservation regulations are typically written to include a solar gain component based on the glazing direction within the figure of merit for low-emissivity performance. These regulations therefore favor low-emissivity coatings with high solar energy transmission, and resulting high shading coefficients or solar heat gains.

In more variable climates such as the US, with cold winters and hot summers, a purely emissivity driven U-value calculation is used to express the night-time (no solar gain) thermal performance. To provide summer day-time solar gain reduction, low shading coefficient coatings are generally preferred for maximum year round energy conservation.

Low-E figures of merit for the US are determined according to NFRC standards for emissivity, U-value and shading coefficient. Figures in merit in Europe are dominated by the German market which is driven by the German energy legislation. Coordinated ISO and CEN standards are under development for emissivity, K-value (corresponding to US U-value) and G- or solar factor (equivalent to the US shading coefficient, multiplied by the solar heat gain factor of single strength glass of 0.87). However, the German legislation specifies a K-effective factor, which modifies the emissivity driven K-value with a directional solar gain factor. However, differences in solar weighting functions, treatment of convection corrections in the air gap, and other minor issues make direct comparison of US and European calculations difficult.

The low-E market is growing rapidly in the US and Europe. The most recent production figures for the US show a 1991 production level of 15 million square meters, rising to 47 million square meters in 1995. European production was 14 million square meters in 1993, and will rise to 26 million square meters in 1996, largely led by recent energy conservation legislation enacted in Germany.

A wide variety of low-emissivity coatings have been developed to meet demands for performance optimized for visible transmission, low-emissivity, high or low shading coefficient, materials choice, coating durability, etc. The various coating stacks currently in production are shown in figure 3. The performance advantages of these products, and coating families currently under development are discussed below.

Low-Emissivity Coatings for Winter Climates

For the residential market, very high visible transmissions (at least 75% for 4 mm glass double pane IGU's) and neutral color are required.

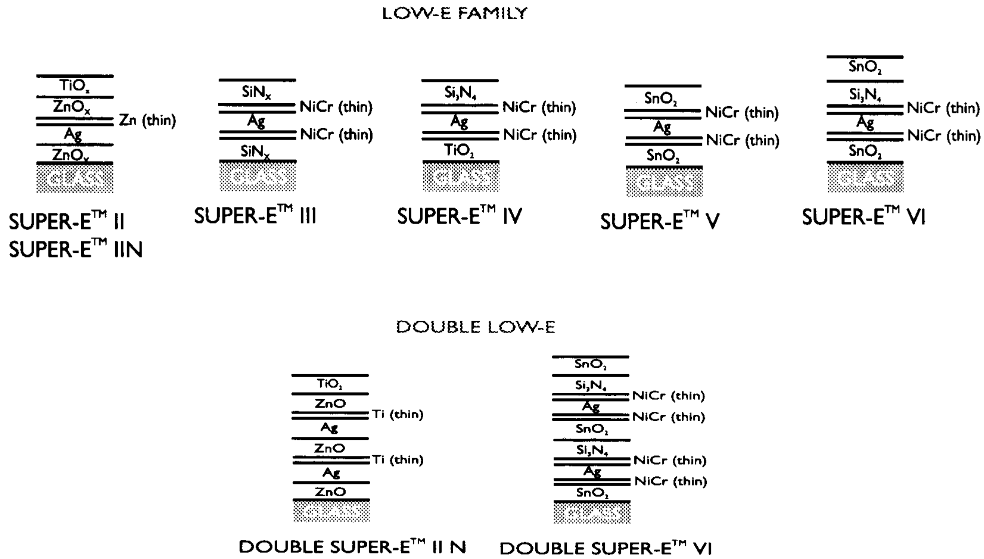

Figure 3- Structure of Standard Coatings Low-E Family

The basic product for heating dominated markets is a single silver layer coating, using either tin oxide or zinc oxide to de-reflect the silver. These products typically achieve a visible transmission of 84-87%, with a solar transmission above 60%. Emissivities of 0.10 are typical for tin oxide based coatings. Zinc oxide based coatings achieve lower emissivities of 0.08 or better. Corresponding U-values for IGU's with a 12.7 mm Argon filled gap are 1.5 W/m²-°C or less. Due to the high solar transmissions, shading coefficients are high at 0.75.

The typical visible and thermal performance factors for these coatings are shown in Figure 4. The net night-time heat loss, when their is no solar gain available, is reduced considerably, from 108 W/m² to 70 W/m². (All thermal performance values presented are center of glass calculations performed using Window 4.1)

Parameter		S-E II N	S-E V	S-E VI
T Vis		87	84	84
R film	Y	5.1	6.0	4.0
	a*	-4.0	-2.6	-0.5
	b*	-7.7	-4.1	-3.4
Rg	Y	6.0	5.0	5.0
	a*	-4.0	-2.7	-1.1
	b*	-10.1	-7.6	-7.6
Tsol		66.3	61.8	61.2
Rf sol		20.0	20.0	20.8
Rg sol		16.9	15.2	15.6
E normal		0.073	0.098	0.096
U-value (Ar)		1.45	1.54	1.53
S C		0.78	0.75	0.75

Figure 4- Base Single Low-E

High durability products have also been developed, which replace these oxide layers with silicon nitride or combinations of silicon nitride and titanium dioxide. These are extremely corrosion and abrasion resistant materials. These products achieve similar thermal performance, with greatly enhanced resistance to abrasion, humidity, salts, acid and base attack. The deposition of materials such as silicon nitride is made possible by the use of the rotatable magnetron source. Typical coating stacks utilizing Si_3N_4 are shown in figure 5, and the corresponding thermal performance values are shown in figure 6.

Low-Emissivity / Low Shading Coefficient Glazings

To provide thermal insulation in winter and solar shading in summer requires products with a low-emissivity and low shading coefficient. The commercial glazing market can accept products with more moderate visible transmission levels and more color options than the residential market. For commercial applications, coatings based upon modifications of the single silver layer coatings can be used.

Super-E III

glass / Si_3N_4 / NiCr Ag NiCr / Si_3N_4

Super-E IV

glass / TiO_2 / NiCr Ag NiCr / Si3N_4

Figure 5- Silicon Based Coatings

	Super-E III	Super-E IV
%T	76	82
%Rg	4	6
%Rf	8	4
%Tsol	62	63
%Rg sol	12.4	15.5
%Rf sol	14	19
En	0.16	0.10
K(Ar)	1.92	1.51
S C	0.78	0.78

Figure 6- Silicon Based Coatings Thermal Performance

The "Sunbelt" low-E products are based upon single layers of silver where either the silver or protective metal layer are increased in thickness to lower the visible transmission of the coating. As measured on 4 mm clear glass, the visible transmission can be reduced from a value of greater than 84% for residential application, to approximately 50-60% for commercial solar control applications. The Sunbelt series film stacks are based upon the use of silver and tin oxide (SnO_2).

The "Sunbelt" series consists of three products. Figure 7 shows the visible, and thermal performance values for these products. The Sunbelt Neutral coating has a very low visible reflectance and little color, and is finding increased use in commercial low-E applications. This product can be used in markets which restrict the external visible reflectance of glazing systems. There are also blue and silver colored coatings. The silver coating offers the lowest emissivity and U-value, and the most solar shading. However, the external visible reflectance level is more comparable to the brighter stainless steel based solar control coatings.

While a clear IGU will transmit 75% of the available solar radiation, an IGU with the Sunbelt Neutral product glazed on the number 2 surface will transmit only 40% of the solar radiation. Hence a low shading coefficient can be achieved with a high visible transmission product, with minimal visible reflectance to the outside of the building (less than 15% for an IGU).

Even better performance can be achieved with a more sophisticated coating design utilizing two silver layers. "Double Low-E" is basically two low-E film stacks superimposed. This coating provides the highest performance combination of high visible transmission, low U-value and low shading coefficient (see figure 8). As a result, it is now a major low-E product in the US market, and is growing in the European market

Emissivities of less than 0.05 (i.e. infra-red energy reflection levels of greater than 95%) are typically achieved, resulting in U-values for Argon filled units below 1.4. Shading coefficients of less than 0.5 can be achieved. As a result an IGU glazed with double low-E on the number 2 surface reduces the transmission of solar energy from 75% for a clear glass IGU to 41%. (see figure 9). At the same time, visible transmission for the IGU is over 70%. This makes the double low-E coating suitable for both commercial and residential markets. For winter applications, a double low-E IGU filled with Argon gas can achieve a U-value of less than 1.4 W/m² (4 mm glass, 12.7 mm air space)

The use of two silver layers results in a coating system in which visible appearance (reflectivity and color) are much more sensitive to physical thickness variation of individual coating layers. Computer optical modeling has been used to determine the physical thickness uniformity required to

Optical Parameter	Neutral	Blue	Silver
Visible Transmission	57	60	49
Film Side Reflectance			
Y	4	7	34
a	5	-1	1
b	7	-25	-10
Glass Side Reflectance			
Y	10	21	38
a	1	-3	-2
b	-4	-13	-3
Solar			
Transmission	40	45	34
Film Slde R	22	20	56
Glass Slde R	15	20	50
Emissivity	<.10	<.10	<.05
Shading Coefficient (6-12-6 IGU)	0.51	0.47	0.38

Figure 7- Sunbelt Product Optical Specifications

Glass / ZnO / Ag Ti / ZnO / Ag Ti / ZnO / x / ZnO

where, x can be TiO_2, SnO_2 or Si_3N_4

Tvis		**75%**	**Tsol**	**41%**
Rf	**Y**	**4**	**Rf sol**	**34%**
	a	**-2.3**	**Rg sol**	**27%**
	b	**-2.7**		
Rg	**Y**	**4.8**	**E n**	**0.045**
	a	**-0.3**	**U (Air) = 1.77**	**U(Ar) = 1.39**
	b	**-0.5**	**SC**	**0.47**

Figure 8- Zinc Based Double Low-E

achieve high uniformity of appearance. By using ellipsometric measurement of optical constants of individual film layers deposited on production systems, we can predict the variation in appearance associated with total layer thickness variation in a coating stack.

Table 1 shows the comparative thickness and associated appearance uniformity for a typical ZnO based single and double silver layer coating. This table shows the required physical thickness tolerance needed to control visible transmission, film and glass side reflectance to within ± 0.5 - 1.0 %, and to control reflected color (Hunter a, b units) to within ± 0.5 - 1.0 units. As can be seen, the physical thickness uniformity for a double low-E production system must be at least twice as exact as a conventional single low-E system, to achieve comparable uniformity. To meet these requirements, modern production systems are designed to achieve better than ± 2% physical thickness uniformity.

Advanced Low-Emissivity Coatings

Further advances in low-emissivity performance require the capability to reduce the emissivity, while controlling the shading coefficient for winter heat gain or summer solar shading. This requires the use of thicker silver layers to further reduce the emissivity. However, thicker silver layers alone will typically result in lower visible transmissions and higher reflectances. This can be overcome by utilizing transparent oxides, such as TiO_2, which have a higher index of refraction. This allows the silver layer to be more efficiently de-reflected in the visible region. In Figure 10 the results of optical modeling of such stacks, indicates the increasing index of refraction required to maintain coating appearance (visible transmission, color) as silver thickness is increased to reduce emissivity.

Single silver layers utilizing either an all TiO_2 stack, or combining TiO_2 with ZnO for sputtering efficiency, have

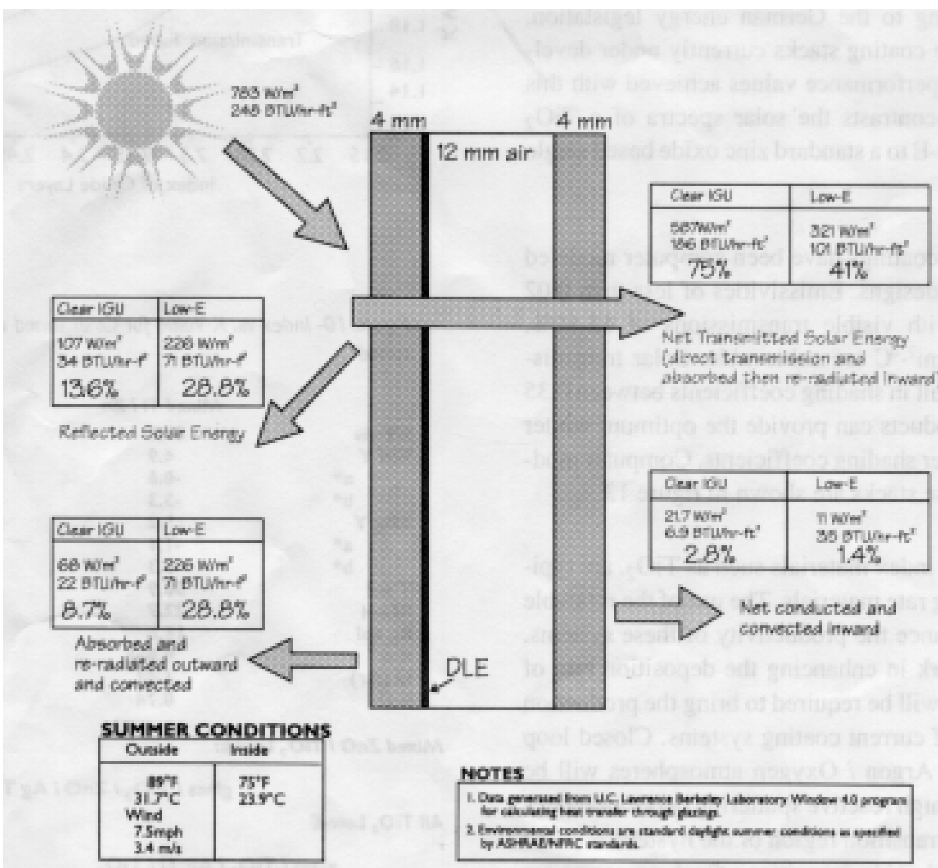

Figure 9- Double Low-E SUMMER: Solar Shading

Parameter Tolerance	%T	%RfY	a	b	%RgY	a	b
Single Low-E							
+ 0.5	7%	9%	<3%	1%	6%	3%	1%
+ 0.75	10%	10%	4%	<2%	<7%	5%	2%
+ 1.0	10%	10%	6%	<3%	7%	6%	3%
Double Low-E							
+ 0.5	2%	3%	<1%	1%	4%	1%	<1%
+ 0.75	3%	5%	<2%	<3%	4%	2%	1%
+ 1.0	4%	6%	<2%	2%	<5%	<3%	<2%

Percentages are thickness tolerances to achieve desired optical tolerance

Table I- Comparative Sensitivity Analysis Zinc Oxide Based Single vs Double Low-E

achieved emissivities of 0.05 to 0.07, with visible transmissions above 82% and high solar transmissions. U-values of 1.4-1.5 approach the level of the double silver layer product, while shading coefficients remain high at 0.7. These products are optimized for climates with very cold winters and cool summers, where lowest U-value and maximum solar gain in the winter is preferable to solar shading in the summer. These products will provide an optimized value of K-effective according to the German energy legislation. Figure 11 shows the coating stacks currently under development and typical performance values achieved with this coating. Figure 12 contrasts the solar spectra of a TiO_2 enhanced single low-E to a standard zinc oxide based single and double Low-E.

Double silver layer coatings have been computer modeled based upon similar designs. Emissivities of less than 0.02 can be achieved with visible transmissions of 65-80%. U-values of 1.3 W/m²-°C are achievable. Solar transmissions of 30-40% result in shading coefficients between 0.35 and 0.50. These products can provide the optimum winter U-values and summer shading coefficients. Computer modeling results for these stacks are shown in figure 13

Unfortunately, high index materials such as TiO_2, are typically slow sputtering rate materials. The use of the rotatable magnetron can enhance the productivity of these systems. However future work in enhancing the deposition rate of high index material will be required to bring the production cost down to that of current coating systems. Closed loop operation in mixed Argon / Oxygen atmospheres will be required to achieve high reactive sputtering deposition rates by operating in the transition region of the hysteresis curve between metallic and oxide depositions. Such processes are currently under development for production systems.

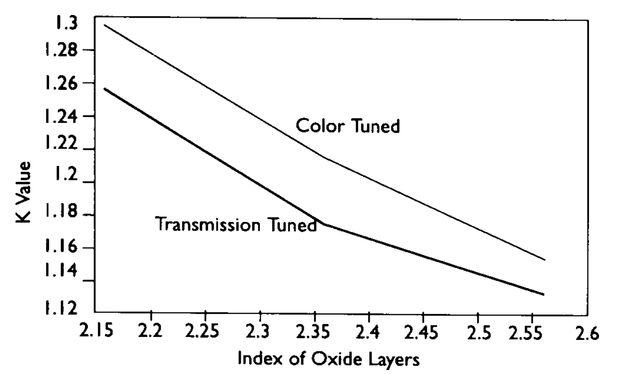

Figure 10- Index vs. K Value for Color tuned and Transmission tuned

	Mixed Ti / Zn	*All Ti*
%T vis	82.8	84.4
%Rf Y	4.9	6.5
a*	-0.6	-7.7
b*	-3.3	-10.6
%Rg Y	5.2	7.5
a*	-1.1	-7.4
b*	-9.3	-12.4
T sol	58.9	58.1
Rf sol	22.7	27.2
Rg sol	16.6	21.8
E n	0.068	0.051
U (Ar)	1.47	1.42
S C	0.74	0.67

Mixed ZnO / TiO_2 Low-E:

glass / TiO_2 / ZnO / Ag Ti / ZnO / TiO_2

All TiO_2 Low-E

glass / TiO_2 / Ag Ti / TiO_2

Figure 11- TiO_2 Based Single Low-E

CONCLUSIONS

Architectural glazings control the flow of solar energy into and out of a building, while adding a broad selection of visual appearance. The glazings act as selective filters, choosing which wavelengths of light and thermal energy will be transmitted or reflected.

The use of low-emissivity coatings for solar control applications, opens up the opportunity to achieve low shading coefficients with a higher visible transmission. Therefore, maximum use of available natural daylight can be made, while reducing summer thermal heat loads and winter thermal losses. The low-E coatings are more selective, providing high visible transmissions with very low infra-red transmissions. Figure 14 compares the transmission of solar control and low-E products over the solar spectrum, from the ultraviolet region between 300 and 400 nanometers in wavelength, through the visible at 400-700 nanometers, to the near infrared between 800 and 2500 nanometers wavelength. The increasingly spectrally selective operation of these coatings are clearly shown.

Future demands for energy conservation and design flexibility will continue to require more advanced products. The capability to control both solar heat gains and thermal losses, will continue to be critical design features for building construction. Future products will be called upon for higher levels performance, by additionally maximizing use of available natural daylight both for user comfort and to reduce energy demand for lighting purposes.

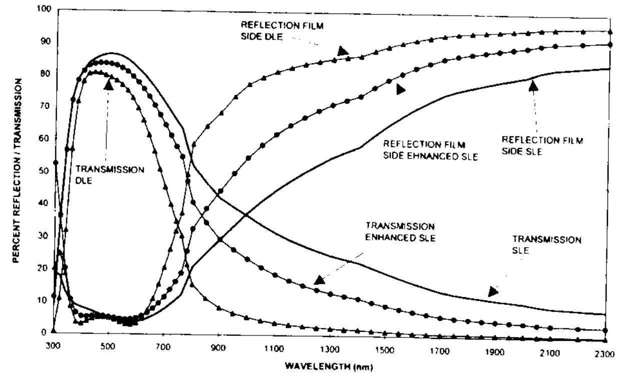

Figure 12-DLE vs. Enhanced SLE vs. SLE

Parameter	*All $TiO_2^{A)}$*	*All TiO_2*	*SnO_2/TiO_2*
T Vis	78	69	65
T sol	42	31	29
Rf sol	40	51	50
Rg sol	30	40	40
E n	.02	.01	.01
U (Ar)	1.34	1.32	1.32
S C	0.48	0.36	0.34

Figure 13-Advanced Double Low-E

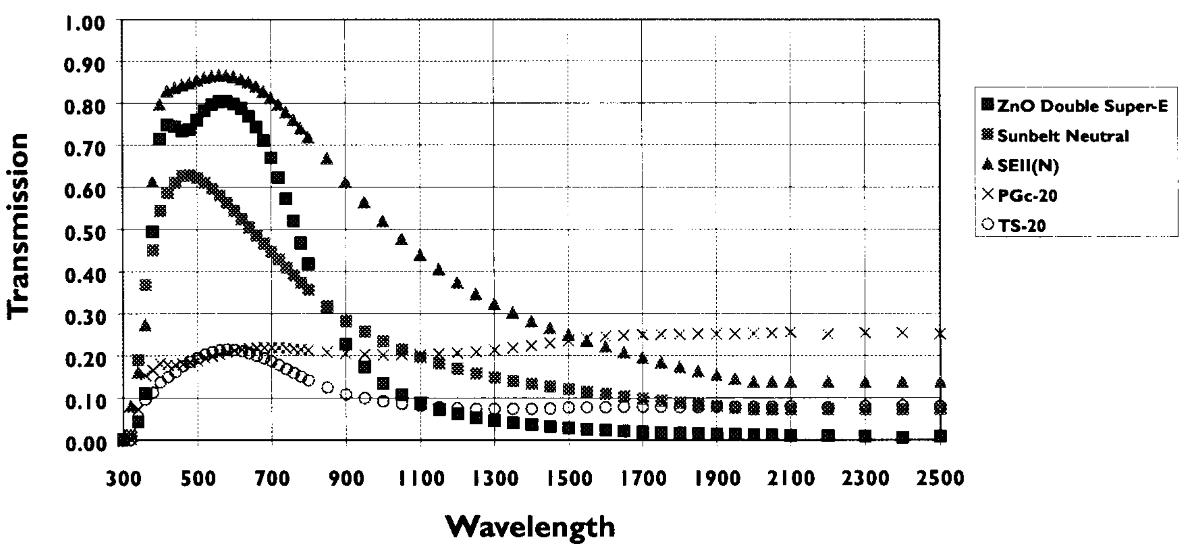

Figure 14- Comparison of Solar Performance