DEVELOPMENT OF TRADE-OFF EQUATIONS FOR ENERGYSTAR© WINDOWS

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ABSTRACT

The authors explore the feasibility of adding a performance option to DOE's EnergyStar© Windows program whereby windows of differing U-factors and SHGCs can qualify so long as they have equivalent annual energy performance. An iterative simulation procedure is used to calculate trade-off equations giving the change in SHGC needed to compensate for a change in U-factor. Of the four EnergyStar© Window climate zones, trade-off equations are possible only in the Northern and Southern zones. In the North/Central and South/Central zones, equations are not possible either because of large intrazone climate variations or the current SHGC requirements are already near optimum.

INTRODUCTION

DOE's EnergyStar© Window program has been very successful in promoting the use of energy-efficient windows, so that by 2003 roughly 40% of all residential windows sold in the US carried the EnergyStar© Window label. One of the reasons for the success of the EnergyStar© Window program is its simple prescriptive criteria: the entire country is divided into four zones, within each are specified the maximum U-factor and Solar Heat Gain Coefficient (SHGC) required to qualify as an EnergyStar© window. Table 1 gives the existing EnergyStar© prescriptive criteria by climate zone and Figure 1 shows the climate zone boundaries as revised in 2003.

Table 1. EnergyStar© Window Criteria by Climate Zone

CLIMATE ZONE	WINDOWS & DOORS		SKYLIGHTS	
	U-factor	SHGC	U-factor	SHGC
Northern	< 0.35 *(< 1.98)*	any	< 0.60 *(<3.40)*	any
North/Central	< 0.40 *(<2.27)*	< 0.55	< 0.60 *(<3.40)*	< 0.40
South/Central	< 0.40 *(<2.27)*	< 0.40	< 0.60 *(<3.40)*	< 0.40
Southern	< 0.65 *(<3.69)*	< 0.40	< 0.75 *(<4.26)*	< 0.40

* U-factor IP Btu/hr·°F·ft^2 *(SI W/hr·°C·m^2)*

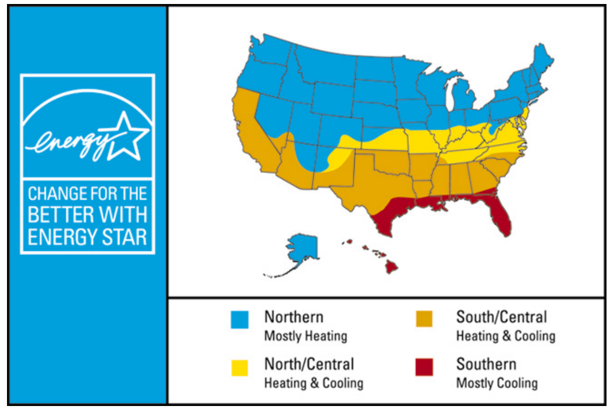

Figure 1. EnergyStar© Window Zones (2003)

To increase the flexibility of the program, DOE initiated work in the fall of 2003 to add a performance option whereby windows of differing U-factors and SHGCs can qualify as EnergyStar© so long as they have equivalent annual energy performance to a base case window meeting the prescriptive criteria.

To the window industry, this performance option will appear as trade-off equations by climate zone indicating the change of SHGC needed to compensate for an increased U-factor, or vice-versa. To define the trade-off equations, DOE-2 simulations are done for prototypical residential buildings of two vintages (new and existing) in 45 US locations over a large range of window conditions. The basic input file and modeling strategy are taken from the *RESFEN* (Residential Fenestration) program that was developed in 1998 as a easy-to-use tool for analyzing residential windows using DOE-2 as the calculation engine (Huang et al. 1998). An iterative procedure is added that, for a given U-factor, finds the SHGC producing the same total energy use as the base case EnergyStar© window.

In addition to defining the trade-off equations, the impact of the trade-offs on peak heating and cooling energy use is also investigated, and limits added to guard against adverse impacts on visible transmittance, condensation resistance, and non-compliance with existing building energy codes. Finally, because of the potential high impact this performance option will have on the window industry, the National Fenestration Rating Council (NFRC) was asked to conduct a detailed review of the modeling assumptions underlying the *RESFEN* computer simulations.

The complete analysis and recommendations are contained in a 35-page memo submitted to DOE on Jan. 24, 2004, and posted on the Web at http://www.govforums.org/e&w/content.cfm?bodycontent=summaryreport#wrs. After receiving public review and comments, DOE will decide on the final course of action on the performance option in Summer of 2004.

SIMULATION PROCEDURE

Analysis Tool

A DOS batch procedure is used with the DOE-2 template file from *RESFEN* to generate the heating and cooling energy uses for a large number of window U-factors and SHGCs in 45 US cities for prototypical new and existing vintage houses. The *RESFEN* template file is a DOE-2.1E text input file with heavy usage of DOE-2 macros that parameterize over 40 key building inputs, such as building type (one-story, two-story), building vintage (new, existing), wall construction (wood-frame, masonry), floor area, HVAC system type (furnace/air-conditioner, heat pump), etc. Since the original purpose of *RESFEN* is to provide the window industry and general public with an easy-to-use tool to analyze residential window energy performance, ¾ of the key inputs relate to the windows, including their area, thermal and solar properties, shading conditions, etc., by orientation and tilt. Once these key inputs have been defined, either through the *RESFEN* user front-end or, as in this case, a DOS batch procedure, they are then inserted at the beginning of the template file. The DOE-2 macros in the file will then produce individual input files tailored to the specified building and window conditions.

For the current analysis, the inputs are even more limited, since only the window U-factor and SHGC, location, and building vintage are varied, while the other key inputs have been kept at constant default values.

Since the DOS batch procedure is functionally identical to how *RESFEN* runs DOE-2, the resultant heating and cooling energy uses are also identical. Thus, all the results can be verified and checked by industry reviewers using *RESFEN*. The advantages of the batch procedure are the ability to quickly generate thousands of DOE-2 results, and to imbed it into an iterative procedure to automatically calculate window U-factor/SHGC combinations having the equivalent total energy use.

Modeling Assumptions

The modeling assumptions used for this regression analysis are from the current version of *RESFEN 3.1*. Most of these, such as building size, window area, and internal conditions, are kept constant for consistency, but others, such as envelope thermal properties and foundation construction, vary depending on location. This set of assumptions covers both technical issues and human factors and is detailed at http://windows.lbl.gov/AEP (Arasteh et. al. 2000). A simplified list of the most important assumptions is shown in Table 2.

These modeling assumptions were reviewed from Nov. 2003 to Mar. 2004 by a Task Group from NFRC's Annual Energy Performance (AEP) Subcomnittee. Although some Task Group members initially proposed six modeling changes – the two with the biggest impact being a 40% increase in the internal gains and lowering the cooling setpoint to 75ºF (23.9ºC), the AEP Subcommitee decided at the NFRC Annual Meeting in March 2004 not to recommend any changes in modeling assumptions because of the lack of hard data and DOE's tight deadline to complete the analysis. Consequently, the assumptions shown in Table 2 will be use throughout in developing the EnergyStar© Window trade-off equations.

Calculation of Total Energy Consumption

To calculate total energy use, a source multiplier of three is applied on the cooling and fan electricity, which is then added to the heating fuel energy use to produce the total energy use in MBtu/year.

Iterative Search Procedure

The trade-off equations define the combinations of U-factor and SHGC producing the same total energy use as the base case EnergyStar© window.

Total Equivalent Energy = f(U-factor, SHGC) (1)

A second DOS batch procedure has been developed that automatically finds the U-factor/SHGC combination through iterative DOE-2 calculations. This procedure first calculates the energy use for the base case EnergyStar© window. It then changes the window U-factor, recalculates the energy use, and based on the difference in total energy use, changes the SHGC and recalculates the energy use until the difference is less than 0.01 MBtu. In using this procedure, two unexpected conditions are found: (1) in some climates, no solution is found to compensate for increased U-factor, (2) in a few climates, two solutions are possible.

Table 2. RESFEN 3.1 Operating Assumptions

PARAMETER	*RESFEN 3.1* ASSUMPTION
Floor Area	2000 ft^2 (186 m^2) One-Story .
House Type	▪ New Construction ▪ Existing Construction
Foundation	Foundation based on location, can be either Basement, Slab-on-Grade, or Crawlspace
Insulation	Envelope insulation levels are based on location. ▪ New: 1993 Model Energy Code ▪ Exist.: (see Ritschard, et al. 1992)
Infiltration (Effective Leakage Area)	▪ New: 0.77 ft^2 (715 cm^2, approx. 0.58 air-changes/hr) ▪ Exist.: 1.00 ft^2 (930 cm^2, approx. 0.70 air-changes/hr)
Structural Mass	3.5 lb/ft^2 (17.1 kg/m^2) of floor area, in accordance with the MEC and AEP Subcom. Sep. 1998 recommendation.
Internal Mass Furniture	8.0 lb/ft^2 (39.1 kg/m^2) of floor area, in accordance with the MEC and AEP Subcom. Sep. 1998 recommendation.
Solar Gain Reduction	▪ Drapes (summer 0.80, winter 0.90); ▪ 1 ft. (0.3 m) overhang; ▪ 67% transmitting same-height obstruction 20 ft (6.1m) away to represent adjacent buildings; ▪ addition solar heat gain reduction by 0.1 due to insect screens, trees, dirt, building and window self-shading, etc.
Window Area	15% of floor area
Window Type	Variable
Window Distribution	Equally distributed on all four orientations
HVAC System	Furnace & A/C
HVAC System Sizing	For each climate, system sizes are fixed for all window options by doing a DOE-2 auto-sizing run for the same house with the most representative window for that specific climate.
HVAC Efficiency	▪ New : AFUE 0.78, SEER 10.0 ▪ Exist.: AFUE 0.70, SEER 8.0
Duct Losses	10% fixed (both heating and cooling)
Part-Load Performance	(see Henderson 1998)
Thermostat Settings	Living Space: Heat 70°F, Cool 78°F Basement: Heat 62°F, Cool 85°F
Night Setback	65°F 11 PM – 6 AM
Internal Loads	Sensible: 59.9 kBtu/day Latent: 12.2 kBtu/day
Natural Ventilation	Enthalpic – Sherman-Grimsrud (78°F/ 72°F based on 4 days' load history)
Weather Data	TMY2

TRADE-OFF CONSTRAINTS

Although equivalent total annual energy use is the major basis for examining performance trade-offs, windows have many other performance attributes that must be considered when the trade-offs are evaluated. The following is a discussion of factors in addition to annual energy use that will influence the range of trade-offs that can be allowed. These factors, such as comfort and view, can be regarded as constraints on the calculated trade-off equations.

Issue: Always Meet or Beat Energy Code

The EnergyStar© program has as one of its central premises the requirement that it exceeds or at least meets local building energy code requirements. The 2003 revisions to the program were developed in part to incorporate recent upgrades and proposed changes to residential energy codes. The development of a performance option with trade-offs may result in windows qualifying for EnergyStar© whose properties do not meet code in some circumstances. To avoid this anomaly, a filter is needed on the trade-off option so that the U-factor or SHGC are not relaxed beyond code requirements. In the longer term, the prescriptive EnergyStar© criteria should be raised above code requirements, at which point the flexibility of the performance criteria could come into play.

Issue: Maximum U-factor and SHGCs for Peak Electric Demand

While the primary reason for establishing U-factor and SHGC criteria is to reduce energy use, these same parameters can also result in reduced equipment size and lower electrical peak demand. Is there a danger that the performance option, by relaxing the individual requirements for U-factor or SHGC, may increase peak summer cooling electric demand in hot locations or peak winter heating demands in electrically-heated houses in cold locations?

A series of DOE-2 simulations using the same procedure as described show that the adverse impacts from a trade-off option on peak loads to be no more than 2% in heating and 5% in cooling. Under the limited range of possible U-factor/SHGC trade-offs, the impacts on heating or cooling peaks are minor. Hence, there is no need to place constraints on the trade-off approach due to concerns about peak electricity demand.

Issue: Comfort and Condensation Resistance

Small variations in U-factors and/or SHGCs from the base requirements will not adversely impact peak, comfort, and condensation. However, larger variations may have detrimental effects. For example, in the South/Central Zone, a window with a very low U-factor and a very high SHGC may have equivalent energy use to the prescriptive EnergyStar© window, but SHGCs significantly higher than the EnergyStar© requirement of 0.4 may not be desirable due to their adverse impact on summer peak and comfort. Therefore, maximum allowable values on SHGC may be needed for reasons of summer comfort. However, these are found to be unnecessary as intrazone climate variations in both the South/Central and North/Central zones made trade-off equations untenable.

Issue: Minimum Visible Transmittance and SHGC

The option of getting credit for SHGCs lower than 0.4 may encourage some manufacturers to promote low SHGC reflective glass as EnergyStar© products. For a variety of reasons reflective and highly absorbing tinted glass has not been normally used in the residential market and it seems unwise for EnergyStar© to implicitly encourage their use by providing alternatives that can only be met with such low transmission products. For this reason, a minimum allowable Visible Transmittance (VT) requirement of 30% is proposed for any qualifying product. This is a whole window value, which translates to a center-of-glass VT of 35-40%, and a whole-window SHGC of 0.25-0.30 for a typical residential window.

TRADE-OFF EQUATIONS

The following section discusses possible trade-offs between SHGC and U-factor for each of the four EnergyStar© climate zones

Southern Zone

EnergyStar© requirements in the Southern Zone are a U-factor less than 0.65 Btu/hr·°F·ft^2 (3.69 W/hr·°C·m^2) and a SHGC less than 0.40. Since the zone is dominated by cooling, SHGC has the primary impact and changes in U-factor will not substantially change SHGC. Alternatively, selecting an SHGC that is lower than the required 0.4 value might allow an increase in U-factor while maintaining constant annual energy use. Table 3 and Figure 2 shows the U-factor and SHGC combinations that would result in the equivalent energy use. The trade-off is between reduced cooling due to lower SHGC against increased heating due to increased U-factors. There is no trade-off in Miami because of the absence of any heating load.

The table shows that lowering the SHGC can permit higher U-factors, with the upper limit of the U-factor trade-off being set to 0.80 IP (4.54 SI) in recognition of existing residential building energy codes. Trade-offs can be developed for lower U-factors and higher SHGCs, but these are not suggested here because such SHGC values will also not meet building energy codes.

Table 3. Southern Zone Trade-offs

U-factor IP (*SI*)	SHGC Trade-offs			
	Jackson ville	Miami	Lake Charles	Browns ville
0.65 *(3.69)*	0.40	0.40	0.40	0.40
0.70 *(3.97)*	0.37	0.40	0.36	0.39
0.75 *(4.26)*	0.34	0.40	0.31	0.38
0.80 *(4.54)*	0.30	0.40	0.26	0.37

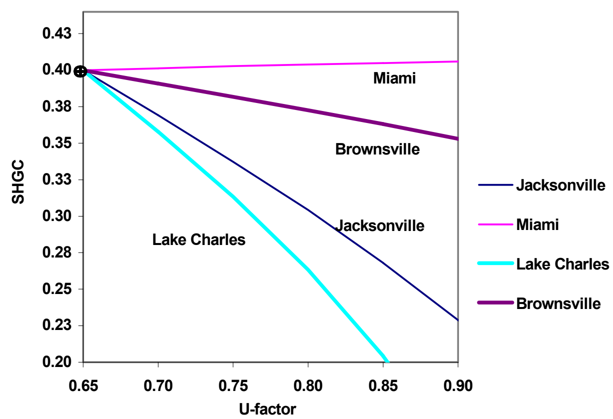

Figure 2. Southern Zone Trade-off Curves

South/Central Zone

EnergyStar© requirements in the South/Central Zone are a U-factor less than 0.40 Btu/hr·°F·ft^2 (2.27 W/hr·°C·m^2) and a SHGC less than 0.40. Table 4 and Figure 3 show the U-factor and SHGC combinations that would result in the equivalent energy use as this prescriptive EnergyStar© Windows criteria. Both show large differences and often contradictory trade-offs between individual cities. Furthermore, in a number of cities no solution can be found for increased U-factors (identified as NS and shown shaded on Table 4).

The reason for these results becomes clear when the DOE-2 runs are analyzed in more detail. Figure 4 shows the heating and cooling energy uses (in source units) for a window with a U-factor of 0.40 IP (2.27 SI) over a wide range of SHGC in a representative city (Oklahoma City) for which there is no solution at higher U-factors. At first glance, the increases in cooling energy seem to be exactly balanced by the decreases in heating energy, resulting in the same total annual energy regardless of the SHGC.

Table 4. South/Central Zone Trade-offs

	SHGC Trade-offs					
U-factor IP (*SI*)	**Birming ham**	**Phoe nix**	**Oak land**	**Sunny vale**	**San Diego**	**El Toro**
0.42 (*2.38*)	NS	0.39	0.42	0.42	0.54	0.48
0.44 (*2.50*)	NS	0.38	0.43	0.44	0.54	NS
0.46 (*2.61*)	NS	0.37	0.45	0.47	NS	NS
U-factor IP (*SI*)	**Pasa dena**	**River side**	**Red Bluff**	**Sacra mento**	**Atlan ta**	**Las Vegas**
0.42 (*2.38*)	NS	NS	NS	NS	NS	0.31
0.44 (*2.50*)	NS	NS	NS	NS	NS	0.18
0.46 (*2.61*)	NS	NS	NS	NS	NS	NS
U-factor IP (*SI*)	**Charlest on**	**Mem phis**	**El Paso**	**Fort Worth**	**San Antonio**	
0.42 (*2.38*)	0.29	0.31	0.32	0.35	0.39	
0.44 (*2.50*)	0.16	NS	NS	0.28	0.37	
0.46 (*2.61*)	0.08	NS	NS	NS	0.34	

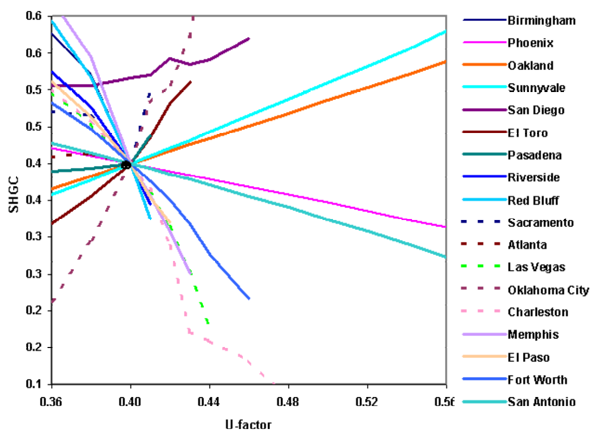

Figure 3. South/Central Zone Trade-off Curves

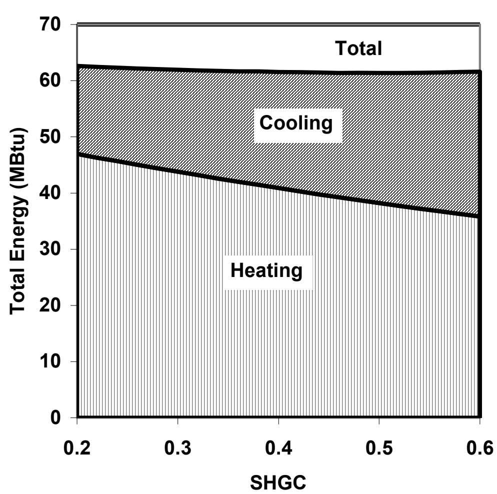

Figure 4. Total Energies in Oklahoma City for windows with U-factor 0.40 IP and varying SHGC

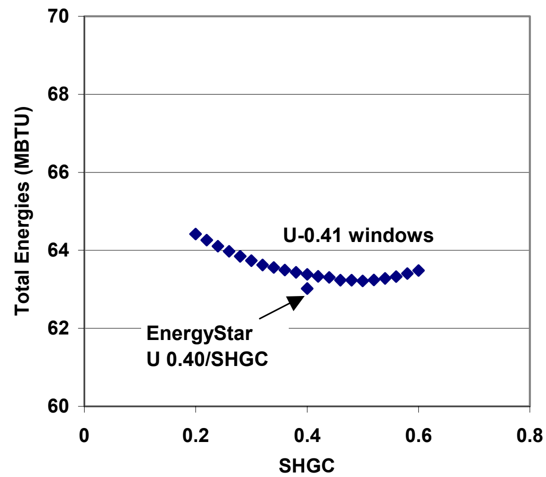

Figure 5. Total Energies in Oklahoma City for Windows with U-factor 0.41 IP and varying SHGC

Figure 5 shows the total energy in more detail for a similar situation for windows with a U-factor of 0.41. There is a slight variation in total energy depending on the SHGC, but the curve is very flat with a minimum at a SHGC of 0.50. Since the base case EnergyStar© SHGC requirement of 0.40 is already very near the optimum SHGC, there is no better SHGC that can be used to compensate for any increases in U-factor.

There is the interesting case of San Diego, which is somewhat heating-dominant and has an optimum SHGC substantially higher (0.55) than the EnergyStar© requirement of 0.40 (see Figure 6). As a result, even at the base case U-factor of 0.40 IP (2.27 SI), it is possible to relax the SHGC to 0.52 and still have the same energy performance as at SHGC 0.40.

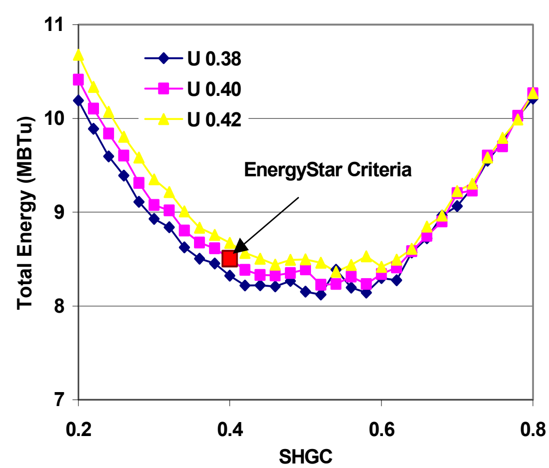

Figure 6. Total Energies in San Diego for windows with U-factors of 0.38, 0.40, and 0.42 IP and varying SHGC

Leaving aside those cities with no solution or double solutions, the rest of the cities in the South/Central Zone are a mix of heating-dominant (California coastal) and cooling-dominant (Phoenix) climates with diametrically opposite trade-offs. Given this hodgepodge of trade-off conditions, we feel that the climate variations within the South/Central Region are too complex to permit a single zone-wide trade-off equation that would be technically defensible.

North/Central Zone

EnergyStar© requirements in the North/Central Zone are a U-factor less than 0.40 Btu/hr·°F·ft^2 (2.27 W/hr·°C·m^2) and a SHGC less than 0.55. Table 5 and Figure 7 show the U-factor and SHGC combinations that would result in the equivalent energy use as this prescriptive EnergyStar© Windows criteria. Both show large differences and often contradictory trade-offs between individual cities. Furthermore, as in the South/Central Zone, a number of cities have no solution for increased U-factors (identified as NS on Table 5).

Table 5. North/Central Zone Trade-offs

U-factor IP *(SI)*	SHGC Trade-off				
	Washington	Kansas City	Raleigh	Albuquerque	Nashville
0.41 *(2.33)*	0. 60	0.63	0.64	0. 58	0.49
0.42 *(2.38)*	0. 66	0.77	NS	0. 61	0.42
0.43 *(2.44)*	0.73	NS	NS	0. 64	NS
0.44 *(2.50)*	0.86	NS	NS	0.67	NS

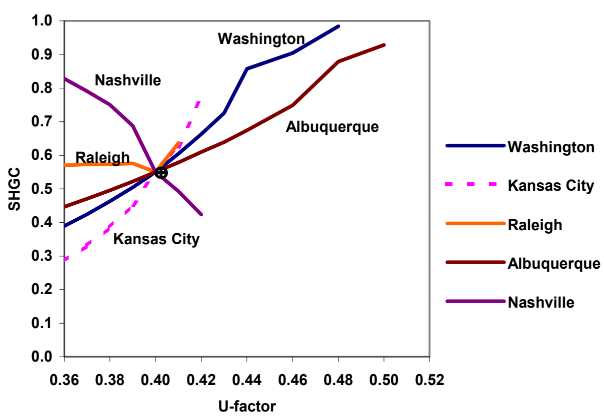

Figure 7. North/Central Zone Trade-off Curves

The DOE-2 results show a mix of cities with no solutions (Raleigh and Nashville) or with slight negative trade-offs (large increases in SHGC to compensate for small increases in U-factors) in Washington, Kansas City, and Albuquerque. Because of this mixture of different trade-off conditions, our recommendation for the North/Central Zone is also that a trade-off equation is not technically defensible.

Figure 8 shows the Heating to Cooling Ratios (HCR) for cities in the South/Central and North/Central zones, and reveals that these HCRs are fairly good indicators of whether a city will have a positive trade-off, no solution, or negative trade-off. When the HCR is less than 0.30, i.e., cooling is more than 70% of the energy use, there is a positive trade-off (reduced SHGC to compensate for increased U-factor). When the HCR is greater than 0.70, i.e., heating is more than 70% of the energy use, there is a negative trade-off (increased SHGC to compensate for increased U-factor). When HCR is between 0.30 and 0.70, i.e., heating and cooling are comparable, there is generally no solution for any trade-off for increased U-factor, but of course there would remain trade-offs for reduced U-factor.

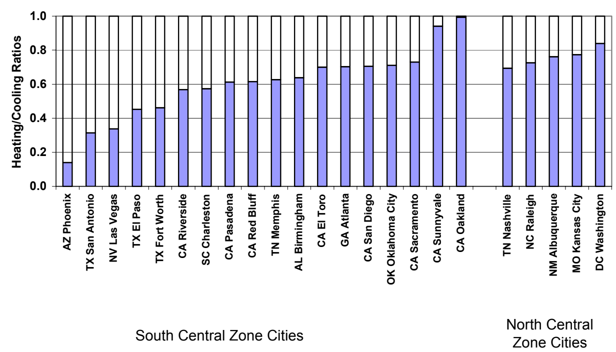

Figure 8. Heating/Cooling Ratios for Cities in the South/Central and North/Central Zones

Northern Zone

The EnergyStar© criterion for the Northern Zone is simply a U-factor of less than 0.35 Btu/hr·°F·ft^2 (1.99 W/hr·°C·m^2), with no SHGC requirement. In order to calculate the base case energy use, it is necessary to define a nominal base case SHGC. In this heating-dominated zone, the trade-off is for increasing the SHGC and allowing the additional solar gain to help offset the winter heating load, thereby compensating for a small increase in the window U-factor. There have been several suggestions for how to select this value, considering both what is allowable as well as what is typically sold in the window market. After considering the various arguments and a wide range of proposed alternatives from 0.27 to 0.55, for this analysis a base case SHGC of 0.40 was selected.

Since all locations in the Northern Zone are in heating-dominant climates, the trade-offs across all the cities in the zone are consistent and relatively well-behaved with respect to each other (see Figure 9). Although a zone-wide trade-off equation can be produced for the current U-factor requirement of 0.35 IP (1.99 SI), there are several concerns with allowing such a trade-off.

First, it may violate building energy codes. Many states in the Northern Zone have or are moving towards building codes that require a window U-factor of 0.35 IP (1.99 SI) for all new construction or major renovation. The only conditions under which a higher U-factor may be allowed is when a performance-based compliance path is chosen for the overall building, or in the case of small retrofit or replacement projects that do not require code compliance. Second, increasing the U-factor will reduce interior glass temperatures, reducing thermal comfort and increasing the probability of condensation of frost. Thus, a window qualifying under this trade-off option may have inferior performance compared to a mandatory code-compliant window. Therefore, our recommendation is that the U-factor not go higher than the mandatory code value, which means that no trade-off is possible with the current EnergyStar© criteria for the Northern Zone.

DOE's long term vision for Zero Energy Buildings will require windows with U-factors in the range of 0.10 - 0.20 Btu/hr·°F·ft^2 (0.57 – 1.13 W/hr·°C·m^2) with dynamic control of solar gain. In the future, as technological advances provide new, cost-effective options for more efficient windows, the EnergyStar© criteria for window U-factor will likely be set below minimum code values, therby providing manufacturers opportunities for trade-offs that do not currently exist. To provide an idea for how this may work, a future EnergyStar© criteria with a U-factor of 0.25 Btu/hr·°F·ft^2 (1.14 W/hr·°C·m^2) and a SHGC of 0.40 is considered for the Northern Zone., while buildings codes are assumed to remain at the current U-factor of 0.35 IP (1.99 SI). This will then allow trade-offs for U-factors between 0.25 (1.14 SI) and 0.35 IP (1.99 SI).

CONCLUSION

This paper has described the technical basis for a proposed performance option to DOE's EnergyStar© Windows program that will allow trade-offs between U-factor and SHGC in zones where such trade-offs have been found to have technical merit. For differing reasons, trade-offs are found not to be possible in three zones, and possible only in the South Zone. In the South/Central and North/Central zones, the climate differences are too great to produce technically defensible zone-wide trade-off equations. In the Northern Zone, trade-off are disallowed to avoid violating existing building code requirements.

Table 6. Future Northern Zone Trade-offs

	SHGC Trade-offs					
U-factor IP (*SI*)	**Ancho rage**	**Denver**	**Chicago**	**Boston**	**Minnea polis**	**Omaha**
0.27(1.53)	0.45	0.44	0.47	0.45	0.46	0.50
0.29 (1.65)	0.50	0.49	0.56	0.49	0.53	0.62
0.31 (1.76)	0.55	0.53	0.63	0.54	0.60	0.84
0.33 (1.87)	0.61	0.58	0.73	0.59	0.67	0.81
U-factor IP (*SI*)	**Reno**	**New York**	**Dayton**	**Phila delphia**	**Salt LakeC**	**Seattle**
0.27(1.53)	0.44	0.46	0.47	0.47	0.47	0.44
0.29 (1.65)	0.48	0.53	0.54	0.55	0.56	0.48
0.31 (1.76)	0.52	0.60	0.62	0.64	0.67	0.52
0.33 (1.87)	0.57	0.67	0.71	0.74	0.72	0.56

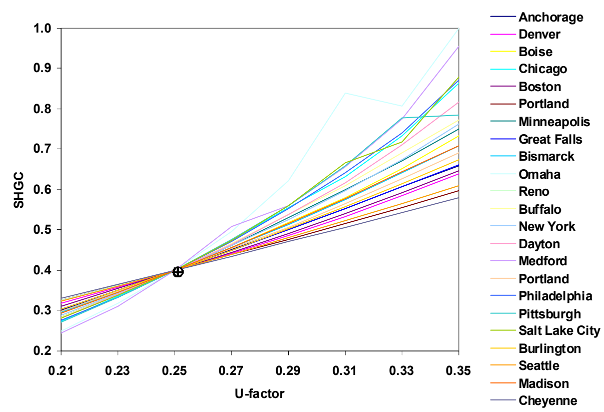

Figure 9. Future Northern Zone Trade-Off Curves

In the four months since the LBNL memo was posted on DOE's Web site, the window industry has submitted over 50 comments concerning either the merits of the trade-off approach or the technical analysis described in this paper. LBNL is currently (June 2004) preparing a response on the technical issues, while DOE is weighing different approaches to the performance option, including ones not involving trade-offs. The final decision is expected to be made mid-Summer of 2004.

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