**Final Report**

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**Project Title:** Sunlight Responsive Thermochromic Window System

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# Executive summary

Pleotint was started by Dr. Byker to develop and commercialize his idea for a thermochromic window film that responded to sunlight to darken and relieve heat buildup and glare.

The project description was to move SRT (Sunlight Responsive Thermochromic) windows toward being a commercial product. We were to do this by:

1. Making an SRT window with a performance of 50% transmission down to 10% transmission of visible light.
2. Durability testing.
3. Develop TC layer with sale price to market of less than $10.00 per square foot.

At the start of the project our emphasis was on making cast in place laminates of thermochromic materials. Cast in place is a process for making laminated glass by taking two pieces of glass or plastic making a space between them and filling the space with liquid resin based material that can then be cured to make a rigid structure. Our focus changed from a cast in place design to an extrudable plastic film during the project as the thermochromic material evolved. We discovered that a cast-in-place material would not achieve the cost, durability or performance range we needed. We were able to develop thermochromic systems that could be extruded into a plastic film. This film could then be laminated between glass with a similar process to that used to manufacture standard laminated glass. This technique opens our proposed market up to existing glass fabricators who can laminate, heat strengthen glass and fabricate an insulated glass (IG) package. These capabilities exist at almost all of the large commercial glass fabricators in the market today. The SRT laminate will be assembled into a triple pane insulated glass unit with a front sheet of glass, a gas space, the SRT laminate, a gas space and a back low-E coated sheet of glass to make up the complete assembly. The front piece of glass is needed as a wind barrier and the back piece of low E coated glass keeps the heat absorbed in the SRT layer from radiating to the interior of a building. A double pane IG can also be made with a sheet of glass facing the outside and the SRT laminate on the inside. In this case we incorporate a hard coat low E layer on the pane closest to the inside. The double pane IG configuration is primarily suited for sloped glass (such as skylights, roof windows and atriums) and casement types of windows. A case can also be made for the use of this structure for panoramic roofs and sunroofs in automobiles.

During the time of the DOE contract we synthesized material for and tested over 1000 different thermochromic formulations. We made and tested over 1500 laminated parts. The largest size we have made, to date, is a 673 x 762 mm or 0.51square meters (26.5 x 30 inch. 5.5 square feet) of SRT film laminated between glass. We have numerous samples on life test, some heated (50 $^{o}$C and 80 $^{o}$C ovens), some heated and in direct sunlight (85 $^{o}$C), and some exposed outdoors in Arizona, Florida and in Michigan.

The cost of the SRT material itself is expected to be $10 per square foot. We anticipate a film for use in lamination to be sold initially for $15.00 per square foot. After a period of time and with large volumes this should be reduced to the $10.00 per square foot level. One must remember that the glass cost is only a portion of the installed cost of the window; the framing

material and the labor to install it are other contributing factors that would be held relatively constant. For the increased cost of our SRT system the following benefits are obtained:

- Variable tint glass that responds to sunlight – by self tinting - when the sun shines it works, and there is always a view out.
- Energy reduction 24 hours a day every day of the year because of the triple glass design.
- Peak energy savings- saves the most expensive type of electrical energy and the most polluting.
- Building HVAC first cost reduction - smaller physical plant needed for heat and cooling.
- Safety/security- laminated glass for intrusion prevention.
- Sound reduction – Laminated glass reduces sound from entering the building.
- Capable of being used with any outside glass as conditions demand, thick glass for high wind loads, laminated for hurricanes or bombs, bullets and blast protection or even tinted glass for a special aesthetic effect.

All of these capabilities come with the glass. In most cases people will pay a premium for these types of features even if offered separately.

## Technical Background on thermochromic films

Many chromogenic phenomena are known in which a change in color or a change in light absorption results from some action or stimulus exerted on a system. The most common chromogenic phenomena are electrochromics, (EC), photochromics, (PC), and thermochromics, (TC). Many phenomena are also known in which optical changes, like light scattering or diffuse reflection changes, take place as a result of some action or stimulus exerted on a system. Unfortunately, referring to these as chromic phenomena has led to a fair amount of confusion in the past. We prefer to distinguish light scattering systems from chromogenic systems by referring to the light scattering phenomena as a phototropic, thermotropic or electrotropic phenomena. This distinction and other distinctions are elaborated on below.

In general, and especially for the sake of this project, the terms used for an optical phenomena, should relate to the direct, primary action causing the phenomena. For example, modern day electrochromic systems generally involve electrochemical oxidation and reduction reactions. Thus an electrical process directly causes materials to change their light absorbing or light reflecting properties. Alternately, electrical energy can also be used to generate heat or light and this heat or light, in turn, may be used to affect a thermochromic or a photochromic change. However, the indirect use of electricity should not make these electrochromic phenomena. For example, a thermochromic layer may increase in temperature and light absorption when in contact with a transparent conductive layer which is resistively heated by passing electricity through the transparent conductive layer. However, in our terminology, this is still a thermochromic device and should not be called an electrochromic device. Also, just because an electric light produced UV radiation that caused a color change by a phototchemical reaction like the ring opening of a spirooxazine compound, that would not make such a procedure a demonstration of electrochromics.

A similar distinction should be made with a thermochromic layer that is responsive to sunlight as described in Pleotint's US Patents 6,084,702 and 6,446,402. The thermochromic layer may be heated by absorbing sunlight or being in contact with another layer that absorbs sunlight. Here sunlight exposure changes the color and/or the amount of light absorbed by the thermochromic layer. However, this is still a thermochromic phenomenon because the heat and temperature change cause the chromogenic change and the same change takes place when the layer is heated by other means. The absorbed photons from the sun are only converted to heat and do not directly cause a photochromic change. From our point of view, the term photochromics should be reserved for systems in which the absorption of a photon directly causes a photochemical or photophysical reaction which gives a change in color or a change in the systems ability to absorb other photons.

In addition to chromogenic systems, there are a variety of systems with reversible changes in light scattering. The more widely studied light scattering systems include: (1) lower critical solution temperature, LCST, polymeric systems; (2) polymer dispersed liquid crystal, PDLC, systems; (3) polymer stabilizer cholesteric texture, PSCT, systems and (4) thermoscattering, TS, systems. Additional description of these and other light scattering phenomena can be found in US Patent 6,362,303. In the past, several of these phenomena have been called thermochromic and even electrochromic. From our standpoint these phenomena are neither thermochromic nor electrochromic since the word choma relates to color and the intensity and quality of color. These are better termed thermotropic or electrotropic to help indicate the change in state that takes place.

Definitions rarely cover every eventuality, especially when it comes to borderline cases. Hence electrochemical systems that change from colorless and non-light scattering to specularly reflecting are still generally termed electrochromic because of the electrochemical nature of these processes. Also, some thermochromic systems involve changes between liquid and solid phases and could conceivably be called thermotropic systems. But these systems have dramatic changes in light absorption and are still termed thermochromic. On the other side, some reversible light scattering systems may have some spectral selectivity to the light scattering and hence give rise to some color appearance. Yet the primary change is between light scattering and non-light scattering states. Even the change in some systems from colorless and non-light scattering to a frosted, diffusely reflecting and white appearance might suggest a color change to the color white. However, we still term these tropic and not chromic changes.

In summary, systems without a change in light scattering, that primarily involve a change in color, intensity of color or absorption of light, as well as those electrochemical and thermochemical phenomena that give a change in specular reflectance, are herein understood to be chromic or chromogenic phenomena. One of these chromic phenomena – thermochromics, as defined herein, was the subject of the project.

Many thermochromic materials and phenomena are known. These include reversible and irreversible changes in optical character. A well known thermochromic phenomena, for use with windows, involves metal oxide thin films. Most notably films of $VO_2$, and doped versions thereof, are known to reversibly change their specular reflectance in the NIR with changes in temperature. Thermochromic processes with changes in light absorption are observed when heating causes: (1) an increase in the amount of ring opening of certain spiro compounds; (2) the dissociation of certain anions from certain triarylmethane dyes or (3) the dissociation of certain "dimeric" substances into highly absorbing "monomeric" free radicals. Thermochromic phenomena are also involved in phase change systems which change from highly absorbing to colorless or nearly colorless when certain pH indicators change their association with certain weak acids during a melting or solidification process.

Still other reversible thermochromic systems involve thermally induced changes in the way ligands associate with transition metal ions. The novel versions of these metal-ligand thermochromic systems and novel combinations of these systems with other thermochromic systems were the subject of our investigation.

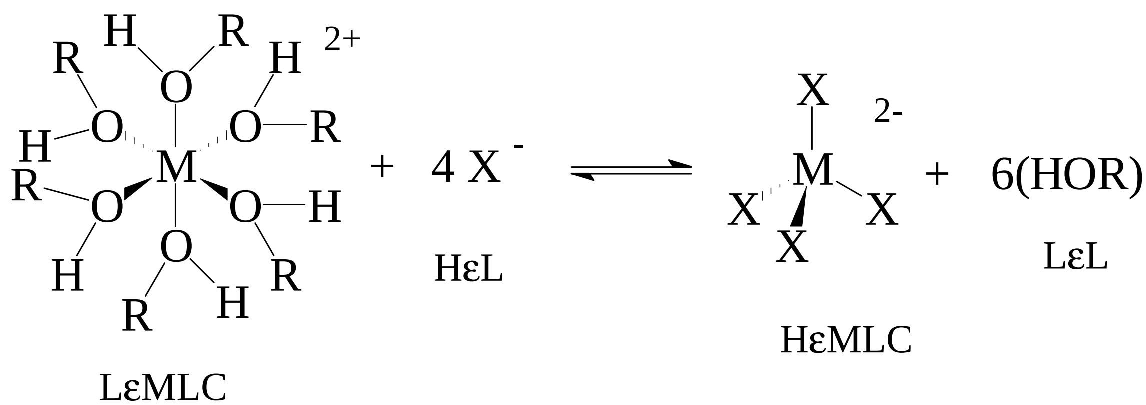
The novel thermochromic systems developed by Pleotint are, herein, termed: ligand exchange thermochromic, LETC, systems. LETC systems have thermochromic activity which results in a reversible change in absorbance of electromagnetic radiation as the temperature of the system is reversibly changed. That the change is reversible means that the amount of change in absorbance remains consistent, for both the increase and decrease in absorbance throughout a given temperature range, on repeated temperature cycling. The thermochromic systems of this research have a net increase in absorbed light energy as the temperature is increased and a net decrease in absorbed light energy as the temperature is decreased for temperatures within the active range of the system. The active temperature range of the system is determined by the thermodynamic properties of the LETC reactions. For many of our preferred applications the active temperature range includes 0 to 85 degrees Celsius.

It is preferred that the electromagnetic radiation, for which absorbance changes occur, be in the ultraviolet, the near infrared and especially the visible portion of the electromagnetic spectrum. The increase in light absorption, in LETC systems, generally results in a change from one color to another color and/or a darkening of the color of the system. However, if the increase in light absorption is predominantly in the UV and/or NIR, the LETC system may still be very useful even though little or no visual color change occurs. We use the term light for UV and NIR as well a visible. See US Patent 6,084,702 for a table of wavelengths in each category of light.

LETC systems comprise one or more than one transition metal ion, which experiences thermally induced changes in the nature of the complexation or coordination around the transition metal ion(s) and thereby the system changes its absorption of electromagnetic radiation as its temperature changes.

When a transition metal ion is surrounded by certain ligands, a metal – ligand complex, (MLC), may be formed which has low molar absorptivity throughout the visible and/or NIR. This MLC is, herein, referred to as a low ε MLC, (LεMLC). When the same transition metal ion is surrounded by other ligands, a MLC may be formed which has a higher level of molar absorptivity somewhere in the visible and/or NIR spectral region. This MLC is, herein, referred to as a high ε MLC, (HεMLC). The LεMLC and the HεMLC may absorb at similar wavelengths or at substantially different wavelengths. Both the LεMLC and the HεMLC generally absorb fairly strongly in the UV, however changes in the amount and the wavelengths of UV light absorbed may be useful aspects of the LETC process. The ε in these designations refers to the molar absorption coefficient or molar absorptivity of the MLC in solution. The units of liters/(mole*cm) are used for ε. HεMLC's have an ε of greater than or equal to 50 liters/(mole*cm) at some or at least one wavelength between 400 and 1150nm. LεMLC's have an ε of less than 50 liters/(mole*cm) for all wavelengths between 400 and 1150nm.

A pictorial representation of a LETC reaction is given below:




Any ligand in a LεMLC is, herein, referred to as a low ε ligand, LεL. Any ligand in a HεMLC is, herein, referred to as a high ε ligand, HεL. When a ligand is not coordinated to a transition metal in a LεMLC or a HεMLC, the determination of whether or not the ligand is a LεL or HεL is not so clear sometimes. The best determination of ligand type is made by the side on which the ligand appears in the equilibrium reaction equation of the LETC system. A ligand, not coordinated to a metal ion, that appears on the same side of an equilibrium equation as the LεMLC(s) is a HεL. A ligand, not coordinated to a metal ion, that appears on the same side of an equilibrium equation as the HεMLC(s) is a LεL.

In reversible LETC reactions like that above, the extent of the reaction, (or the position of the equilibrium), is determined by the thermodynamic parameters of the reaction, the temperature of the system and the total concentrations of each of the reactants/products in the system. One of the many types of LETC reactions, which are governed by a reversible thermodynamic equilibrium reaction, may be represented by the following equation:

$$Me(L\varepsilon L)_x + yH\varepsilon L \Leftrightarrow Me(H\varepsilon L)_y + xL\varepsilon L \qquad (1)$$

where Me is a transition metal ion, LεL is a low ∈ ligand and HεL is a high∈ ligand.

In order for the absorption of the system to increase with increasing temperature the equilibrium must shift to the right in equation (1) as the temperature increases. This would give a net increase in the light energy absorbed since the ε's for $Me(H\varepsilon L)_y$ are larger than the ε's for $Me(L\varepsilon L)_x$ at most wavelengths in the visible and/or NIR for all of the systems studied. In order for the reaction to be reversible the reaction must shift back to the left the same amount as the temperature drops back to its original value. The equilibrium constant for this reaction is given by:

$$K_{eq} = [Me(H\varepsilon L)_y]\,[L\varepsilon L]^x / [Me(L\varepsilon L)_x]\,[H\varepsilon L]^y \qquad (2)$$

where the brackets are used to signify concentration, (although to be more accurate one might want to consider activity). The temperature dependence of the equilibrium constant is determined by the standard free energy change, $\Delta G^o$, of the reaction, which in turn is determined by the standard enthalpy change, $\Delta H^o$, of the reaction. This can be seen from the following well known equations:

$$\Delta G^o = \Delta H^o - T\Delta S^o \qquad (3)$$

$$\Delta G^o = -RT\ln K_{eq} \qquad (4)$$

$$K_{eq} = \exp(-\Delta H^o/RT)*\exp(\Delta S^o/R) \qquad (5)$$

For most of the LETC systems we have discovered, $\Delta H^o$ is constant over the temperature range of 0 to 100 Celsius. If we have a constant value of $\Delta H^o$ over the temperature range of interest, then the magnitude of the change of $K_{eq}$ with temperature is dependent only on the magnitude of $\Delta H^o$. Also, for the equilibrium to shift to the right and for the net energy absorbed by the system to increase with a temperature increase, $K_{eq}$ must increase. This can be seen from the equilibrium constant equation (2) and the mass balance in equation (1). $K_{eq}$ increases as the temperature increases only if $\Delta H^o$ is positive as shown in equation (5). The larger the positive value of $\Delta H^o$ for the equilibrium reaction the larger the increase in $K_{eq}$ as shown by the following equations:

$$K_{eq}(T_H) = \exp(-\Delta H^o/RT_H)*\exp(\Delta S^o/R) \qquad (6)$$

$$K_{eq}(T_L) = \exp(-\Delta H^o/RT_L)*\exp(\Delta S^o/R) \qquad (7)$$

$$K_{eq}(T_H)/K_{eq}(T_L) = \exp((\Delta H^o/R)*(1/T_L - 1/T_H)) \qquad (8)$$

where $T_H$ and $T_L$ are the high and low temperatures over which the LETC is being evaluated. Thus the highest performance for a LETC, in terms of the largest increase in light absorption over a given temperature range, comes with the highest positive value of $\Delta H^o$.

Pleotint has found a large number of LETC with a large positive value of $\Delta H^o$.

Pleotint has discovered novel LETC systems, novel ligands, novel compositions and novel combinations of LETC systems. The novel LETC systems utilize advantageous ratios of ligand to metal ion concentrations and advantageous choices of solvent and/or polymer matrix.

The LETC systems may be used by themselves or in combination with other thermochromic systems and compositions.

Pleotint has developed processes for producing thermochromic layers and novel structures for the use of LETC systems in various applications.

Applications of LETC systems include variable light transmission windows for residential and commercial buildings including skylights and atrium glazing and variable light absorption windows for boats, ships, aircraft and motor vehicles including moon roofs and sun roofs. The windows may include artful designs of different colored LETC systems like a variable light transmission stained glass window. Other applications include LETC systems for use in blinds, shades, and shutters.

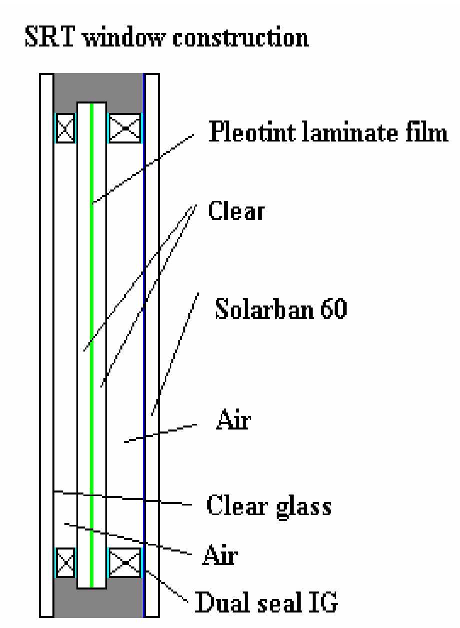
The LETC systems developed are particularly useful in providing the thermochromic activity for the inventions disclosed in US Patents 6,084,702 and 6,446,402.

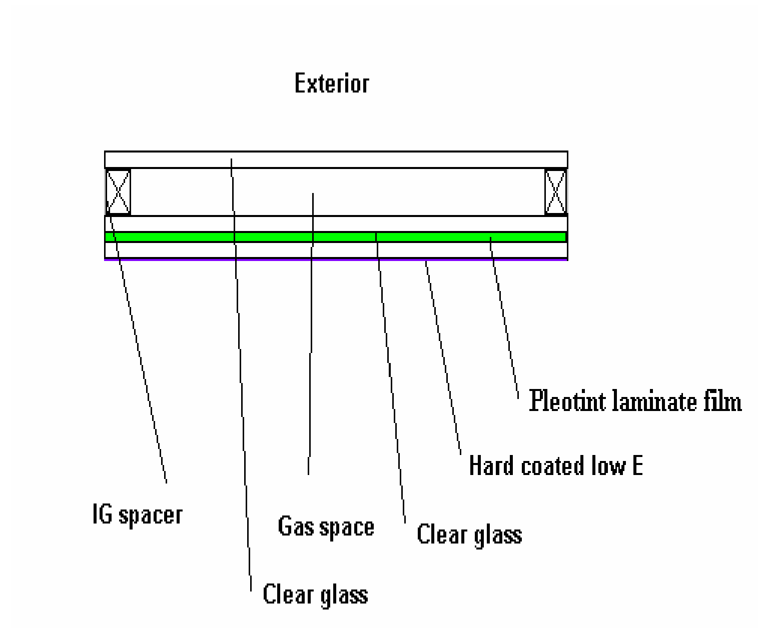
## The Results

SRT windows incorporate the Pleotint LETC film as shown below. When the sunlight is absorbed it heats the thermochromic film. As the film gets warm it reduces its light transmission. When the suns exposure decreases the absorption decreases, the film cools and the light transmission goes back to its original state.

In the SRT window system an exterior pane is used as a wind barrier, the SRT laminate is used as the middle pane and a low E coated glass, preferably one with a very low emissivity, (we found Solarban 60 from PPG to be particularly good) for the inside pane. An alternative construction of a glass pane on the outside with an SRT layer laminated between two sheets of glass one of which has a hard coat low E coating can be used for skylights and atriums as well as casement types of windows.

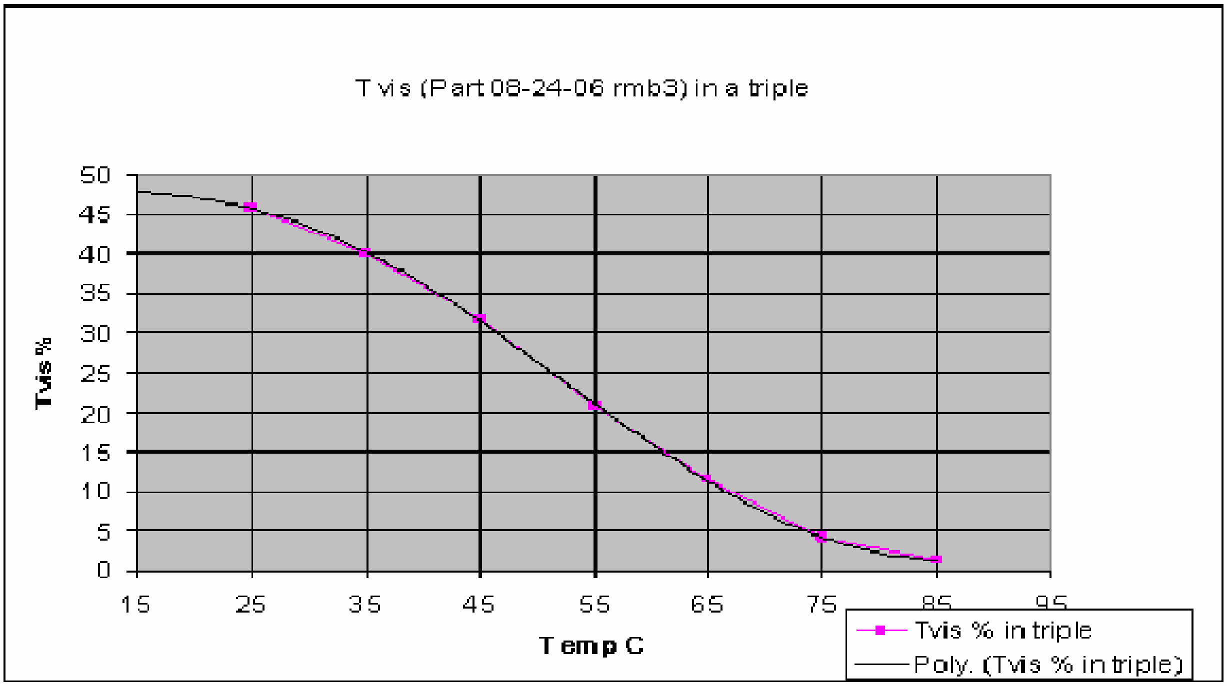
The two constructions of window design are shown below.



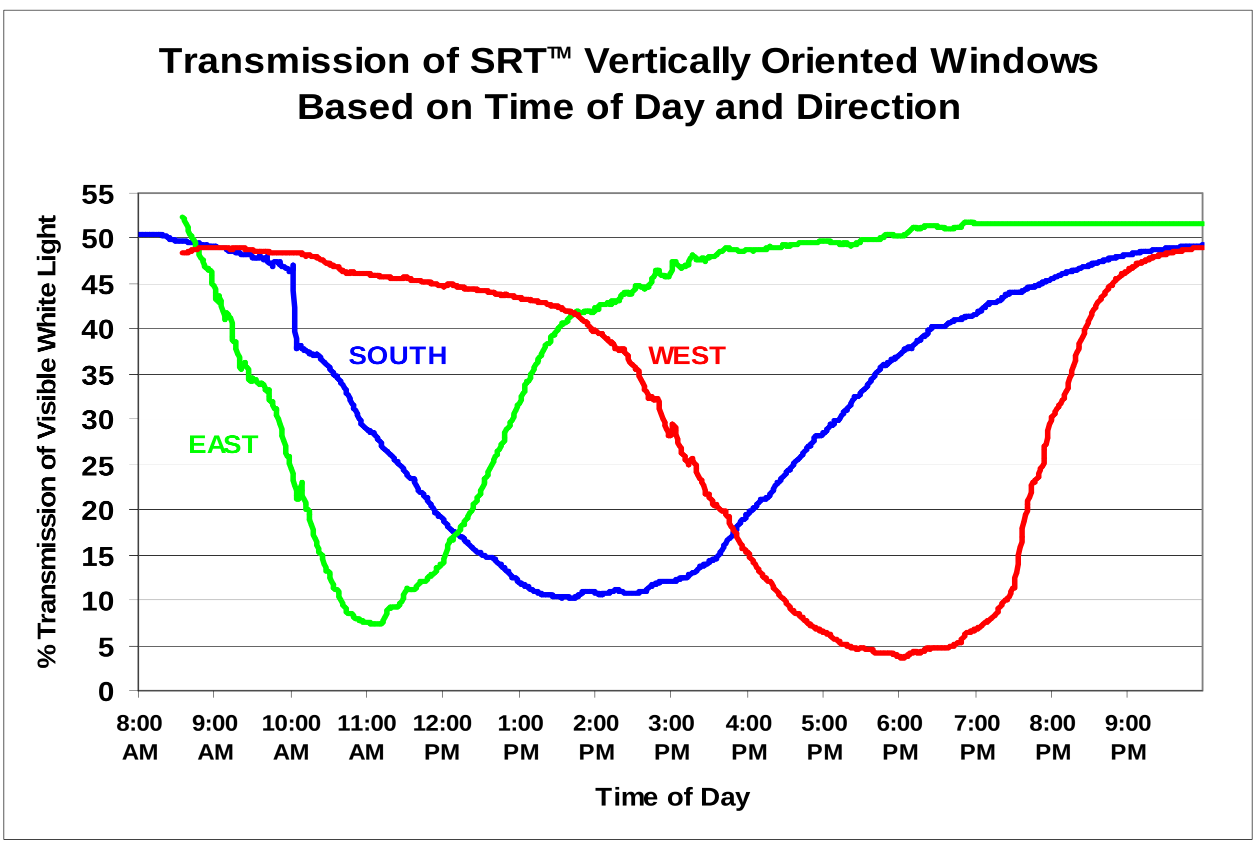




To determine the performance of our LETC films we first make a laminate between sheets of glass then we heat the laminate up to 95 $^{o}$C and monitor the temperature on the glass and record the white light transmission as it cools, data taken at 85, 75, 65, 55, 45, 35, and 25 $^{o}$C.

The white light transmission versus temperature for a triple glass that includes the SRT laminate is shown below. Using this plot and regression line we can determine the transmission for any given temperature measured. Note: between 25 °C and 75 °C the data is nearly linear.




When actual windows were exposed to sunlight they darkened as shown below.



The curves show the suns effect on the light transmission as the sun angle shifts during the day.

The response in these curves shows the beauty of sunlight responsive thermochromic concept. Every window darkens to the appropriate level of light transmission and at the appropriate time based only on the directness of sunlight exposure. Providing this type of control for time of day, time of year and sunlight conditions with electrochromic windows would be nearly impossible.

Below are pictures of a large size thermochromic laminate being tested with our Ocean Optics spectrophotometer. The size is roughly 0.5 $m^2$ (actual size is 26 x 30 inches).


Picture above was taken with the laminate at 75 c.


Picture above was taken with the laminate at 26c.

The large laminate pictured above had the following performance:

| °C | 25 | 45 | 65 | 75 | 85 |
|---|---|---|---|---|---|
| Y | 73.5% | 58.4% | 24.8% | 11.7% | 5.1% |
| L* | 88.7 | 81.0 | 56.9 | 40.8 | 26.9 |
| a* | -12.3 | -11.7 | -7.0 | -1.4 | 5.2 |
| b* | 18.4 | 19.2 | 19.8 | 20.5 | 20.8 |

Performance below is the SRT made into a triple IG - 3 mm clear on the outside, an air space of 3.3 mm, the SRT laminate (from above), 12.7 mm space filled with argon gas, and Solarban 60 (from PPG) 3 mm glass on the inside with the low E coating facing out. Values are based on LBNL windows program 5.2a v5.2.17a with Pleotint measured values input for the SRT laminate.

All values are based on center of glass.

Insulation values

| | |
|---|---|
| $W/m^2$-K | 1.135 |
| U value | 0.2 |
| R value | 5 |

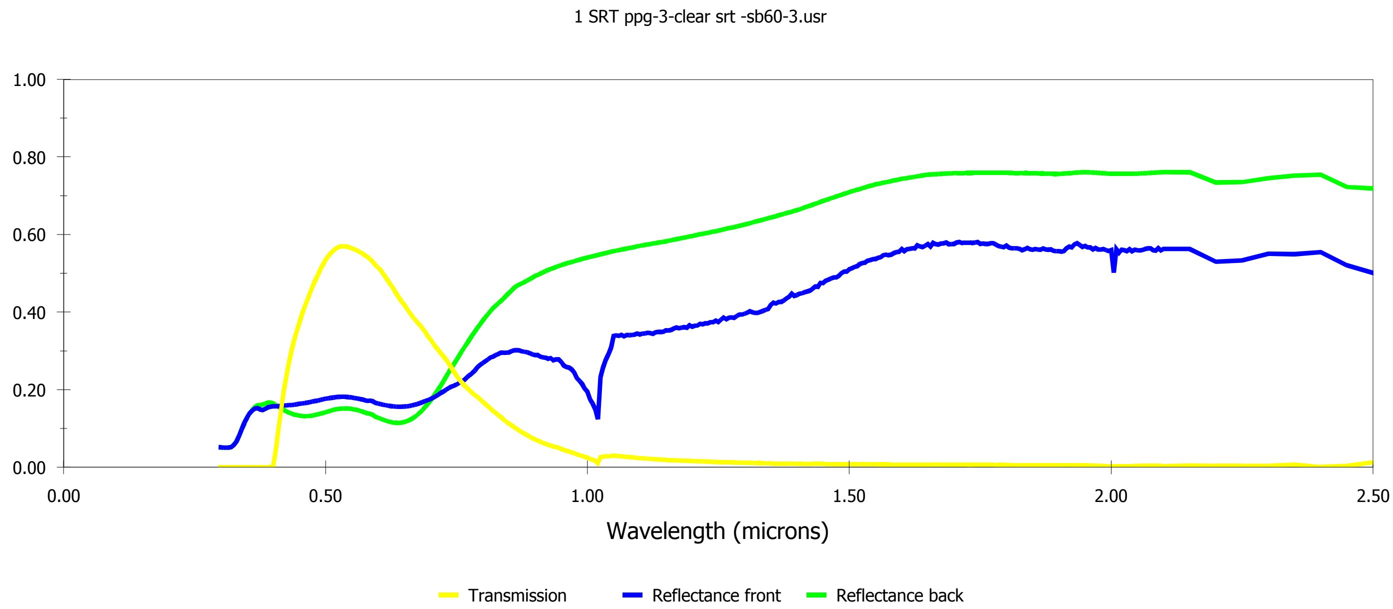
Performance Values

| °C | 25 | 45 | 65 | 75 | 85 |
|---|---|---|---|---|---|
| T vis | 53.6% | 42.6% | 17.9% | 8.5% | 3.6% |
| T sol | 22.40% | 18.10% | 9.10% | 5.60% | 3.50% |
| SC | 0.39 | 0.34 | 0.25 | 0.21 | 0.18 |
| SHGC | 0.34 | 0.3 | 0.21 | 0.18 | 0.16 |

T vis = Total light transmission in visible range 380-770 nm
T sol = Total solar transmission range 300-2500 nm
SC = Shading coefficient
SHGC = Solar heat gain coefficient

The graphs below were generated by the LBNL optics 5.1 program with the Pleotint SRT data, above, made into a Triple IG window. The graphs show the UV, visible and IR wavelengths of light in yellow. The blue and green lines are reflectance values.

25 °C - high visible transmission




85$^{o}$C - low visible transmission


While we believe the most acceptable color is gray we also can make other colors, we have made blue, green and red films, and combined to make gray.

Picture above is an SRT laminate with a blue film at 75 °C

Picture above is the blue film at 25 °C

Performance of the SRT window system is easily changed to accommodate the desires of the engineer, architect window maker or home owner. Gas spaces can be filled with air, argon, krypton, or one space may be filled with one gas and the other space may be filled with another. Space width can be varied to adapt energy performance; space width can be increased or decreased to give better insulation or better heat rejection. Either hard coat low E or soft coat low E can be used to maximize insulation values or heat transfer. The design allows for heavy glass or hurricane resistant glass to be used if required by code. All of these options are readily available at the glass fabricator and can be incorporated and tuned to get the most out of the SRT effect on the home or building.

**Some of our concepts to utilize the absorbing nature of our thermochromic material are described in appendix E. Theses concepts can be used in northern climates to capture heat in the winter and reject heat in the summer. Some of the concepts are applicable for double envelope commercial buildings to maximize energy efficiency. The absorbing nature of the film needs to be fully explored to maximize its potential.**

The SRT glass design incorporates value added features and benefits that people already pay for when there is a special need. The price of energy has gone up drastically in the past year making the energy savings economic case much better. Pleotint is incorporating energy savings with other added benefits as part of the glass package to enhance the desirability and acceptability of the SRT window.

***SRT windows advantages:***

- A laminated glass design gives us the ability to make a film that can be sent to the glass fabricators in bulk and used in their existing process. This allows large scale volume production yet allows for local or regional assembly of the SRT window.
- Manufacture of laminated glass is common in the window industry today- there is no need to invent a new manufacturing process.
- Improved comfort—an energy-efficient building envelope reduces temperature fluctuations and increases occupant productivity.
- Reliability—SRT are designed to continue functioning even during power interruptions.
- Security - SRT windows protect its owners from intrusion. The laminate middle is difficult to penetrate rapidly and will deter the intruder.
- Better UV absorption than that of standard laminated glass, provides fade control and dimming feature reduces fading even in the visible region. Fading of furniture and fabrics is a major problem.
- Heating, ventilation and air-conditioning units can be down sized reducing installation cost and operating cost
- No electrical connections – no wires, no electricity, no computer control, no connections to fail.
- The ability to channel heat into or out of the building utilizing the absorbing nature of the SRT film.
- Especially good at reducing direct sunlight for low sun angle conditions such as east and west facing walls of buildings while preserving a view out.
- Better sound reduction than just laminated glass. The triple pane configuration deters sound to a greater degree than traditional IG's or traditional laminated glass.
- Can be retrofit into existing buildings or as new construction.
- Allows for the use any type of glass for the outboard lite, such as the new self-cleaning glass, hurricane glass, or thick glass to handle wind loads.

- Environmental sustainability—an SRT window saves energy, especially peak demand energy and reduces pollution. Energy savings of up to 30% over ASHRAE 90.1 based glass.
- Suitable for all climates.
- Thermal efficiency is optimized 24 hours a day.
- Optimized lighting – intense direct sunlight is reduced, indirect sunlight is admitted

**See appendix F for complete description of features and benefits.**

As part of the grant proposal we indicated we would do an energy analysis to get a better sense for how our glass compares to existing fixed tinted glass and to electrochromic glass. GMB architects and engineers were chosen to do this study. GMB has extensive experience in load profiles of commercial buildings and working with energy management simulation programs, they used eQUEST V3.55 a DOE 2.2 based building energy simulation program for the study. The study concluded that the energy savings of thermochromic glass was as good as electrochromic glass and considerably better than base case static fixed tinted/reflective glass (specified to comply with ASHRAE 90.1 for buildings). The savings over code compliant base glass were up to 30 % in the Midwest and 14% in Miami. The savings had two components, the monthly savings in reducing peak energy operating loads and first cost savings from being able to install smaller cooling capacity. The additional benefits of SRT windows: better insulating, sound reduction, UV blocking, comfort and always having a view just make the economic case more enticing.

The film below was made in the lab; this film was used for the energy calculations performed at GMB Architects for our energy analysis.

Data below is: light green at 25 $^{o}$C variably down to dark gray at 85 $^{o}$C. Data taken from this sample, from the spectrophotometer, were converted to transmission and imported into the Lawrence Berkeley Labs Optics (version 5.1) program format. Data was compiled for the following: [Laminate constructed using clear PPG, 3 mm-glass, and Pleotint film].

**Note: As shown in the discussion above we have extended the performance rage in both the high transmission state and at the lower transmission state than what was tested by GMB.**

| Green (Light green) laminate data: | Dark Gray: |
|---|---|
| At 25 $^{o}$C | At 85 $^{o}$C (electrically heated) |
| Visible transmission (300-770 nm) 63.4% | Visible transmission 4.3% |
| Color, L* 83.67, a* -11.01, b* 6.8 | Color, L* 25.56 , a* -13.73 , b* 0.31 |
| Total solar, 59.9 % | Total solar, 32.5% |

The data were then imported into the LBNL windows program (version 5.2) and a triple glass construction was simulated with the following results: [Construction was 6 mm clear PPG glass/ 6 mm air space-with air /Pleotint laminate (from above)/ 12.7 mm space-with argon gas/ 6mm Solar Ban 60 low E glass from PPG]

Triple IG simulation

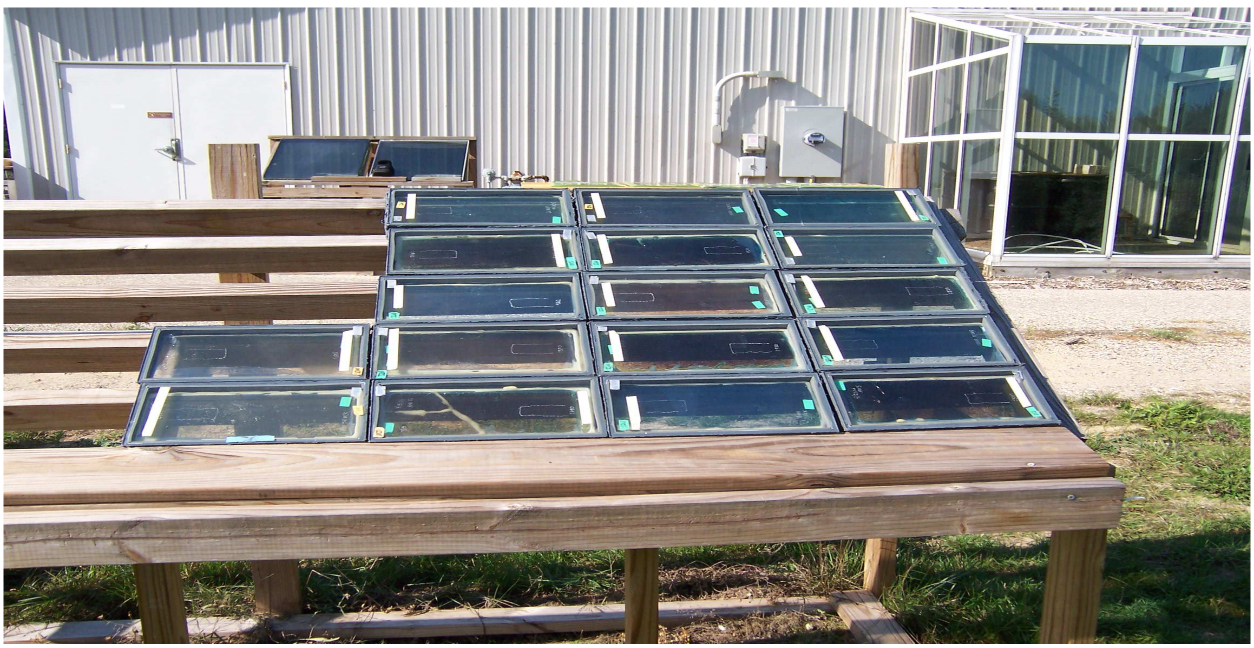
At 25 $^{o}$C
Visible transmission (300-770 nm) 45.1%
Color, L* 72.96, a* -13.5, b* 7.5
Total solar, 19.2%
SHGC, 0.321

At 85 $^{o}$C (sunlight heating)
Visible transmission (300-770 nm) 3.1%
Color, L* 20.98, a* -14.5, b* 0.53
Total solar, 3.7%
SHGC, 0.174

The insulation value of the glass package is a U value of 1.05 w/m$^{2}$K or 0.185 BTU/h-ft$^{2}$-F, or an R-value of 5.4. A second low E and Krypton gas could be used for even lower U values. The air space closest to the outside was set at 6 mm to let heat absorbed by the thermochromic pane to escape to the outside. This lowered the shading coefficient of the glass assembly. The inside air space was set at 12.7 mm and filled with argon gas to better insulate the interior.

## Long term testing

Pleotint sent 20 samples each to Arizona and Florida and set up 20 in Michigan. The samples are laminated films made at Brabender and Leistriz. The laminates were constructed using Superspacer (by Edgetech) and sealant supplied by Adco. The laminates were tested on the Ocean Optics spectrometer. These samples are for sunlight durability testing, we will get them back in 6-9 months to compare the spectral curves to see if any degradation has happened to the performance.



Above pictures are of an outside test rack at Pleotint.
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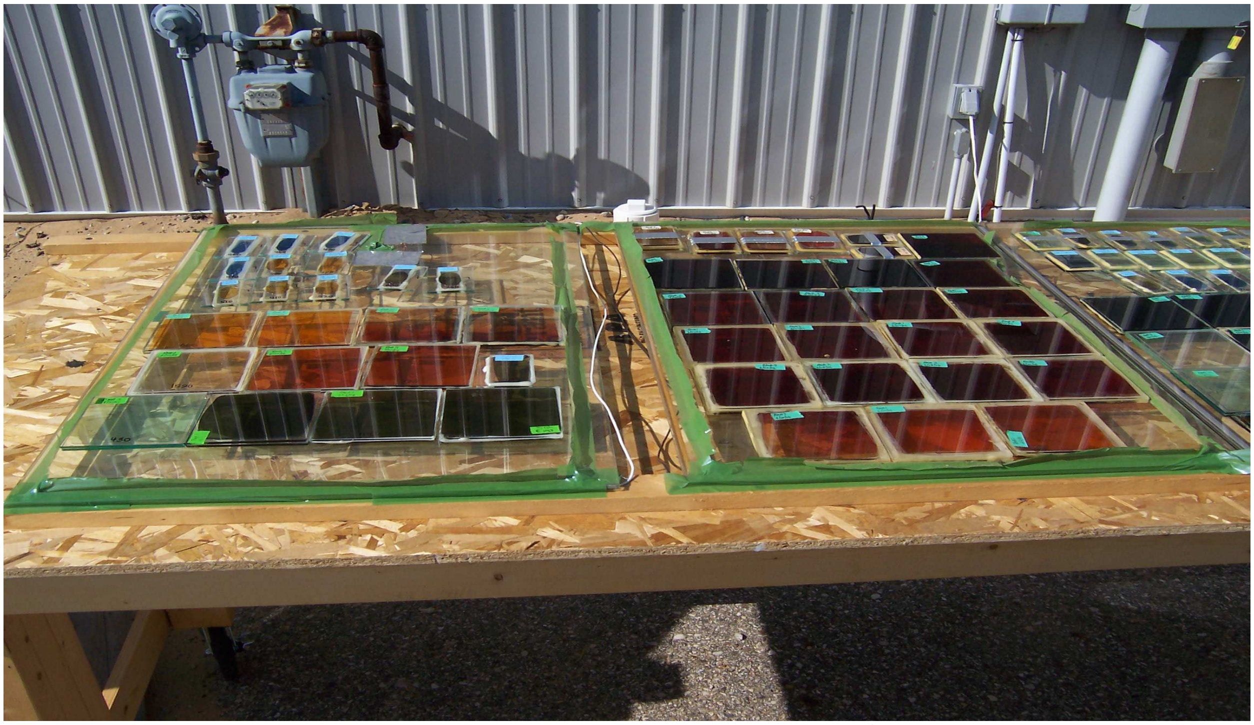


Picture above is parts being test in sunlight and heated to 85 °C

# Commercialization Strategy

Pleotint's product is a special plastic film that can be laminated between glass or plastic. The film is very similar to the film (PVB) that is used in glass lamination throughout the world today for automotive windshields, hurricane resistant windows and in laminated safety glass. Pleotint will manufacture and sell rolls of laminating material to the existing manufacturing infrastructure for commercial and residential laminated glass. Pleotint's SRT film will be applied in essentially the same manner, utilizing the same equipment that laminated glass is produced with today.

The insulated glass fabricator that heat strengthens and laminates glass will be part of SRT windows and ultimately Pleotint's success. Pleotint plans to work with insulated glass fabricators to push the SRT product through their distribution channels while also working with their customers – window manufacturers, architects and engineers – to pull the SRT film through their distribution channels. Expanding insulated glass fabricators' market capability with new, high performance products while bringing them business from window manufacturers and glazing contractors through specified projects should be a key to convincing fabricators to offer Pleotint's window system.

The Pleotint SRT window system will essentially expand the market for laminated glass that the fabricator can offer. Pleotint's SRT window system will allow the fabricator to offer a unique and very high performance window that previously was unavailable. The SRT film will allow fabricators to add significant value to the end product, making the fabricator a partner in the success of the film. The SRT film will also allow glass fabricators to supply a product with a very short lead time to serve markets that require such.

Market segments identified as early adopters are:

1. High end residential windows that can replace existing windows and solve customer complaints about heat gain and glare problems that are not solvable using present technology.
2. High end residential windows that are sensitive to sound, safety, and/or ultraviolet light exposure.
3. Commercial buildings where heat gain and glare issues already exist.
4. Commercial buildings requiring a “green” product (LEED specification).
5. Commercial buildings desiring energy savings, where first cost and operating costs lead to use of Pleotint’s SRT window system.
6. Atriums, sunrooms and skylights that can utilize a double insulated glass construction – preferably in a sloped glazing application. Code requirements for sloped glazing already require a laminated or tempered glass on the room side.
7. Automotive sunroofs and roof windows that provide solar control at a nominal cost, without additional wiring or power requirements.

The first six segments are presently served in the marketplace by insulated glass fabricators that cut glass to size, wash, heat treat, laminate and make it into insulated glass systems. Pleotint’s film will utilize the existing glass fabrication infrastructure and allow a value added film to be readily available at existing factories, negating some of the transportation issues of shipping glass. A secondary market for automotive sunroofs is also anticipated and will be served by existing laminators of automotive glass products and sunroof manufacturers.

Considering the way windows are produced and introduced into the marketplace today, this commercialization strategy has an advantage over strategies that might be used to bring other smart window technologies to the marketplace as it allows current producers and distribution channels to play the same role they play today. Currently architects and building designers specify the windows to be used and many small and medium sized manufactures throughout the country, (or world), use various types of glass, tempering and laminating processes and insulated glass, IG, unit fabrication processes to make windows that are installed by glazing contractors. In our marketing approach, many of these same fabricators could be trained and certified to produce SRT windows by using only small modification of the processes they currently use to temper, laminate and fabricate IG units. As compared to electrochromics, gasochromics and SPD windows there are no power supplies and wiring issues and no large coating equipment to purchase, maintain or operate. Thus from the glazing contractors standpoint the only difference might be a small increase in thickness due to the triple pane construction of the SRT windows. We believe the concept of providing key components to the existing fabricators that already serve the commercial and residential markets, and letting them have a portion of the value added, will facilitate the process of introducing this window product into the market.

**Impact of successful project completion to future success in the marketplace**

SRT windows will give existing glass fabricators access to a smart window system without the lead times that would be associated with other smart window systems. Our marketing strategy also allows existing glass fabricators to contribute value to the production process. SRT windows will give architects choices of glass characteristics and aesthetics (colors). SRT windows have the potential to change how glass is used in new buildings by solving heat gain problems and adding daylighting. SRT windows also provide a solution for problem areas in existing buildings. With SRT windows, the assembly of the insulated glass system can be made using existing glass fabricating techniques in any facility that can temper or heat strengthen glass, with minimal investment is additional equipment. Glazing contractors will not need to learn new technologies or hire other contractors, (electrical or plumbing), to help install the glass. Preliminary discussions have been conducted with window and door companies and commercial glazing manufacturers with very positive feedback on the concept. The new SRT windows will create jobs in fabrication throughout the US. Value added from making the TC materials, assembly of these units and the taxes generated from wages and product sales will benefit the Federal government. Export of the product is also likely and will have a positive influence on the US balance of trade.

**Energy Savings, Environmental and Economic Benefits**

SRT glass has the potential to lower the energy consumption in commercial and residential buildings during the most important energy savings time of the day (during peak electrical demand) and during the most costly time in terms of rate structure, cost of production and cost of pollution. Our study by GMB architects and engineers indicated up to 30% savings in energy cost in commercial buildings. We augment these savings by enhancing the potential for daylight and by using a realistic insulating glass system, so the energy savings go beyond the daylight hours. Our system is self responding without controls; it only lowers the light transmission when the sunshine is direct, so that the window works as intended without human or computer interface.

Existing technology (fixed tint, or fixed reflective glass) and proposed electrochromic technology (variable tint glass) absorb or reflect the light energy before it penetrates the building. In the case of electrochromic glass it also allows light energy to enter (high transmission state) but at the expense of glare. SRT windows can be configured to capture the light energy and direct it either into or out of the building. The ability to absorb the light energy and turn it into useful heat is an area that can maximize a buildings energy performance and minimize the use of natural resources and should be studied further ( see appendix E).

A window is necessary architecturally and most importantly aesthetically. Maximizing the view while minimizing the environmental effects such as energy cost (for heating and cooling), glare control, noise, and comfort is the goal. A window that can control these environmental effects has been a dream for many years. Windows exposed to the sun without proper consideration for the heat being gained, due to sunlight, cause most of the unpleasant environmental effects in a building. Glass that can control the heat gain will reduce the cooling cost of taking this heat away - usually air-conditioning costs. Commercial buildings, in northern sections of the US, are air-conditioned during the peak period of the day even in winter. In south and west regions buildings are air-conditioned most of the day. Air conditioning is only, at best, about 20% efficient and subsequently a very high electrical energy user. The maximum cooling time for a building corresponds to the highest energy demand period - the peak energy time of the day.

Peak energy can be 10 times, or more, the cost of normal energy costs. The energy we purchase is only a fraction of the total primary energy, oil, gas, or nuclear needed to produce it. The ability to control heat gain, and hence cooling costs, during these "peak" times is mandatory for any glazing material. One of the benefits of our variable transmission glass is that it works at the time of a building's peak loads. This provides energy savings through peak load shaving and demand-side management capabilities.

All energy is not created equally. For space heating the conversion from primary fuel to heat is 80+%. The conversion of primary fuel to electricity is 33% due to generation and losses in transmission and distribution. Converting from electricity to air-conditioning is 10-20%. The net energy to cool then is less than 7% efficiency at best. The air conditioning comes at the most expensive time of day, that of peak demand. The average person on the street readily appreciates the benefit of having a window that would tint to relieve the discomfort of too much heat and glare from direct sunlight.

At Pleotint we believe we have a significant new product that can contribute to lowering energy usage in buildings throughout the world. We have fulfilled all of the tasks we started as part of this project and consider this project complete. We thank the DOE for their contribution in moving the SRT window concept forward.

**Patents:** A provisional patent named "Ligand Exchange Thermochromic, (LETC), Systems" was filed on 9-1-06.

**Publications / Presentations:** A presentation was given at the DOE windows roadmap session on March 2, 2006. Visit the web site to view a copy of the presentation: http://www.govforums.org/e&w/documents/Pleotint_March_2_Roadmap.pdf

# Appendix A

## Task Schedule

| Task Number | Task Description | Task Completion Date | | | | Progress Notes |
|---|---|---|---|---|---|---|
| | | Original Planned | Revised Planned | Actual | Percent Complete | |
| 1 | Small area prototypes | Ongoing | | 7/31/06 | 100% | Completed |
| 2 | Large area prototypes | 08/31/06 | | 08/15/06 | 100% | Completed. |
| 3 | Insulated glass construction | 09/01/05 | | 09/01/05 | 100% | Completed |
| 4 | Resin matrix | 07/01/05 | | 06/30/05 | 100% | Completed |
| 5 | TC molecular design | Ongoing | | 07/31/06 | 100% | Completed. |
| 6 | General Matrix development | Ongoing | | 07/31/06 | 100% | Completed |
| 7 | Additives | 05/01/06 | 12/01/05 | 12/01/05 | 100% | Completed |
| 8 | Energy savings calculations | 03/01/06 | 08/01/05 | 8/19/05 | 100% | Completed |

# Appendix B

# Final Spending Plan

Final Spending Schedule

| Task | Approved budget | Final Projected Expenditures |
|---|---|---|
| Sunlight Responsive Thermochromic Window System | $818803 | $1078248.91 |
| Total | $568803 | $1078248.91 |
| DOE share | $250,000.00 | $250000 |
| Cost Share | $568803 | $828248.90 |

**Note: Investors in Pleotint have contributed over $3.5 million in cash toward the development of SRT windows during the total history of the development.**

# Appendix C

## Cost Share Contributions

| Funding Source | Approved Cost Share | | Cumulative to Date | |
|---|---|---|---|---|
| | Cash | In-Kind | Cash | In-Kind |
| Pleotint L.L.C. | $568,803 | | $828,248.91 | |
| DOE | $250,000 | | $250,000 | |
| | | | | |
| | | | | |
| | | | | |
| Total | $818,803 | | $1,078,248.91 | |
| | | | | |
| Cumulative Cost Share Contributions | | | $1,078,248.91 | |

# Appendix D

Based on the GMB study and the characteristics of our SRT windows with triple pane IG construction, low-E and dynamic daylight and solar gain control, we estimate an efficiency improvement of a minimum of 30% for SRT windows. The SRT window will add daylight and reduce lighting requirements. Additional energy savings can be achieved with lighting controls in the building, and the capture and redirection of absorbed heat energy, not included here.

| % Energy savings | x | National energy consumption for windows | x | Maximum potential market penetration % | | |
|---|---|---|---|---|---|---|
| Residential quads 30% | x | 0.73 quads | x | 20% | = | 0.0438 quads |
| Commercial quads 30% | x | 0.70 quads | x | 30% | = | 0.063 quads |

**Total energy quad savings of 0.1068**

One quad [quadrillion BTU's] = the electricity from 194 coal fired power plants of 300 MW each in one year, 48 million short tons of coal or 168 million barrels of crude oil. (From DOE, 2003, Buildings Energy Databook http://btscoredatabook.eren.doe.gov/)

The SRT window directly impacts peak energy demand and this is predominately natural gas and coal fired electric power plants.

Strategies involving daylighting (size and number of windows) as well as solar heat gain management offer significant demand reduction potential without the negative drawbacks of occupant discomfort. Peak daylight availability coincides with summer peak demand periods enabling reduction of lighting and cooling demand, given careful control of solar heat gains in perimeter zones. This is a critical concept associated with the strategies listed in this report. Many people recognize that control of solar heat gains during peak periods can be accomplished by simply blocking all solar radiation before or just after it enters the window. People also recognize that admitting daylight (solar radiation) reduces the need for electric lighting. Determining the optimum energy balance between solar heat gains (increased cooling) and daylight (decreased lighting and cooling) is a critical issue and is key to optimizing window and lighting peak demand reductions during the summer. Other long-term opportunities exist with SRT window systems to allow windows to become part of the space-conditioning solution. Natural ventilation, heat extraction or retention, and nighttime cooling strategies using operable windows are all possibilities to reduce a building's dependence on mechanical cooling or shift the load to off-peak hours.

Energy inputs to manufacture an SRT window include making raw glass, cutting, edging and washing the glass, tempering, laminating and making into an IG. Shipping the raw glass and the film then the completed assembly are also energy users. As our window can be made locally at the fabrication point the shipping cost of the competed window are reduced as well as the cost of replacing any window damaged in shipment. Overall the energy needed to make SRT windows is small compared to what they may save over the life of the window.

# Appendix E

The absorbing nature of the SRT film can be utilized to capture heat and direct it internally or back outside. Figures below represent a few of the possibilities.

Description of figures:

Figure 1 - Cross-sectional view of a triple window pane with air flow over the SRT laminate on the inside (air space designed to capture heat through radiation and convection) and insulated window pane on the outside.

Figure 2 - Cross-sectional view of a triple window pane with air flow over the SRT pane on the inside (air space designed to capture heat through radiation and convection) and insulated pane on the outside. Design to capture heat or trap heat. Louvers to let cold air in when glass is warm and trap air when glass cools.

Figure 3 - Cross-sectional view of an SRT laminate triple with air flow over the SRT on the outside pane.

Figure 4 - Cross-sectional view of an SRT plastic laminate made in the form of Venetian blinds. Included is a sealed IG for better insulating value. These are put between glass and function to reduce solar gain when closed yet can be made to open or retract at the individuals will. Additionally the ability to capture and direct the heat is included.

Figure 5 - Cross-sectional view of an SRT plastic laminate made in the form of Venetian blinds. Included is a sealed IG for better insulating value. These are put between glass and function to reduce solar gain when closed yet can be made to open or retract at the individuals will. A second set of privacy blinds could also be added.

Figure 6 - SRT made of plastic fixed at the top and guided at the bottom to stay spaced apart. The thermal expansion of plastic versus glass is a factor of 10. This configuration allows for the plastic to float and allow the thermal expansion to happen without binding or distorting the window.

Figure 7 – SRT window designed to pivot about its axis, either horizontal or vertical. The triple glass configuration would allow the low E to face out in the summer yet be rotated to have the low E face inward during winter. This would allow the window to let heat in during the winter and keep heat out during summer. Adapatable to all climates but especially good for heating climates.

Figure 8 - SRT window system designed to be placed on an existing window. Retrofit of SRT windows to existing single or double pane windows.

Figure 1

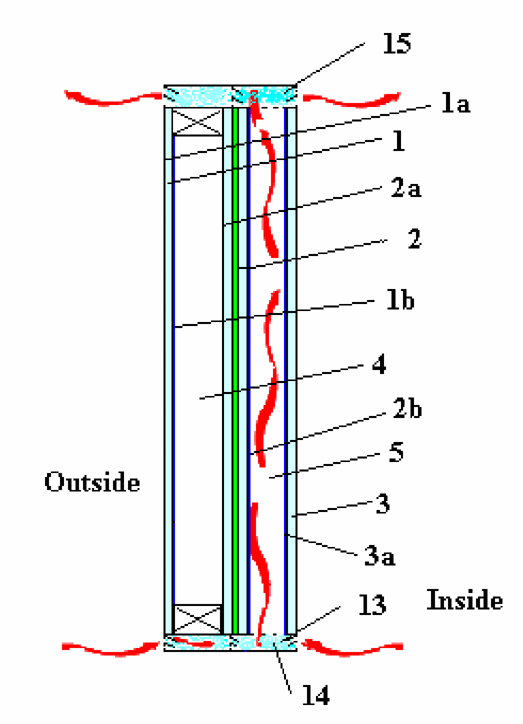



Figure 2

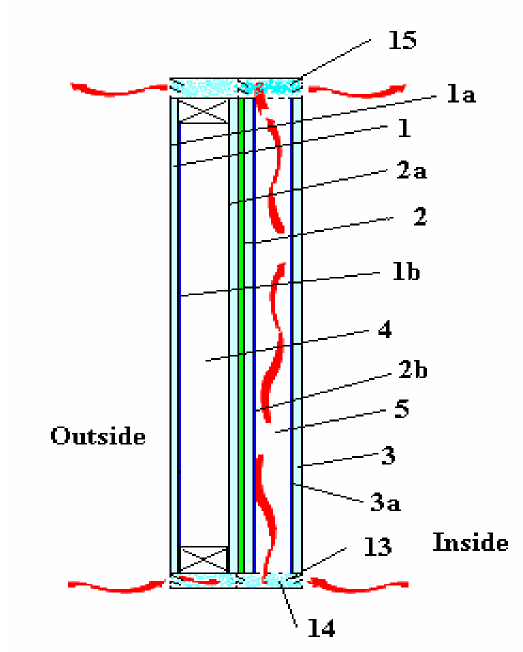



Figure 3

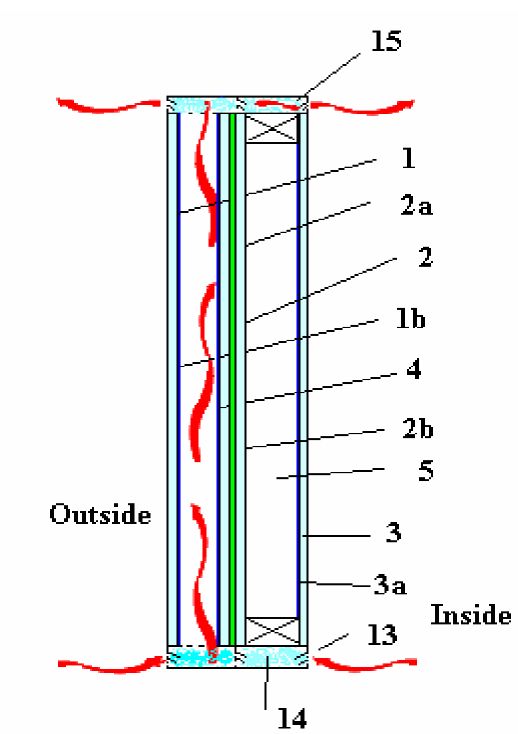



Figure 4

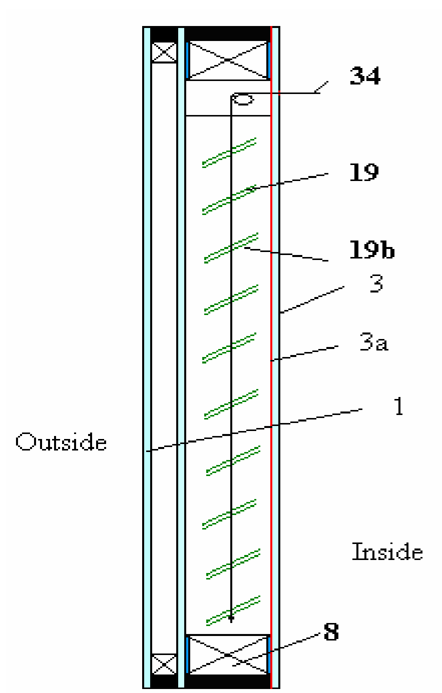


Figure 5

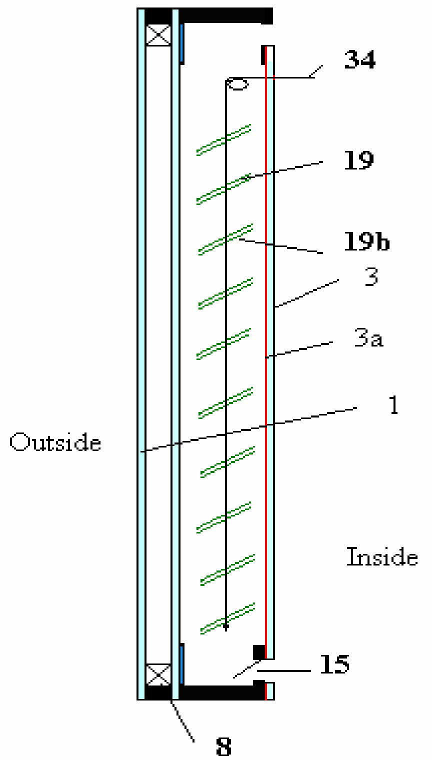



Figure 6

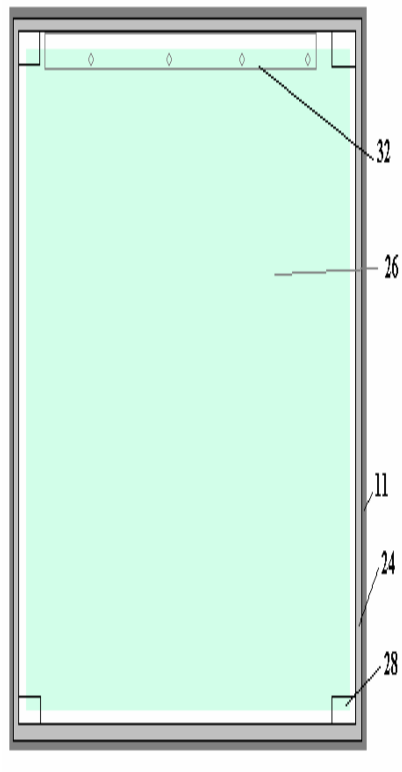



Figure 7

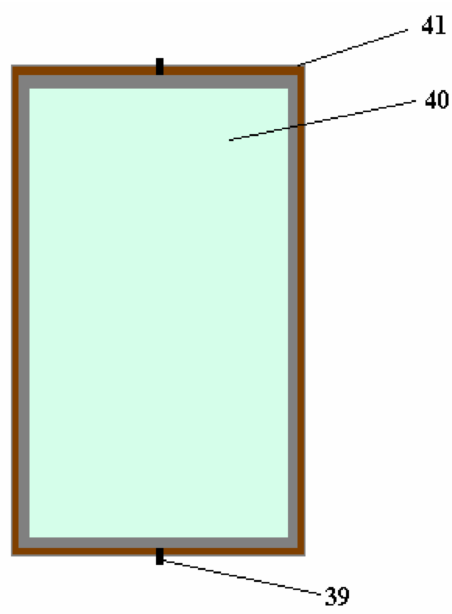
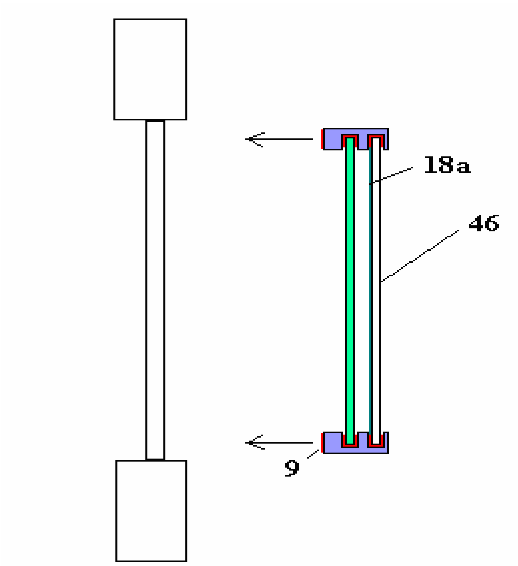



Figure 8



# Windows structure drawing reference numbers

| | |
|---|---|
| 1 | Outside substrate |
| 1a | Outside surface of outside substrate |
| 1b | Outside substrate inside surface |
| 2 | SRT laminate |
| 2a | Outside surface of SRT laminate |
| 2b | Inside surface of SRT laminate |
| 2c | First substrate of SRT laminate |
| 2d | Second substrate of SRT laminate |
| 2e | SRT material |
| 2f | Hole |
| 3 | Inside glass |
| 3a | Outside surface of inside substrate |
| 3b | Inside surface of inside substrate |
| 4 | Outside IG gas/vacuum space |
| 5 | Inside IG gas/vacuum space |
| 6 | Polyisobutylene (PIB) |
| 7 | Aluminum foil |
| 8 | Spacer |
| 9 | Adhesive |
| 10 | Aluminum backed tape |
| 11 | Structural adhesive |
| 12 | Capillary tube |
| 13 | Filter |
| 14 | Desiccant |
| 15 | Louvers to direct air in or out |
| 16 | Frame |
| 17 | Hinge |
| 18 | Plastic film |
| 18a | Low E coating |
| 18b | Low E coating |
| 19 | SRT blind |
| 19b | Low E coating |
| 20 | Insulated glass system |
| 21 | Structural foam |
| 22 | Vacuum seal |
| 23 | Spring |
| 24 | Metal spacer to support Plastic sheet |
| 25 | Rivet or grommet |
| 26 | SRT rigid plastic sheet |
| 27 | Spring clip |
| 28 | U groove / Bearing material |
| 29 | Screen |
| 30 | Post |
| 31 | Gas space |
| 32 | Elastic material |
| 33 | Obscure blind |
| 34 | Tilting, raising and lowering mechanism |
| 35 | Cover to hide edge of SRT plastic and or springs |
| 36 | Expandable bladder |
| 37 | Blind spacer |
| 38 | Substrate |
| 38a | Outside surface of substrate |
| 38b | Inside surface of substrate |
| 39 | Pivot pin |
| 40 | SRT window assembly |
| 41 | Window sash |
| 42 | Breather tube |
| 43 | Pressure equalization tube |
| 44 | Magnetic strip |
| 45 | Oven door |
| 46 | Window insert assembly |
| 47 | Existing window structure |

# Appendix F

# Features / benefits of Pleotint Thermochromic glass:

1. Feature - Variable light transmission (visible range), there is always a view – (benefit is always able to see out -shaded when the sun is out - clear at night or when clouds are present)

   Glass that automatically darkens as the sunlight intensity increases (the glass gets darker the warmer it gets) – no need to pull the blinds or shades unless privacy is needed.

   The glass has a high visible transmission of around 50% (depending on design) when the sunlight is not shining, at night or early morning. As the sunlight warms the glass it slowly changes its transmission from 50% down to 10% (depending on the sunlight intensity) This reduced transmission also reduces the sunlight glare. As the sun moves away the light transmission returns to the 50% state.

2. Feature- Variable shading coefficient, Benefit -solar heat gain is drastically reduced.

   Solar heat gain is the amount of sunlight (all light frequencies) entering through the window. This is advantageous to warm the room if it is not occupied but in most cases the heat is too intense and the shade or blinds are pulled cutting the view. Control of solar heat gain is the most important aspect of controlling heat entering a building.

3. Feature - Very low infrared light transmission. Benefit - heat stays outside.

   There are three components of sunlight that need to be controlled; these are UV, visible and infrared. Result – glass that does not change the room environment, getting too hot due to the sun intensity

4. Feature - Triple IG - Benefit - saves energy 24/7 –

   a. Passive solar, works during peak electricity hours to save energy. Control of heat gain lowers the amount of a/c needed and lower operating costs.

   b. Triple glass for a very low U value, low U value saves on A/C during the day and heat energy at night

5. Low E glass on inside pane to reflect absorbed solar energy

   Low E glass is recognized as an accepted part of an energy efficient window

6. Feature - Windows install just like traditional windows. Benefit - only glass installers are needed, no electrical connections to fail, no controllers, no electrical union to contract and coordinate

Pleotint Thermochromic glass is the only glass technology that functions as a variable light transmission device without the need for electricity.

a. No wires or electricity needed, no electrician needed to run wires or make connections. No wires penetrating the IG to cause a leak path.

b. No control scheme to operate the glass, when the sun shines the glass works

c. No electrical connections to fail due to short circuits, oxidized connections or electrical surges

d. Sliding/swinging glass doors can be achieved without concern for wire connections.

e. Operable windows can be designed to let fresh air in yet still control the solar heat gain.

7. Window shapes like half circles, triangles or stars are possible. Can even be made using bent glass

   Design possibilities are endless and the glass still performs

8. Feature glass Laminate on the inner pane in combination of triple glass benefit-

   a. will have sound reduction properties over that of a standard type window

   b. Safety-glass will stay in place if broken

   c. Security of laminated glass and vandal resistant.

   d. Glass will continue to function until replaced

   e. Local laminators can provide quick turnaround.

   With two air spaces and a plastic film layer on the laminated middle piece the sound reduction is significant over a double IG. This sound reduction means better comfort to the people working/living inside.

9. Can be combined with different tinted (absorbing) glasses for various colors and various visual light transmission ranges.

10. Outside pane of glass can be clear, laminated, or the new self cleaning glass

    If laminated glass is required by code, it can easily be incorporated in the design

    If the new self-cleaning glass is desired it can also be incorporated in the design

11. If an accident happens

    a. The windows are easily replaceable. Only a glazing contractor is needed, no need for an electrical contractor

   b. The window will function until replaced.

   c. SRT film can be located regionally improving lead times and lowering transportation costs

12. Fading control - Blocks UV. While many glasses advertise that they block UV generally they only block a portion of the UV range. The Pleotint Thermochromic glass blocks from 230-420 nm, the whole UV range. Fading control is achieved by the SRT glass absorbing direct sunlight in the visible as well as the UV range.

The disadvantage of thermochromic glazing:

1. They are not conducive to individual control. While a negative to some the reliance on human interaction can negate the energy savings function of the window if not properly activated at the proper time. If automatically (programmed) controlled then the electrical function will replicate the action of the thermochromic glass.

2. Triple glazing is needed to make it work in many cases. Triple glass is needed for some applications due to wind effect on cooling the outside glass and insulating the inside from the glass as it warms. Atriums, sloped glazing, skylights and casement types of windows can use double glazing if desired. Triple glazing gives maximum insulating capability when the sun is not on the glass.

3. Triple glass makes it heavier than a double IG.

4. Reflected light will still cause glare. The SRT window will absorb reflected light and indirect light and when warmed will reduce its light transmission.

5. Range of light transmission is lower than for electrochromics. When compared with a complete window system, and all of the associated benefits of the SRT system, the difference is minimal.

6. SRT windows (as well as all chromogenic windows) are not a privacy type of glass, blinds or shades are still needed for privacy.

7. Shading the glass will not allow it to function. SRT windows do not work without sunlight.