Design strategy for Low e windows with effective insulation

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ABSTRACT

Optimal window glass assemblies have been developed for three use cases, when the average outside temperature is greater or less than the target indoor temperature. These assemblies have 2x better insulation than a standard double glazed window. They were developed by identifying insulation strategies for each of the 4 energy bands that transfer heat through windows. The insulation strategies were identified through analytical models for each energy band. The strategies were then applied to glasses in the DOE International Glass Data Base and evaluated using the industry standard modelling programs. These evaluations provided a systematic method to developed optimal glass assemblies.

1.0 INTRODUCTION

A typical house looses 1-4kW of energy through double pane windows, depending on location. Improving the energy efficiency of windows is a significant cost and energy saving opportunity. Identifying the best window assembly is complicated by the fact that there are literally thousands of glasses that claim to provide improved energy savings. Furthermore, there can at least a 30C variation in outside temperature depending on the season and time of the day.

The goal of this paper is to de-mystify the process for selecting optimal window assemblies.

The first step is to recognize that there can only be a single window design so of necessity the design must be based on the average temperatures at the location; which simplifies the problem to 2 use cases whether the average temperature is higher or lower than the target temperature inside the structure.

The second step is to recognize that the optical properties of window glass means that there are 4 different energy bands that determine the effectiveness of a window; visible transmission, solar near IR heating, mid IR re-radiation from structures, and thermal convection. It is desirable to reflect solar near IR in hot climates to reduce A/C bills, and to transmit solar near IR in cold climates to heat the structure. The impact of solar near IR is known as Solar Heating Gain Coefficient or SHGC.

The next step is to develop analytical models for each energy band and use the insights to create design rules for selecting glasses and glass assemblies.

Finally these design rules were applied to the DOE International Glass Data Base and associated modelling programs to design optimal windows for the 2 use cases.

2.0 CLASSIFICATION OF ENERGY BANDS

As a warm blooded species, our body temperature (37C/98F) determines the temperature that we feel comfortable. We are most comfortable in an environment that is just cool enough to remove the heat we generate internally. The heat and air conditioning are used to keep the structure at a constant temperature, around 68F/20C. When the environment is hotter that the structure then energy flows into the structure. When environment is colder and energy flows out of the structure. The bigger the temperature difference, the greater the energy flow. The energy is being exchanged by conduction and radiation.

The natural variation in energy flows includes the daily and seasonal swings in air and ground temperature, and whether there is cloud cover. Of necessity, the design of the structure can only be optimized to the average environment that structure will see over its useful life. There are only 2 use cases that are relevant, either the average environment is higher or lower in temperature than the structure. The average annual temperature in the “city ratings” show that of 140 cities around the US all but 12, have an annual average below the comfort target [1] . The first conclusion is that most US structures are at a net energy deficit, favoring insulation that keeps heat in the building and heat harvesting decisions such as south and west unshaded exposure.

In hotter climates, avoiding heating during the day is critical. As an example, in Austin Tx, the yearly average 68F is essentially the same as the target comfort temperature. The average mid summer temperature is 85F (+15F from comfort) max 105F (difference 35F from comfort); average mid winter 48F (difference -22F) min 32F (difference -38F). As expected, the summer AC and winter heating bills are very similar.

The variation within a single day is also important. As a general observation for the planet, we know that radiative heating during the day must balance radiative cooling to avoid thermal runaway. In cooler climates, the average temperatures are below comfort and the daily cycle of outside temperature means the night time differential (T comfort – T night) will be greater than day time (T comfort – T day). The larger the differential, the greater the heat transfer. This analysis suggests that night time heat trapping is more important that day time solar heat harvesting for cooler climates. In each use case, heat transfer during the day and at night must both be considered.

In summary there are 3 scenarios for heat transfer; average environment higher or lower than the structure, and night time, combined into 2 use cases.

2.0 PROPERTIES OF WINDOWS

The properties of window glass separate heat transfer into energy bands illustrated in Figure 1. The energy spectrum is shown on the left side of Figure 1, including the solar output in the visible and near IR, black body re-radiation in the mid IR, and thermal conduction. The optical transmission of Soda Line glass, middle section of Figure 1, passes the visible and near IR and absorbs the mid IR. The absorption of the mid IR gives rise to the well known “greenhouse effect” in which re-radiation from inside the greenhouse is trapped.

The requirement for visible transmission also limits the materials choices to mitigate re-radiation. Emissivity is primarily a function of coating conductivity. Materials based on tin oxide such fluorine doped tin oxide ($SnO_2:F$) are used an transparent conductors for displays and have an emissivity of 0.25. Very thin (15 nm) silver (Ag) is partially transparent and used in “partially silvered mirrors” with a very low emissivity of 0.02, as shown in optical properties of silver also shown above. To minimize conduction, multi-pane windows with the high atomic weight noble gases are preferable as a gas fill also shown in Figure 2.

To evaluate the insulation properties of windows, the 4 different energy bands that must be considered are; visible, near IR down to 3 um, mid IR below 3 , and thermal conduction.

3.0 ENRGY BANDS FOR HEAT TRANSFER

Having identified the heat transfer scenarios and the energy bands defined by the properties of window glass, the next step is to analyze heat transfer in each scenario. The scenario that most people relate to is the desire to reduce air conditioning during the day in hot climates illustrated at the top of Figure 2. In hot climates, the goal is to reduce solar near IR that passes through the window, which is accomplished using spectrally selective coating such as thin silver layers. Warmed by the sun, the earth and all its structures also act as a black body that re-radiates in the mid IR centered on 10 um. Window glass absorbs in the mid IR,

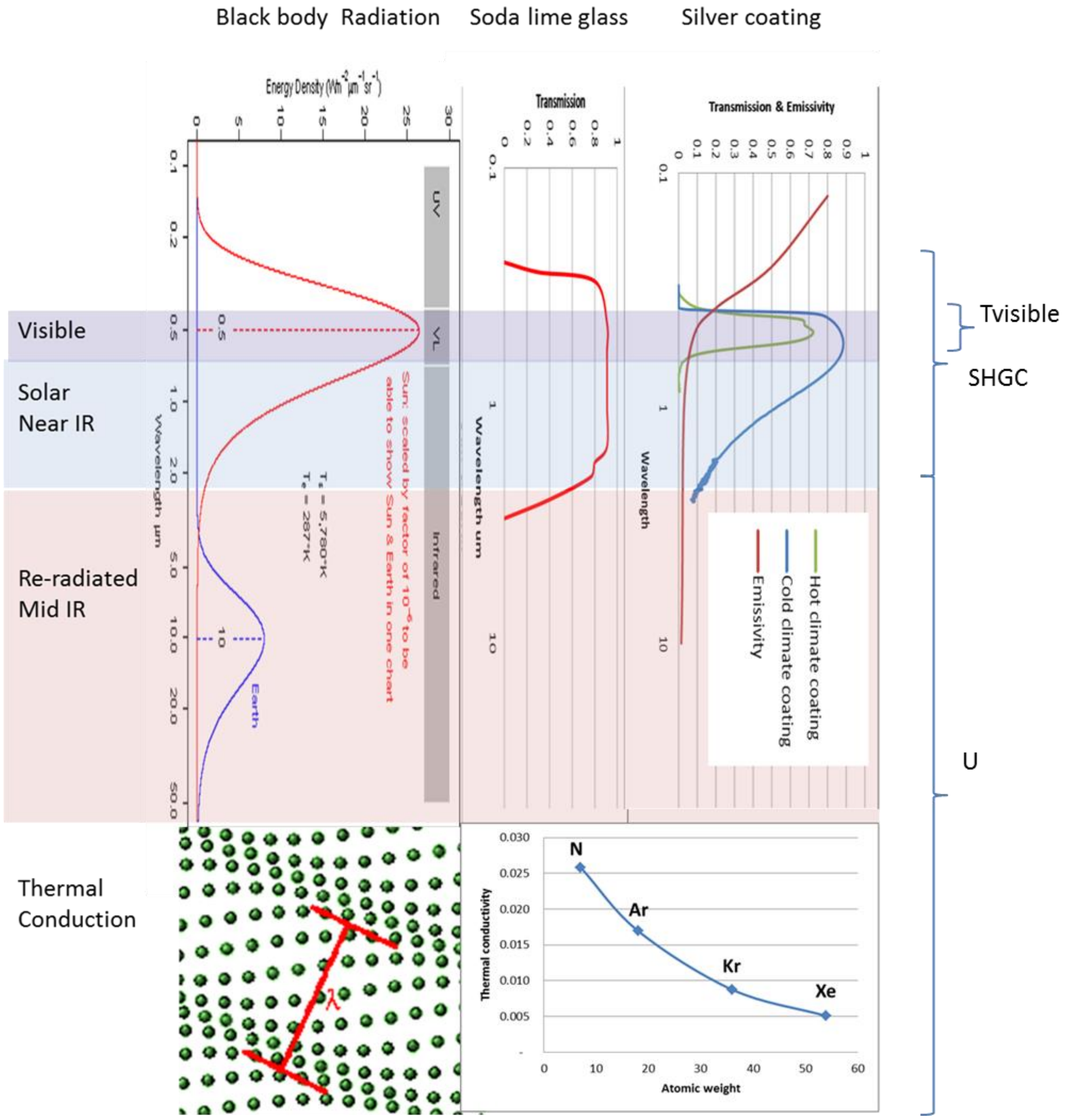

Figure 1Materials engineering the optimal solutions. At top left, the black body emissions of sun and re-radiation from earth , In middle, the transmission of soda lime glass . At top right, the transmission spectrum of the optimal coatings for cold climates (IGDB#6261), hot climates (IGDB#1506), and emission spectrum of Ag films . At the bottom, thermal conduction illustrated by phonon vibrations and the reduction of thermal conductivity with atomic weight for the noble gases. The bands contributing to the different insulation metrics are shown at the extreme right, the Solar Heating Gain Coefficient (SHGC) and thermal conductance (U).

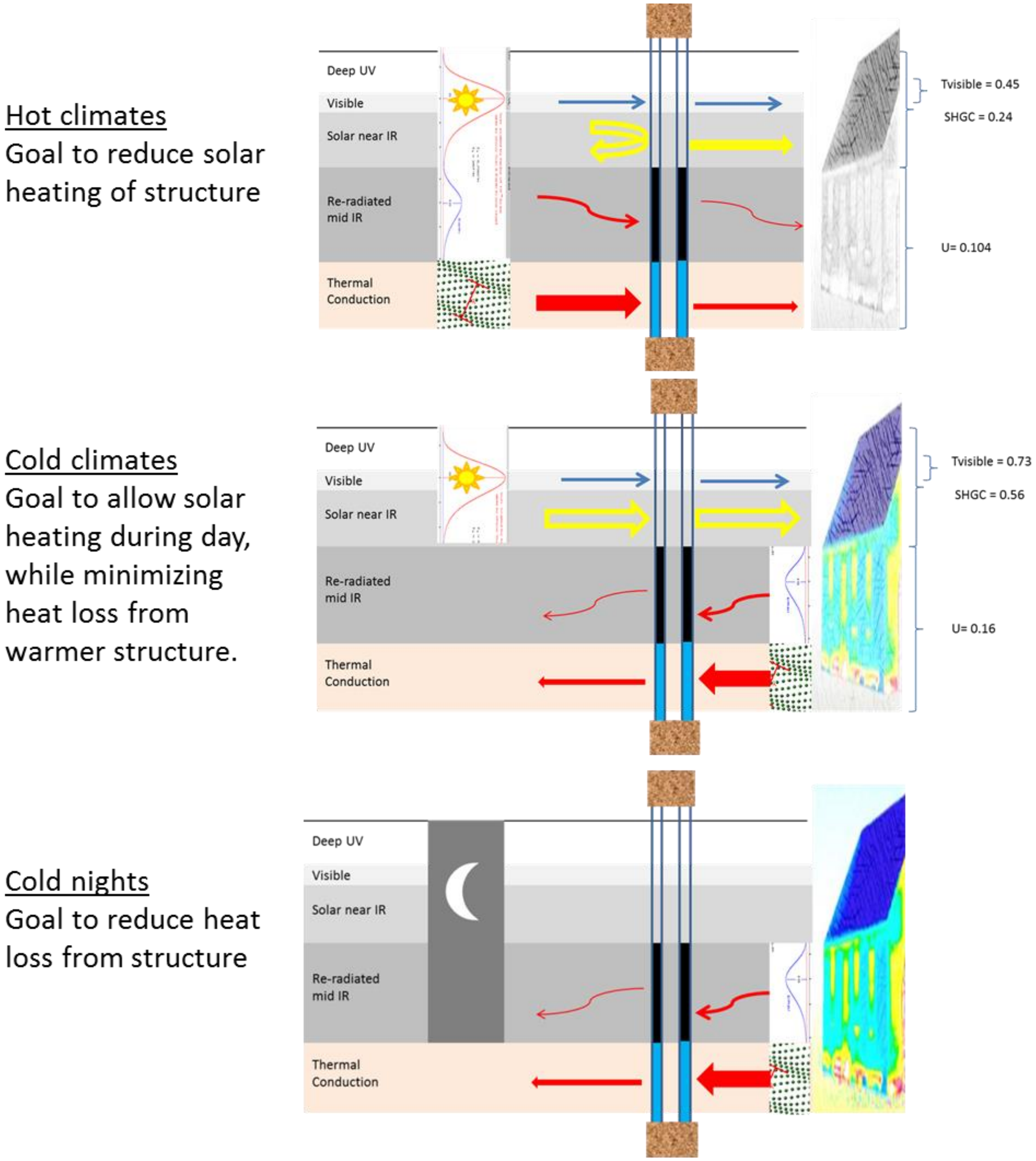

Figure 2 Schematic of energy transfer in hot and cold climates, and at night. The optimal window performance in both climates based on windows designed using selection criteria applied to the IGDB data base of window glass.

so mid IR is transferred through glass by absorption and re-radiation. Re-radiation is reduced using coatings that have low “emissivity” of black body radiation. Finally, thermal convection is reduced by using double pane windows with a thin layer of static air that acts as a thermal insulator

The second scenario is daytime solar heating in cold climates. In this case, the goal is to make the window transparent to the solar near IR so as to heat the structure during the day, while minimizing thermal losses in the mid IR and thermal convection from the warm structure.

The third scenario occurs at night where the structure is much warmer that the environment and the goal is to reduce both re-radiated heat loss in the mid IR, and thermal conduction.

The optimal performance of windows designed using commercially available glass is also shown in Figure 2.

4.0 ANALYSIS OF ENRGY TRANSPORT

To develop selection critieria for window glass, conduction and re-radiation will be analyzed separately and then combined together and matched to a commercial simulator. Then the control of solar IR heating will be discussed.

4.1 Estimation of convection insulation of windows

Personal comfort is primarily determined by air temperature, and air temperature is controlled by heat passing through windows, floors, walls and ceiling and changed the air temperature by conduction. Conduction heat transport between a surface of the house and the outside, include three steps, transfer between air and the surface, conduction through the surface, and transfer to air on the other side.

This model can be easily expanded for double and triple pane windows. The series resistances in a double pane window are;

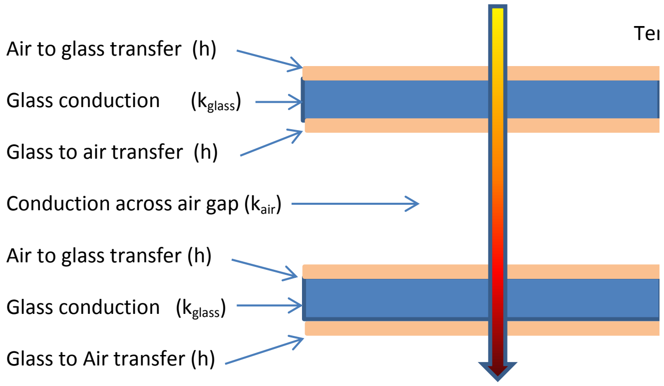

Figure 3. Schematic of conduction through a double pane window.

The heat transfer through a single pane is represented by a set of series resistors shown below:

The equation for heat transfer through p planes (p>1) is;

$$U = \frac{(T_1 \ \ - T_2 \ )}{\frac{2p}{A \ \ h} + \frac{p * L_g}{A \ \ k_g} + \frac{(p-1) * L_a}{A \ \ k_a}}$$

Series resistance model for heat transfer depends on Temperature (T), heat transfer coefficient (h), area (A), surface thickness L, the conductivity of the material (k)[2] either glass or air. The terms 1/hA, L/kA, at a standard 1 ft^2 are the "R" values for the heat exchange steps. The heat transfer "U" in Figure 3 is generally known as thermal conductance.

4.2 Estimation of mid IR re-radiation insulation of structures

The warm glass absorbs the mid IR emitted by the hot side of the glass, and the re-radiates as a black body to the cold side of the glass. The radiation heat transfer from a hot body to cooler surroundings is based on the properties of black bodies. There are a series of paired emission and absorption events between absorbing layers separated by transparent gaps. A double pane glass is shown in Figure 4, with 3 paired exchanges.

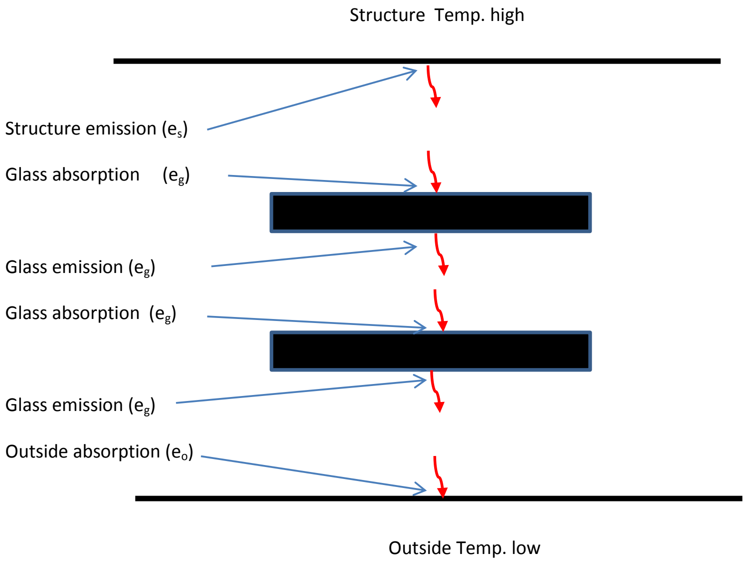

Figure 4 Schematic of paired emission and absorption events in a double pane window

The equation for energy transfer for a multiple pane window is ;

$$U = \frac{\sigma(T_1^4 - T_2^4)}{\sum_1^{p+1}\left[\frac{1-\epsilon_1}{A_1\epsilon_1} + \frac{1}{A_1F} + \frac{1-\epsilon_2}{A_2\epsilon_2}\right]}$$

Black body energy transfer for a "p" pane window with p+1 emission – absorption pairs [3], where T_1 = hot body absolute temperature (K), T_2 = cold surroundings absolute temperature (K), A = area of the object (m^2), ε =emissivity of the surface, F is a shape factor which is 1 for two parallel planes. and σ = Stefan Boltzmann constant 5.7 10^{-8} W/ m^2 K^4. In the case of structure and its surroundings, the temperatures are low and the differences are small, so when T_1 is 20C

(293 K) and $T_2 = T_1 +-20C$, $(T_1^4 – T_2^4)$ approximates to a straight line with a slope $9.5x10^7$/C. The radiation heat transfer becomes = 5.5 W/ m^2 C. When its freezing outside and the structure is a typical house with 50 $meter^2$ of windows, the radiation losses are 2.5 kW.

4.3 Combined Thermal insulation radiation and conduction

Conduction (U_c) and re-radiation (U_{rr})are two energy transfers that occur in parallel through the window, so the thermal conductances (U) get added together. The thermal conductance of the window (U_{window}) as a whole is given by ;

$$U_{total} = U_{rr}+U_c$$

The individual thermal conductivities and emissivities are well known material constants. The heat transfer coefficient of air is a function of wind speed, inside a house the air speed is zero. The materials constants used to calculate the thermal convection and re-radiation transfers are shown in Figure 5.

Materials	**Heat transfer Coff.**	**Thermal conduction**	**Black body emissivity**
	W /m2/C	W/ m C	
Air	7[4]	0.025[5]	
Krypton		0.01[6]	
Glass, smooth (uncoated)		1.05	0.91[7]
Silver, polished			0.02[8]
SnO2:F			0.25[9]
Inside and outside structure			0.9[10]

Figure 5Materials constants.

The individual contributions to insulation are illustrated in Figure 6, as the cumulative “R” (=1/U) for re-radiation and conduction. Figure 6 shows that resistance to re-radiation comes from the low emissivity of the silver coatings. Resistance to thermal conduction comes from the low conduction trapped gas layer in a multipane window.

The models can also be used to compare different window designs. Using the materials constants in Figure 5, the thermal conductance can be calculated. The thermal conductance “U” has units in the US, of Btu in/h ft^2 K. The calculated “U_c” values for various window configurations are shown in Figure 7.

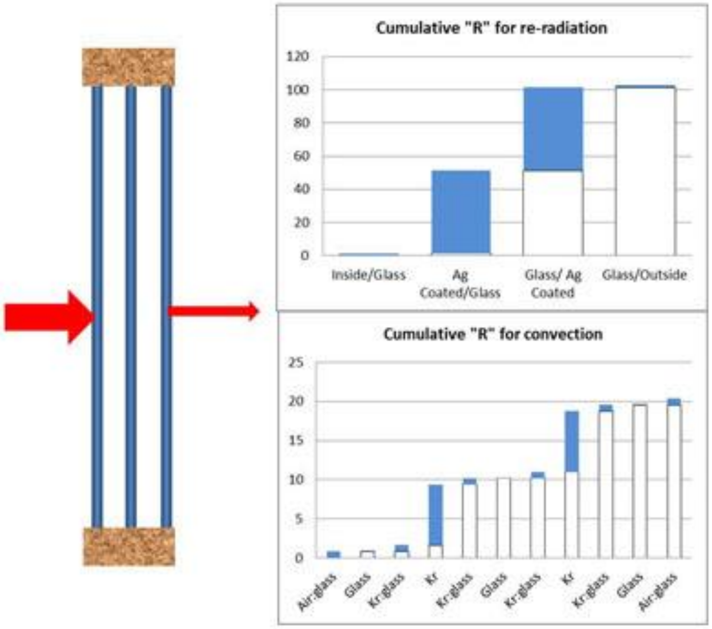

Figure 6 Window engineering for conduction and re-radiation of an optimal triple pane window, showing silver coatings and Kr fill as the biggest contributors to window insulation.

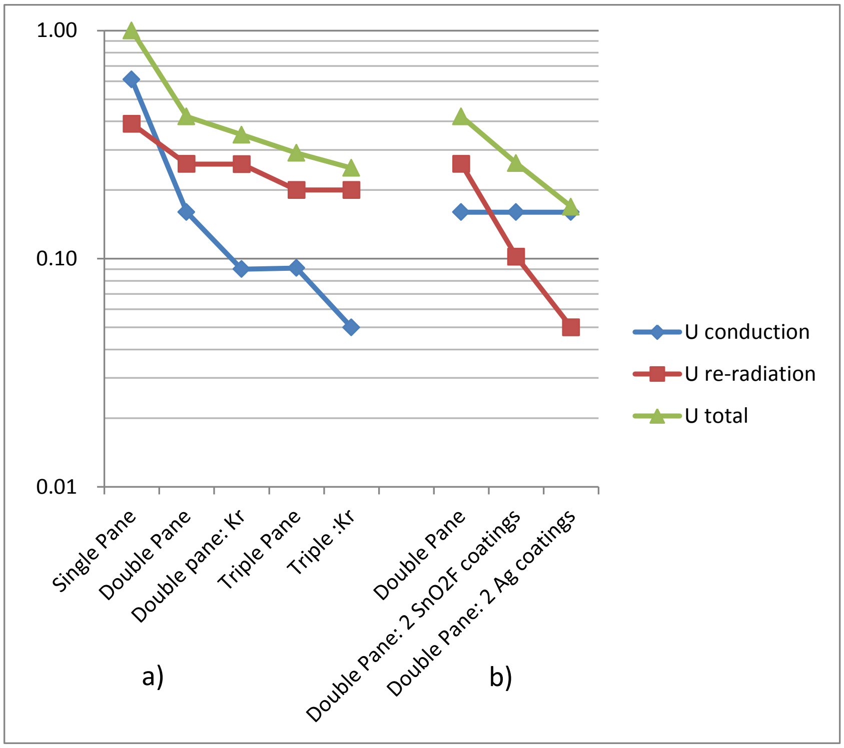

Figure 7 Analytical model results showing the U values for conduction and re-radiation components for different window designs in a) and window coatings in b).

The results for the conduction component of "U_c" for different windows is shown with the blue points in Figure 7a . The addition of multiple panes and using a lower conductivity gas, Krypton (Kr), reduce the thermal convection through the window.

The calculated U_{rr} for different windows are also shown in Figure 7b. As the number of re-radiation pairs in multiple pane windows increases, the re-radiation transfer is reduced. The effect of adding a low emissivity coating is shown in Figure 7b. Commercial low e coatings are limited to SnO2:F and Ag. The conductivity due to re-radiation drops significantly in double pane windows with paired low e coatings.

The combined U_{total} values are also shown in Figure 6. To obtain a low U value of 0.2, requires at least a combined double pane window and Ag coatings.

The analytical model was checked by comparing with a reference calculation for window performance developed by Lawrence Berkeley Labs to compare different window solutions. The U_{total} values from the analytical model showed the same trends as the reference calculation, but the values were 20% smaller.

4.4 Visible and solar near IR

Window glass has excellent transmission to visible and near IR wavelengths, as shown in Figure 1. Transparency to visible light is a basic requirement of the application. In cold climates, the solar IR acts to warm up the structure saving heating bills. In hot climates, solar IR adds to heat that must be offset by air conditioning. Therefore the goal is to design multilayer coatings that either reflects or transmits solar near IR, depending on climate.

As noted previously, there are two materials used for coatings on windows, Flourine doped tin oxide (SnO2:F) a transparent conductor at 1 um thick, and silver which becomes partially transparent in the visible when it is coated in layers that are only 0.03 um or 100 atoms thick, as shown in Figure 8.

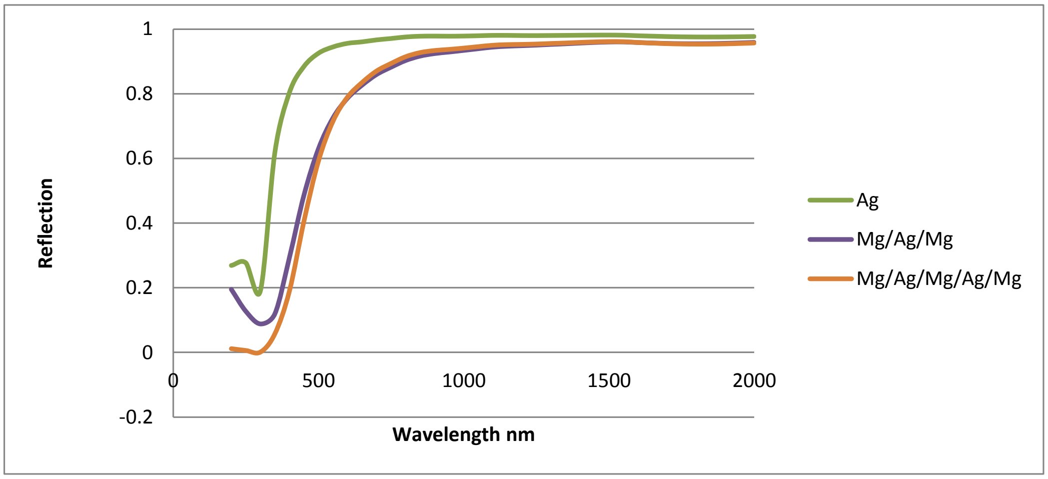

Figure 8 Calculated reflection of multilayer silver films

Silver has high reflectivity, particularly in the near IR, so the goal is to increase transparency in the visible. These are combined with high refractive index dielectric layers to maximize transparency as shown in Figure 9 using a classic thin film interference calculation. There is a long history in optics of using repeating multilayer film stacks to increase the

The calculated transmission for a 2 silver / magnesium oxide layer stack shows a clear visible window with low transmission in the near IR, a useful coating for a hot climate window with low solar heating.

5.0 OPTIMAL WINDOW ASSEMBLIES

Based on the analytical model results, the design rules for effective windows, derived from the analytical model, are;

1) Multipane window to reduce conduction
2) Low emissivity coating, preferably silver, to reduce mid IR re-radiation
3) Multlayer coating to maximize visible transmission and either increase or reduce near IR transmission.

The optimal window is found using a “bottoms up approach by searching the hundreds of “solar glasses” available today, and suppliers do not disclose the materials they use. The Department of Energy has developed the International Glass Data Base (IGDB) and programs (Window and Optic6) to calculate window performance. These programs are the industry standard for reporting window performance to customers.

The window glasses are characterized by a number of metrics, the selection process focused on transmission over visible wavelengths, transmission over solar wavelengths and emissivity. The glasses in the IGDB were grouped into 10% increments in visible transmission. In each increment, one glass with the lowest solar transmission was selected along with one glass with the highest solar transmission.

To evaluate the properties of a window assembled using the selected glasses, a double pane window was assembled in the “Windows” program,, with both panes made of the same glass, and the coated surfaces oriented inward to a 0.5” air gap. The important metrics for the windows were; thermal conduction “U” that combines conductivity and mid IR emission, visible transmission, and Solar Heat Gain Coefficient (SHGC). The SHGC is effectively the transmission over visible and solar near IR. The optimal window for hot climates will be discussed first.

An optimal window for hot climates require a high visible transmission with low solar transmission (SHGC), so the results for the selected glasses were plotted as SHGC versus visible transmission in Figure 9.

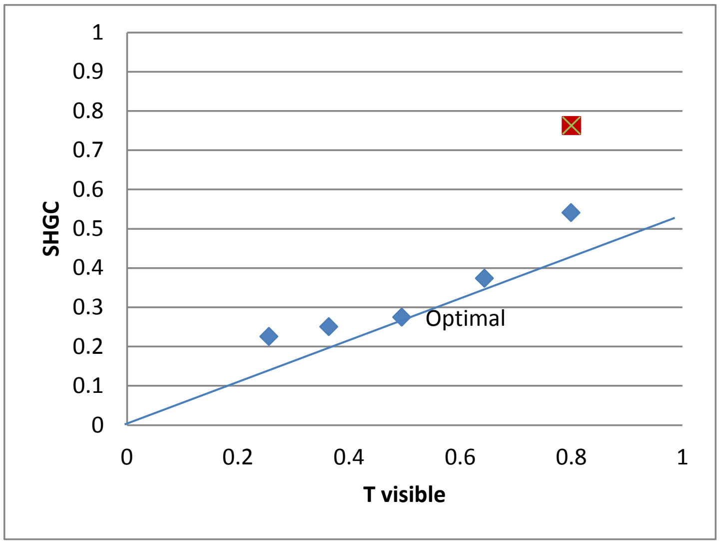

Figure 9 Optimal hot climate window. The trend in blue rectagles shws how SHGC drops with T visible, the optimal glass (IGDB#6261) has the lowest SHGC/Tvisible ratio . The square is a standard double pane window.

The lowest SHGC relative to visible transmission is indicated by the line through the origin and the point marked for the glass IGDB # 6261. All the windows in Figure 10 were assembled from low e glass with e=0.02 and had a low U = 0.2

consistent with low emissivity Ag coatings. The optimal window had a SHGC of 0.25, compared to 0.76 for a standard double pane window a 3 x improvement. For comparison, a triple pane window with an Ag coated plastic film (#1503) as the mid-pane is also shown..

The glass and window metrics are shown in Figure 10.

	Glass					**Window**				
Climate	**IGDB #**	**emissivity**	**T vis**	**T solar**		**Pane**	**Glasses**	**U**	**T vis**	**SHGC**
Std	102	0.84	0.90	0.83		Double	102/102	0.48	0.81	0.76
Hot	6261	0.02	0.70	0.28		Double	6261/6261	0.28	0.50	0.27
Hot						Triple	6261/102/6261	0.16	0.45	0.28
Hot						Triple: Kr	6261/102/6261	0.10	0.45	0.24
Cold	3335	0.30	0.90	0.81		Double	3335/3335	0.34	0.83	0.75
Cold	1506	0.11	0.88	0.63		Triple	3335/1506/3335	0.20	0.73	0.56
Cold						Triple: Kr	3335/1506/3335	0.16	0.73	0.57

Figure 10 Glass and window metrics for the optimal windows.

The U value was further improved by making a triple pane window with a clear glass midpane, and by using Kr gas in the gap, shown in Figure 10. The optimal cold climate window requires a different optimization strategy, because of the need for best insulation to offset the cold night time temperatures. Solar Gain (SHGC) is plotted against U value to access the optimization. Using the glasses with the highest Tsolar, the windows had high solar gain , but also high U. The glasses had emissivity's around 0.2-0.3, consistent with a SnO2:F coating, and are plotted blue points in Figure11.

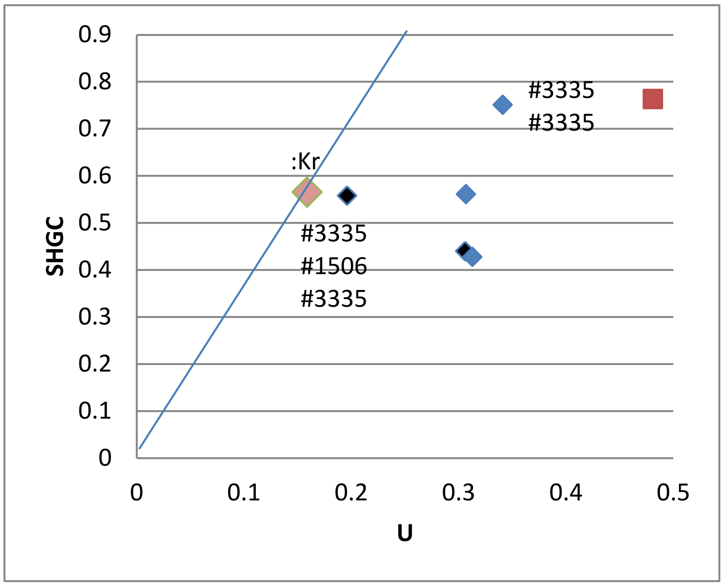

Figure 11 Optimization of cold climate window with high solar gain (SHGC). Pyramids are double pane windows built with glasses with the highest T solar. A triple pane using a silver coated plastic film (IDGB #1506) had improved U. The optimal point, :Kr, is a triple pane with IDGB #1506 as the mid pane, IDGB#3335 as the two outer panes, and Krypton gas fill. The red square is a standard double pane window.

Lower emissivity coatings are needed to obtain a lower "U". A search of the IGDB for coatings with lower emissivity and the high solar transmission identified a plastic film IGDB #1503.   A triple pane window with plastic film

(IDGB#1503) as a mid-pane, is shown in Fig 12 The window had a lower U resulting from both low e and the dual air gap in the triple pane window. When the coated mid-pane is combined with 2 coated outer panes (3335/1506/3335), the U value is further reduced to 0.2, with a SHGC of 0.55. Adding Krypton (:Kr) as a gas fill reduces U as well, as shown in Figure 11.

The transmission spectra of the 2 optimal glasses are shown on the right side of Figure 1. The hot climate glass has a narrow band pass in the visible, the cold climate glass has a much broader band pass transmitting the near IR.

The complete performance of the optimal hot and cold windows are shown in Figure 2 . There is a 2x difference in Solar Heat Gain Coefficient (SHGC) for optimal hot and cold climate windows. The insulation is usually ranked by "R" values (= 1/U), and R= 7-10 for the optimal windows. This is a big improvement over conventional double pane windows with R=2.

6.0 CONCLUSION

Optimal windows for the two use cases, in which the average environmental temperature is either higher or lower than the environment, have common features including a triple pane structure with inert gas fill and at least two silver coatings. The silver layers are in two different multilayer stacks, for a hot climate the coatings must have a narrow visible band pass, for a cold climate the coatings must have a broad visible and near IR band pass.

The insulation value of these windows is 5x better than a conventional double pane window, and similar to a well constructed wall. Factoring in the relative area of windows and walls, and the efficiency of AC and heating systems, a reduction of 50% in heating and cooling costs might be expected. These savings justify these windows to be installed in new construction.

7.0 REFERENCES

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[10] Structure and outside emissivity's were assumed to be 0.9.