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Progress Report:

Development of Condensation Resistance Procedure for the Component Modeling Approach

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TASK 1: IDENTIFICATION OF LEADING FACTORS FOR THE CALCULATION OF CONDENSATION RESISTANCE

SELECTION OF REPRESENTATIVE SPECIMENS

In order to properly identify leading factors for the calculation of condensation resistance factors (CR) of fenestration products, representative specimens are identified. While CMA methodology was originally devised for the non-residential (commercial) fenestration systems, its applicability can clearly be extended to residential products as well. For this reason, the development of CMA based CR calculation methodology will not be limited to non-residential products only. Several framing, glazing and spacer systems are considered.

Framing Systems:

Because the framing of non-residential products tend to be made of stronger materials, such as Aluminum or reinforced polymers, the frames made of wood or PVC will be represented through the typical residential products. The following frame materials are therefore considered:

- F1 – Aluminum Horizontal Slider
- F2 – Thermally Broken Aluminum Fixed Window
- F3 – Thermally Improved Curtainwall
- F4 – Thermally Broken Curtainwall
- F5 – Fiberglass Casement Window
- F6 – Reinforced PVC Fixed Window
- F7 – PVC Fixed Window
- F8 – Wood Fixed Window

Figure 1 to Figure 8 show geometry and materials for representative framing systems

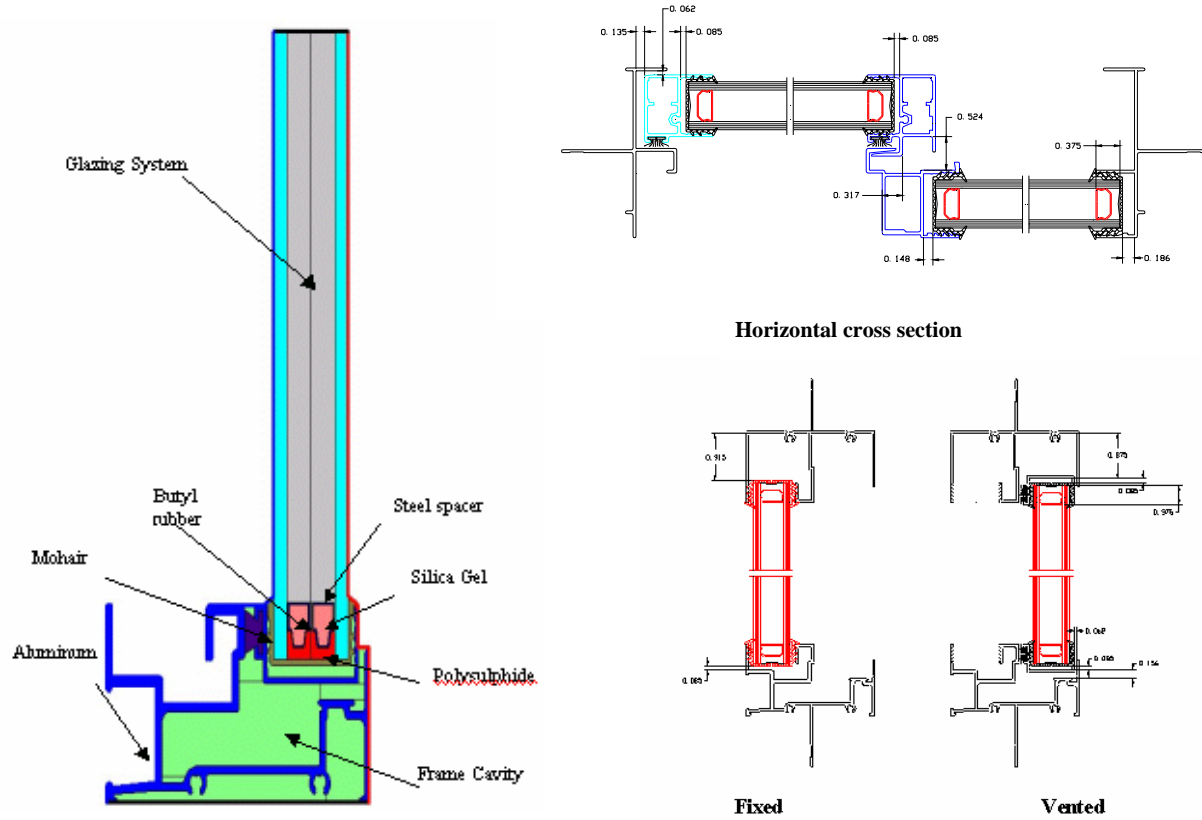


Figure 1. F1 - Aluminum Horizontal Sliding Window

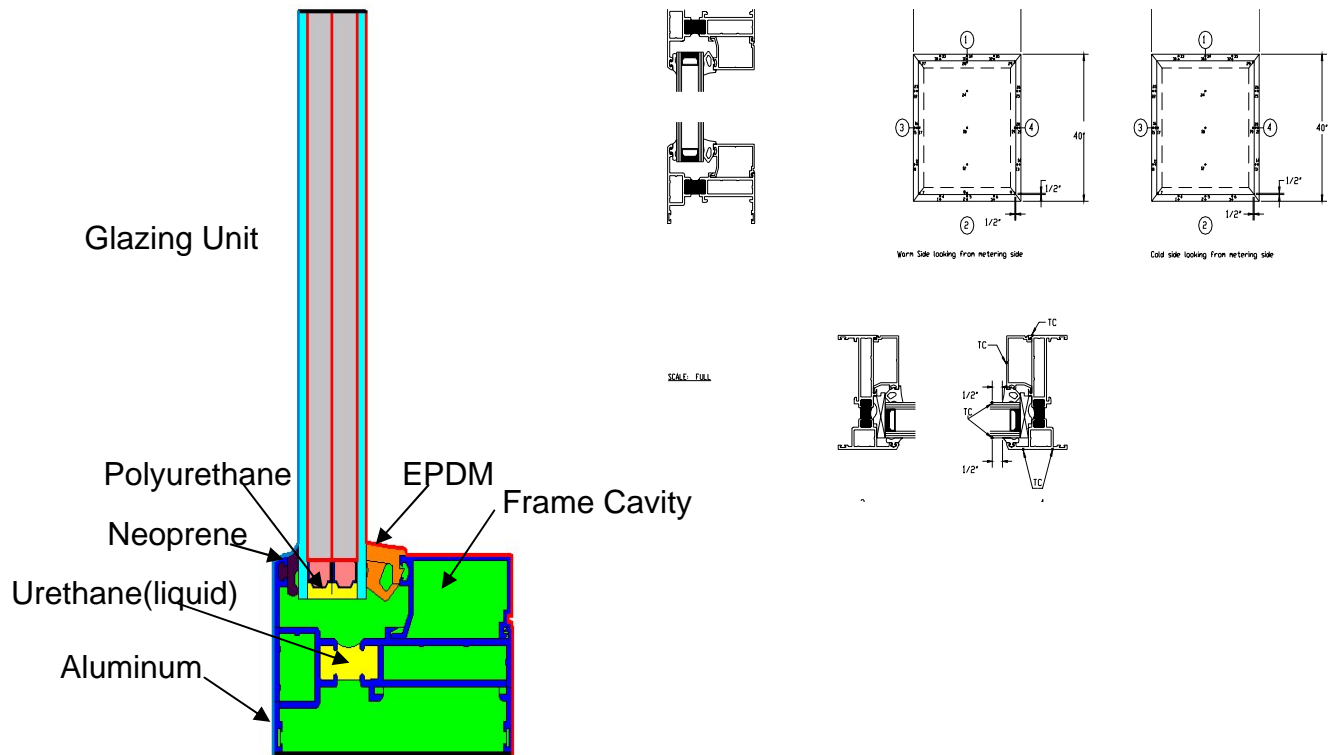


Figure 2. F2 - Thermally Broken Aluminum Fixed Window

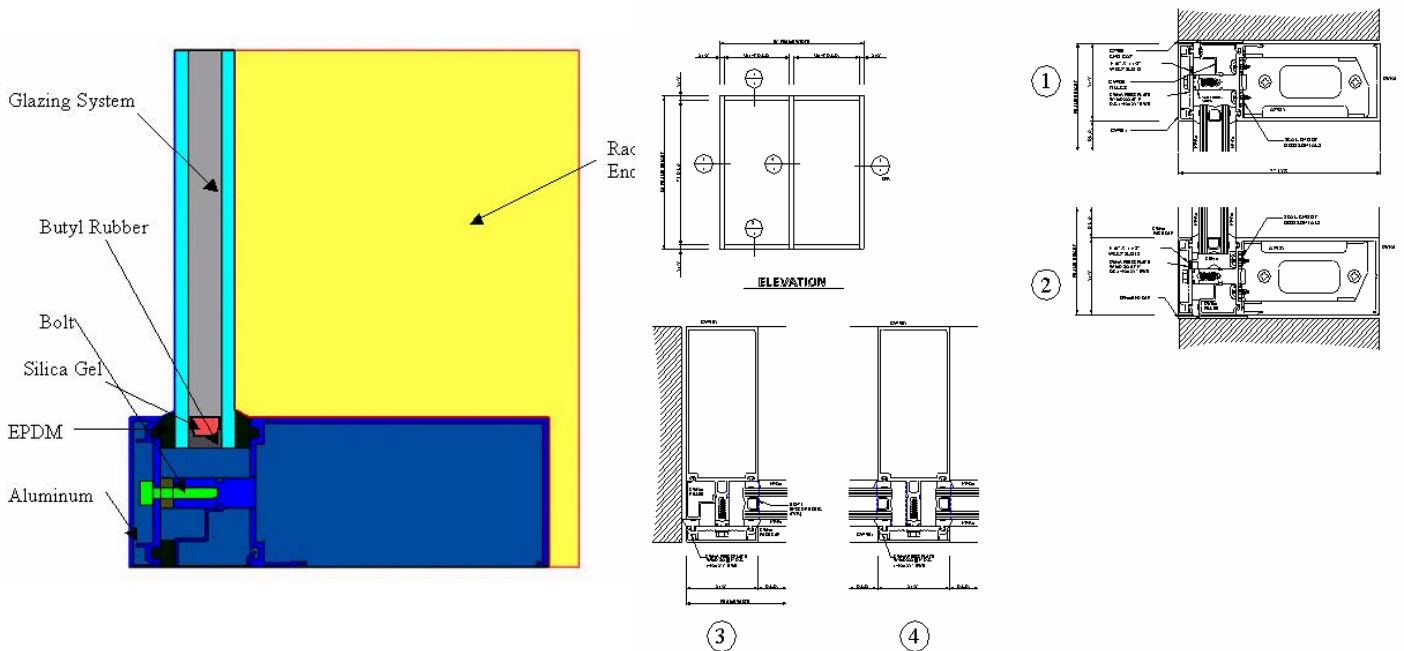


Figure 3. F3 - Thermally Improved Curtainwall

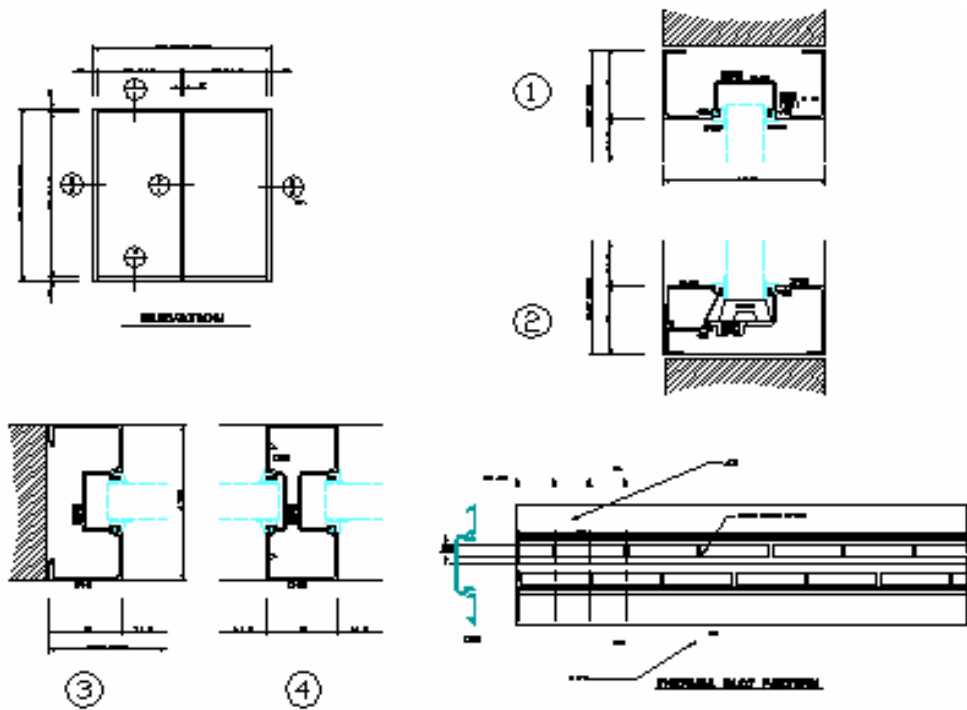
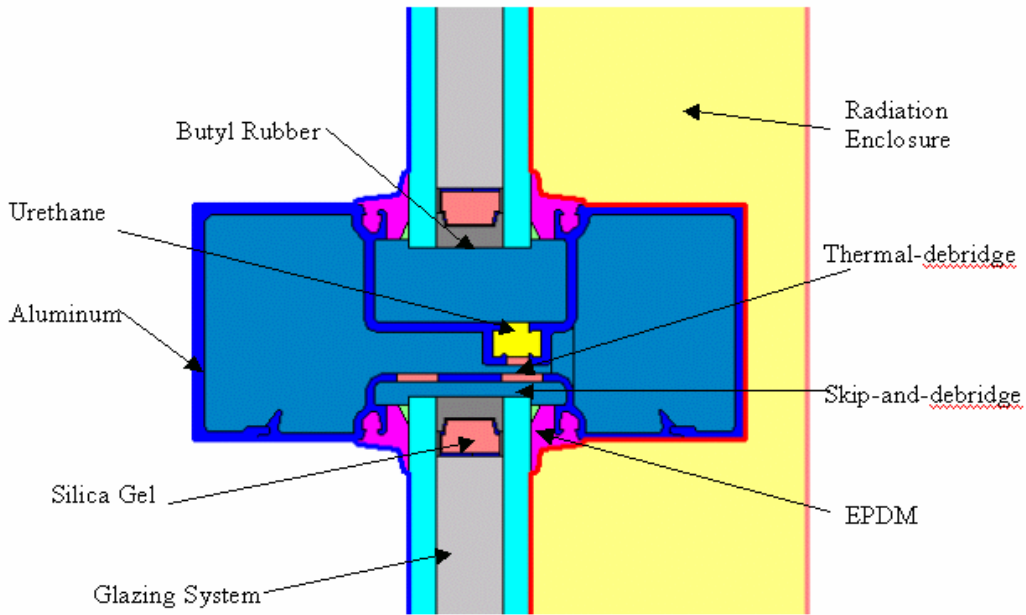


Figure 4. F4 - T/B Aluminum Curtainwall

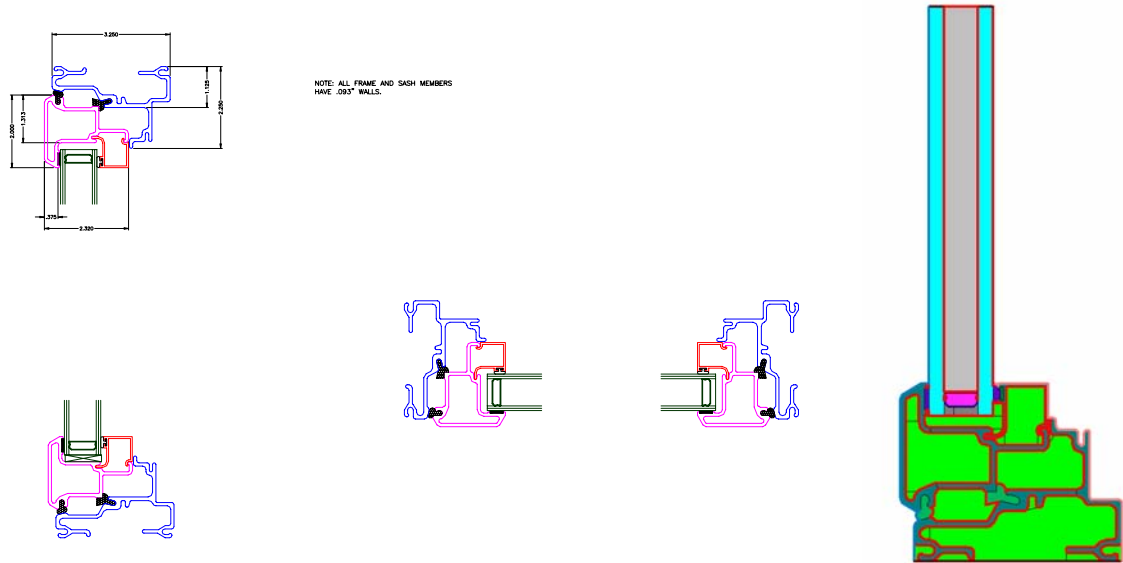


Figure 5. F5 - Fiberglass Casement

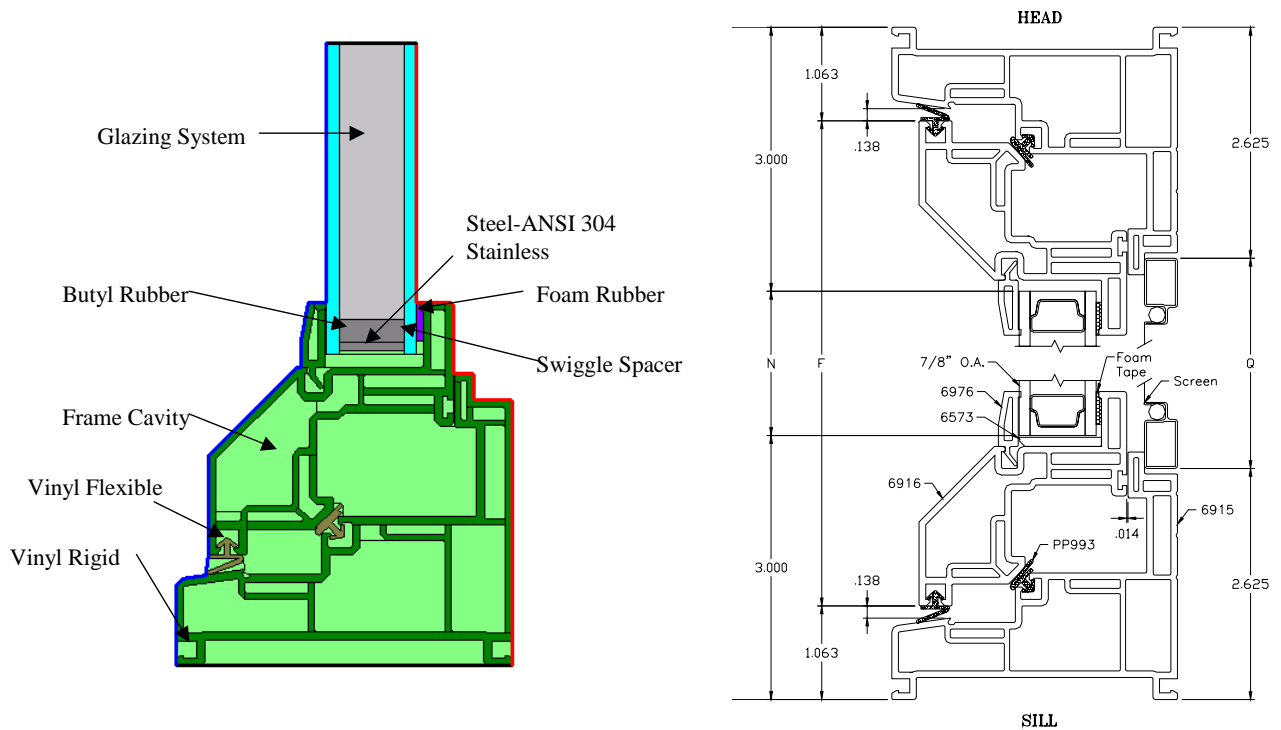


Figure 6. F6 - Reinforced PVC Window

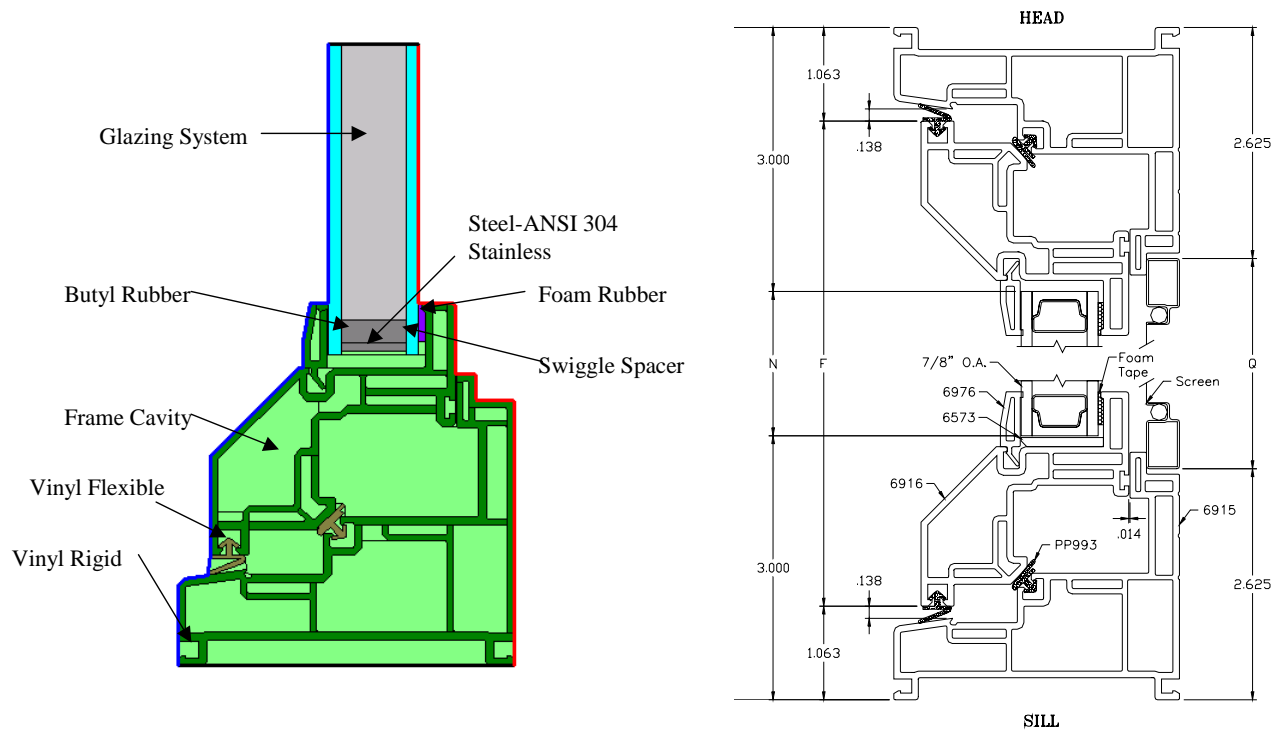


Figure 7. F7 - PVC Window

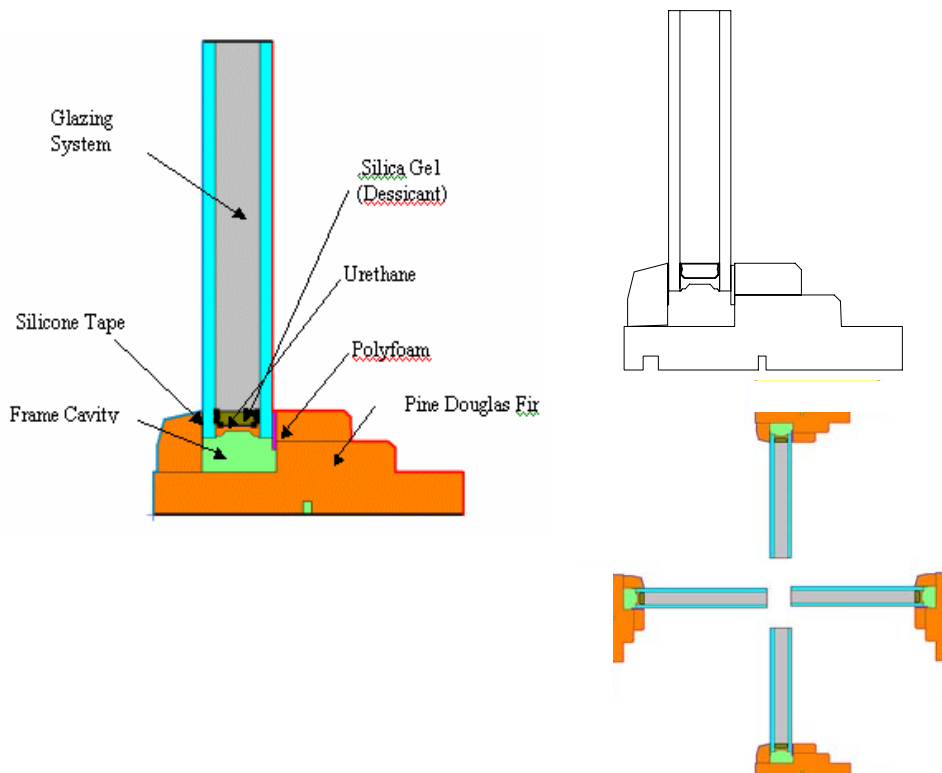


Figure 8. F8 - Wood Window

Glazing Systems:

Besides the framing system, the performance of a fenestration product also depends on the glazing system used. The following glazing systems, comprising of various type of glasses i.e. ranging from low performance clear glass to high performance soft coat low-E glass. Also considered in the glazing configuration were various existing gas fill technologies. Table 1 shows the U factor, SHGC and VT of the glazing systems used in the analysis.

- G1 – Single: Clear
- G2 – Single: Low-e (HC)
- G3 – Double: Clear Air Clear
- G4 – Double: Clear Argon Low-e (HC)
- G5 – Double: Clear Argon Low-e (SC)
- G6 – Triple: Clear Argon Low-e (HC) Argon Low-e (HC)
- G7 – Triple: Clear Krypton Low-e (SC) Krypton Low-e (SC)

Note: HC stands for “hard coat” low-e (emissivity is typically around 0.2) and SC stands for “soft coat” low-e (emissivity is typically around 0.05)

Table 1 lists U-factors, SHGC and VT for glazing configurations G1 to G7. WINDOW 5 program was used to calculate these indices.

Table 1: U factor, SHGC and VT of the Representative Glazing Systems (For IGUs Nominal Thickness is 1 in.)

ID	Name	U factor		SHGC	VT
		W/m ² ·K	Btu/hr·ft ² ·F		
G1	Single: Clear	5.808	1.023	0.816	0.884
G2	Single: Low-e (HC)	3.802	0.670	0.704	0.821
G3	Double: Clear Air Clear	2.699	0.475	0.702	0.786
G4	Double: Clear Argon Low-e (HC)	1.730	0.305	0.668	0.731
G5	Double: Clear Argon Low-e (SC)	1.359	0.239	0.377	0.623
G6	Triple: Clear Argon Low-e (HC) Argon Low-e (HC)	1.282	0.226	0.521	0.648
G7	Triple: Clear Krypton Low-e (SC) Krypton Low-e (SC)	0.708	0.125	0.161	0.217

Note: Argon and Krypton fills are mixtures of 10% air and 90% respective gas.

Spacer Systems:

Spacer also affects the performance of the fenestration product condensation resistance (perhaps one of the most important effects), therefore the following spacer assemblies are considered:

- S1 – Standard Aluminum bar single seal

- S2 – Standard Steel bar dual seal
- S3 – Polymer with metal reinforcement
- S4 – U-shaped Stainless Steel Spacer
- S5 – Solid polymer bar
- S6 – Foam Spacer

Thermal performance of spacer assemblies are expressed in terms of effective conductivities, k_{eff} . Appendix A details the calculation process, while Table 2 lists calculated k_{eff} .

Table 2: Effective Conductivities, k_{eff} of Spacer Assemblies.

ID	Name	k_{eff}	
		W/m·K	Btu/hr·ft·F
S1	Standard Aluminum bar dual seal	2.992	1.729
S2	Standard Steel bar dual seal	1.859	1.074
S3	Polymer with metal reinforcement	0.620	0.358
S4	U-shaped Stainless Steel Spacer	0.376	0.217
S4	Solid polymer bar	0.245	0.142
S5	Foam Spacer	0.180	0.104

STANDARD MODELING CONDITIONS

Standard NFRC modeling conditions are employed. Table 3 lists standard boundary conditions used for thermal modeling.

Table 3: NFRC Standard Boundary Conditions

Boundary Condition	Radiation Model	Convective Film Coefficient Boundary	
		Tilt = 90°	
		W/(m ² AK)	Btu in./h. ft ² F
NFRC 100-2001 Exterior	Blackbody	26.00	4.578
Interior Thermally Improved Frame (convection only)	Gray Body Diffuse	3.12	0.549
Interior Glazing System boundary condition	Gray Body Diffuse	Calculated by WINDOW for each glazing configuration using formulas in Section 8.3.2 in ISO 15099	

Emissivity of all opaque surfaces were assumed to be 0.9 for the baseline case.

SUMMARY OF THE CALCULATION PROCEDURES FOR CR

The Condensation Resistance (CR) of the fenestration product is determined from the lower of the Condensation Resistance rating for the frame (CR_f), edge-of-glass (CR_e) and center-of-glass (CR_c). The following are equations for each of the CR components:

Frame CR (CR_f):

$$CR_f = \left\{ 1 - \left\{ \frac{\sum_k SS_{f_k} * A_{f_k}}{A_{f_k}} \right\}^{1/3} \right\} * 100 \quad (1)$$

k = frame section

where for each frame cross-section, k :

$$SS_{f_k} = \frac{\sum_j (S_f)_{j=RH @ 30\%, 50\%, 70\%}}{3} \quad (2)$$

where for each relative humidity:

$$S_f = \frac{\sum_i (t_{dpp} - t_f)^+ * \Delta L_{f_i}}{(t_{dpp} - t_o) * L_f} \quad (3)$$

i = subdivided element
 $+$ = positive values only

For each frame cross-section, frame boundary facing indoors is subdivided into smaller segments, as dictated by the size of the numerical grid, which is utilized for the computation of thermal performance of the frame cross-section (see THERM program User's Manual). Each of these segments is one of " i " subdivided elements in the above equation.

Edge-of-Glass CR (CR_e):

Edge of glass is a region between the sightline on indoor side and center-of-glass region, where 2-D and 3-D heat transfer effects dominate in a glazing system. Calculation of edge-of-glass CR, CR_e is done in much the same way as for frame members, except that subdivided elements resulting from the numerical grid pertain to the edge-of-glass region of glazing. The equations for calculating CR_e are given below.

$$CR_e = \left\{ 1 - \left\{ \frac{\sum_k SS_{eog_k} * A_{eog_k}}{\sum_k A_{eog_k}} \right\}^{1/3} \right\} * 100 \quad (4)$$

k = edge of glass sections, respectively

where for each cross-section, k :

$$SS_{eog_k} = \frac{\sum_j (S_{eog_k})_{j=RH@30\%,50\%,70\%}}{3} \quad (5)$$

where for each relative humidity, j :

$$S_{eog_k} = \frac{\sum_i (t_{dpp} - t_{eog_i})^+ * \Delta L_{eog_i}}{(t_{dpp} - t_o) * L_{eog_k}} \quad (6)$$

i = subdivided element
 $+$ = positive values only

Center-of-Glass CR (CR_c):

Center-of Glass CR is calculated for the area of glazing where 1-D heat transfer dominates. While dividers affect thermal performance of glazing system and consequently the CR_c , for clarity in the first part of the analysis they will be excluded. The equations for calculating CR_c without dividers are as follows:

$$CR_c = \left\{ 1 - \left[\frac{\sum_k SS_{cog_k} * A_{cog_k}}{\sum_k A_{cog_k}} \right]^{1/3} \right\} * 100 \quad (7)$$

k = individual glazing system

where for each glazing system, k :

$$SS_{cog_k} = \frac{\sum_j (S_{cog_k})_{j=RH@30\%,50\%,70\%}}{3} \quad (8)$$

where for each relative humidity, j :

$$S_{cog_k} = \frac{\sum_i (t_{dpp} - t_{cog})^+}{(t_{dpp} - t_o)} \quad (9)$$

$+$ = positive values only

In the above equations, the following quantities were used:

t_{dp} = Dew point temperatures at the given relative humidity (RH);

$t_{dp,1} = 2.9^\circ\text{C} (37.3^\circ\text{F}) \quad @ \text{RH} = 30\%$

$t_{dp,2} = 10.3^\circ\text{C} (50.6^\circ\text{F}) \quad @ \text{RH} = 50\%$

$t_{dp,3} = 15.4^\circ\text{C} (59.8^\circ\text{F}) \quad @ \text{RH} = 70\%$

t_{dpp} = condensation reference point temperatures, $t_{dpp} = t_{dp} + 0.3^{\circ}\text{C}$
 ($t_{dpp} = t_{dp} + 0.5^{\circ}\text{F}$)

$t_{dpp,1} = 3.2^{\circ}\text{C}$ (37.8°F)

$t_{dpp,2} = 10.6^{\circ}\text{C}$ (51.1°F)

$t_{dpp,3} = 15.7^{\circ}\text{C}$ (60.3°F)

t_o = exterior ambient temperature -18°C (0°F)

t_{f_i} = average temperature of the frame segments i

t_{eog_i} = average temperature of the edge-of-glass segments i

t_{cog_i} = average temperature of the center-of glass area i ,

t_{deog_i} = average temperature of the divider-edge area i ,

t_{d_i} = average temperature of the divider area i ,

ΔL_{f_i} = length of subdivided segments on each modeled frame cross-section

ΔL_{eog_i} = length of subdivided segments on each edge-of-glass cross-section

L_f = total (wetted) length of each modeled frame cross-section,

L_{eog} = total length of each modeled edge-of-glass cross-section,

A_{f_k} = projected frame area of each modeled section

A_{eog_k} = edge-of-glass area of each modeled cross-section

A_{cog_k} = center-of-glass area of each center-of-glass section

Note: all segments are located on the indoor facing boundary

SUMMARY OF THE CALCULATION PROCEDURES FOR CMA

Algorithms for the calculation of the total product indices, U, SHGC, and VT for individual glazing options and spacer systems are based on the results of calculations for the strategically selected best and worst glazing and spacer options (4 total) and linear interpolation of results in between glazing options and logarithmic interpolation in between spacer options.

U-factor of a fenestration product, U , is calculated as a function of center of glass U-factor, U_c , using the following equation, which is based on linear interpolation formula:

$$U = U_b + \frac{(U_w - U_b)(U_c - U_{c,b})}{U_{c,w} - U_{c,b}} + \frac{\left(U_c - \left(U_b + \frac{(U_w - U_b)(U_c - U_{c,b})}{U_{c,w} - U_{c,b}} \right) \right) \cdot (V - V_1)}{100 - V_1} \quad (10)$$

where:

- U_w = U factor of a window incorporating "worst" IGU,

- $U_b = U$ factor of a window incorporating “best” IGU,
- $U_{c,w} =$ “center of glass U value for the “worst” IGU,
- $U_{c,b} =$ “center of glass” U value for the “best” IGU,
- $U_c =$ “center of glass” U value for requested IGU,
- $V_1 =$ Vision percentage of a window with base dimensions,
- $V =$ Vision percentage of a window with requested dimensions.

Vision percentage is calculated from the following equation:

$$V = \frac{A_v}{A} \cdot 100 \quad (11)$$

where:

- $A_v =$ Vision area, calculated as:

$$A_v = A - \sum_i A_{f,i}$$

$A_{f,i} =$ Individual frame areas:

- $A =$ Total product area

$$A = a \cdot b$$

where:

- $a =$ total window width
- $b =$ total window height

The total window indices for the window with given spacer assembly are calculated from the calculated performance of the same window with the “best” and “worst” spacer and IGU configurations, using to following two formulas:

$$U_w = U_{w1} + \frac{(U_{w2} - U_{w1}) \cdot [\ln(k_{eff}) - \ln(k_{eff1})]}{\ln(k_{eff2}) - \ln(k_{eff1})} \quad (12)$$

$$U_b = U_{b1} + \frac{(U_{b2} - U_{b1}) \cdot [\ln(k_{eff}) - \ln(k_{eff1})]}{\ln(k_{eff2}) - \ln(k_{eff1})} \quad (13)$$

where:

- $U_{w1} = U$ -factor of window with “worst IGU” and “best spacer”,
- $U_{w2} = U$ -factor of window with “worst IGU” and “worst spacer”,
- $U_{b1} = U$ -factor of window with base dimensions, “best IGU” and “best spacer”,
- $U_{b2} = U$ -factor of window with base dimensions, “best IGU” and “worst spacer”,
- $k_{eff1} =$ effective conductivity of the “best spacer”
- $k_{eff2} =$ effective conductivity of the “worst spacer”
- $k_{eff} =$ effective conductivity of the requested spacer.

Solar heat gain coefficient of the window with, incorporating “worst” IGU and requested spacer, $SHGC_w$, and Solar heat gain coefficient of the window incorporating “best” IGU and requested spacer, $SHGC_b$ are calculated in the same way as U-factor, presented in equations (5) and (6), where U is simply replaced by $SHGC$. VT is calculated by using simple area weighting of opaque and transparent portion of the fenestration product.

Notes:

- “Worst” and “Best” IGUs are the two extreme glazing options, having highest and lowest performance index (i.e., U, SHGC).
- “Worst” and “Best” spacers are the two extreme spacer options, having highest and lowest k_{eff}
- Figure 9 and Figure 10 show distribution of U-factors and SHGC for actual glazing configurations vs. vision percentage. Figure 11 and Figure 12 show distribution of U-factors and SHGC for actual spacer configurations vs. vision percentage.

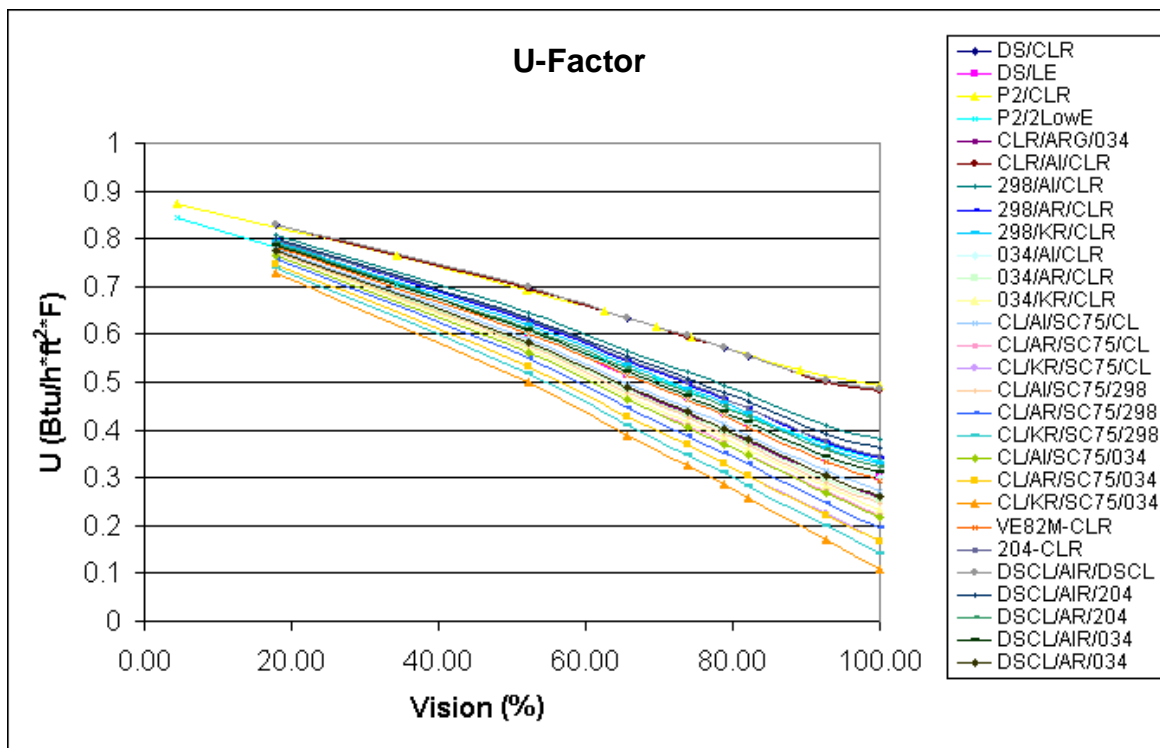


Figure 9: Variation of U-factor with Vision Percentage

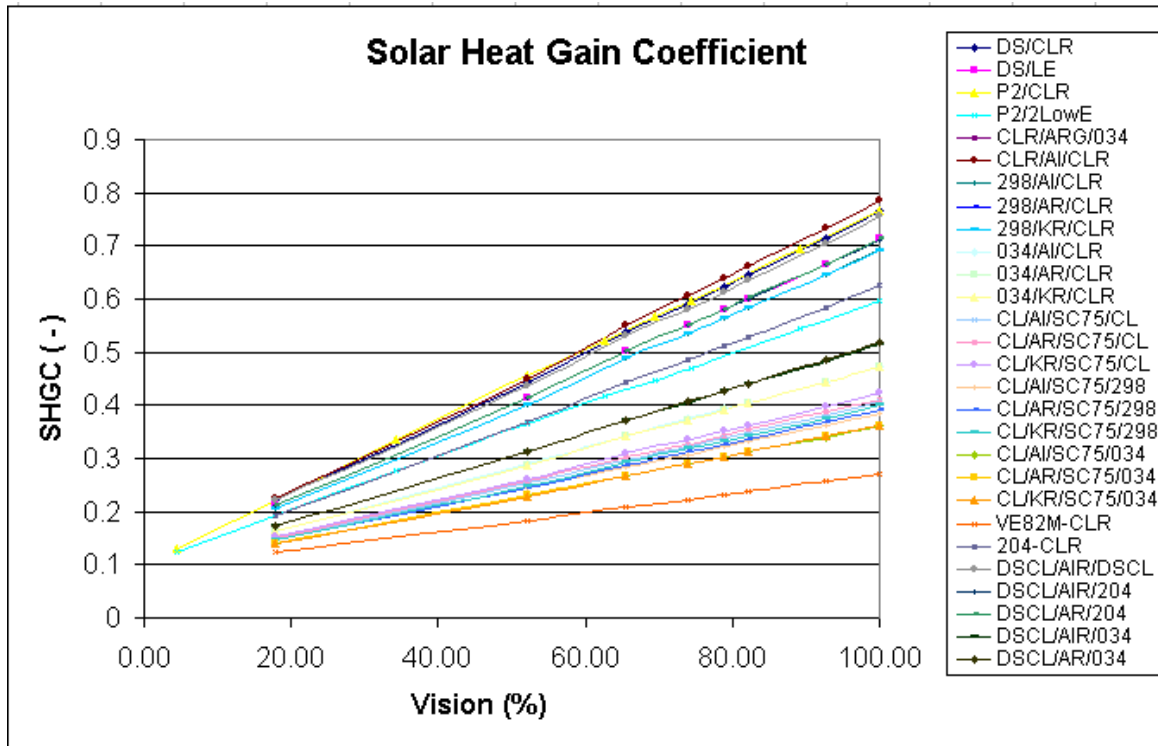


Figure 10: Variation of SHGC with Vision Percentage

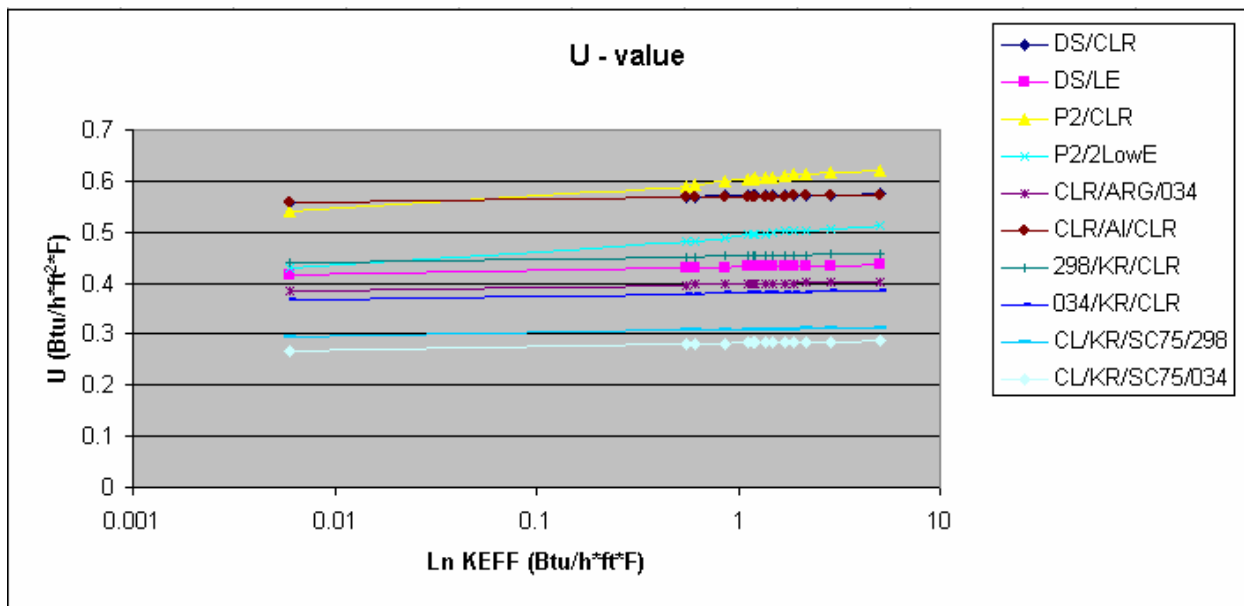


Figure 11: Variation of U-factor with k_{eff}

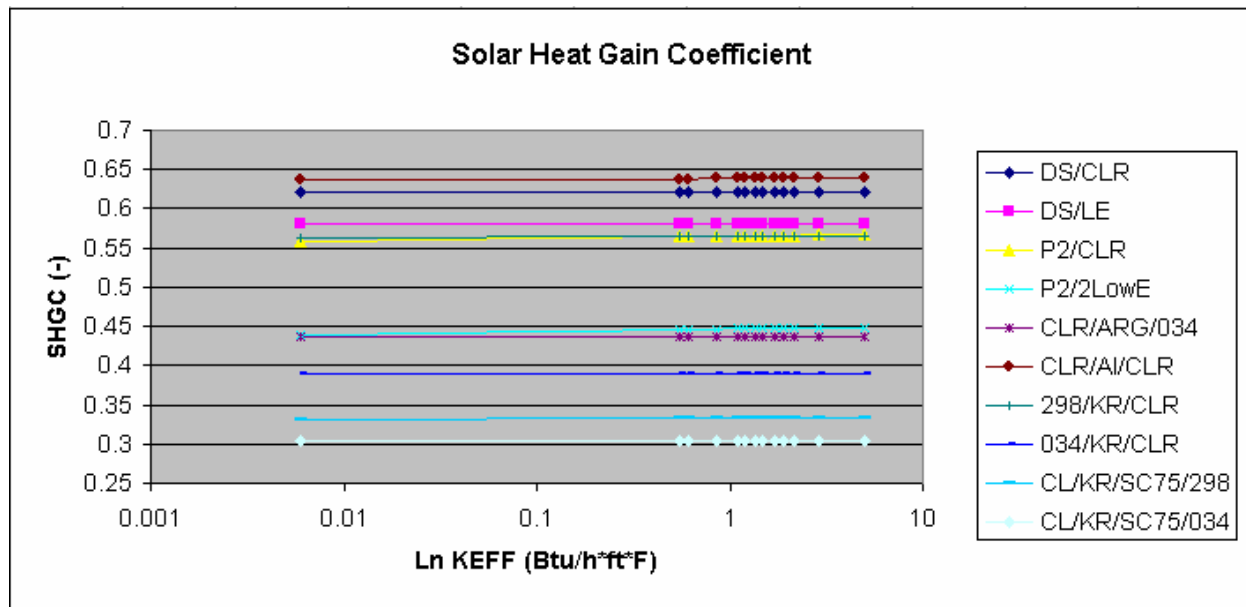


Figure 12: Variation of *SHGC* with k_{eff}

SELECTION OF RELEVANT PARAMETERS FOR CMA-CR

By using analogy to the *U* and *SHGC* fenestration product calculations using CMA methodology, one could conclude that the same would apply to the CR. However, while *U* and *SHGC* are numbers that are directly proportional to the rate of energy transfer and therefore were conducive to the development of interpolation procedure, CR is highly non-linear index calculated from the surface temperature and relative humidity of air as primary quantities. Because of this, it will not be possible to develop CMA procedure for CR using the same process. Instead either fundamental quantities (i.e., indoor surface temperature) or basic derived quantities, such as *SS* (see equations 2, 5 and 8), or *S* (see equations 3, 6 and 9) need to be investigated as potential candidates.

Because of its linear relationship with temperature and because it is already area averaged quantity, the most likely candidate is going to be the *S* quantity. In order to check this hypothesis, *S* is being calculated for each of the representative products, including representative glazing and spacer options, as well as for B/W options for each product. The distribution of *S* for actual glazing and spacer systems is being plotted for frame, and edge-of-glass vs. vision percentage and vs. center of glass *S*. In addition, the relationship between B/W product options and actual product options is compared in order to develop functional relationship leading to the development of the algorithm.

At this time, calculations are being undertaken for each of the product lines and product options and distribution of *S* is being plotted.

At the same time, *SS* quantity is also being looked at. This may serve as an alternate candidate for the reference quantity in calculating CR using CMA. This quantity incorporates the same linear relationship as *S*, however, the averaging is done on the higher level, which includes relative humidity effects. The *SS* is initially investigated for

the framing system F2 and depending on the relationship resulting from using S quantity, the investigation may either stop or proceed to the remaining product lines.

For the next progress report, it is planned to provide results of the calculation of S for several product lines and SS for F2 product line. Plots of the S and SS distribution will be provided as a part of the progress report.

APPENDIX A: CALCULATION OF EFFECTIVE CONDUCTIVITIES (k_{eff}) of SPACER ASSEMBLIES:

Spacer assembly can be converted into the solid block with the conductivity equal to the effective conductivity of the spacer assembly, calculated using the procedure outlined below:

- 1) Prepare THERM model of spacer assembly and assign boundary conditions as shown in Figure 1 and with values given below (these values are mostly arbitrary since they are subtracted in the process, but they are recommended because they are equal to the standard NFRC boundary conditions):

Outdoor Boundary Condition (BC):

Convection/linearized radiation (combined) surface heat transfer coefficient with the following values:

- Temperature = - 18 °C,
- $h_o = 30 \text{ W}/(\text{m}^2\cdot\text{K})$

Indoor Boundary Condition (BC):

Convection/linearized radiation (combined) surface heat transfer coefficient with the following values:

- Temperature = 21 °C,
- $h_i = 8 \text{ W}/(\text{m}^2\cdot\text{K})$

- 2) Assign U-factor surface on Indoor BC boundary (e.g., "Spacer")
- 3) Calculate results in THERM and write down calculated U-factor. From this U-factor calculate total thermal resistance as:

$$R_{TOT} = \frac{1}{U} [\text{m}^2\cdot\text{K}/\text{W}]$$

- 4) Calculate effective conductivity of the spacer assembly, k_{eff} using:

$$k_{eff} = \frac{L}{R_{TOT} - \frac{1}{h_o} - \frac{1}{h_i}} [\text{W}/(\text{m}\cdot\text{K})] \quad (3)$$

Where:

L = Width of spacer assembly [m]

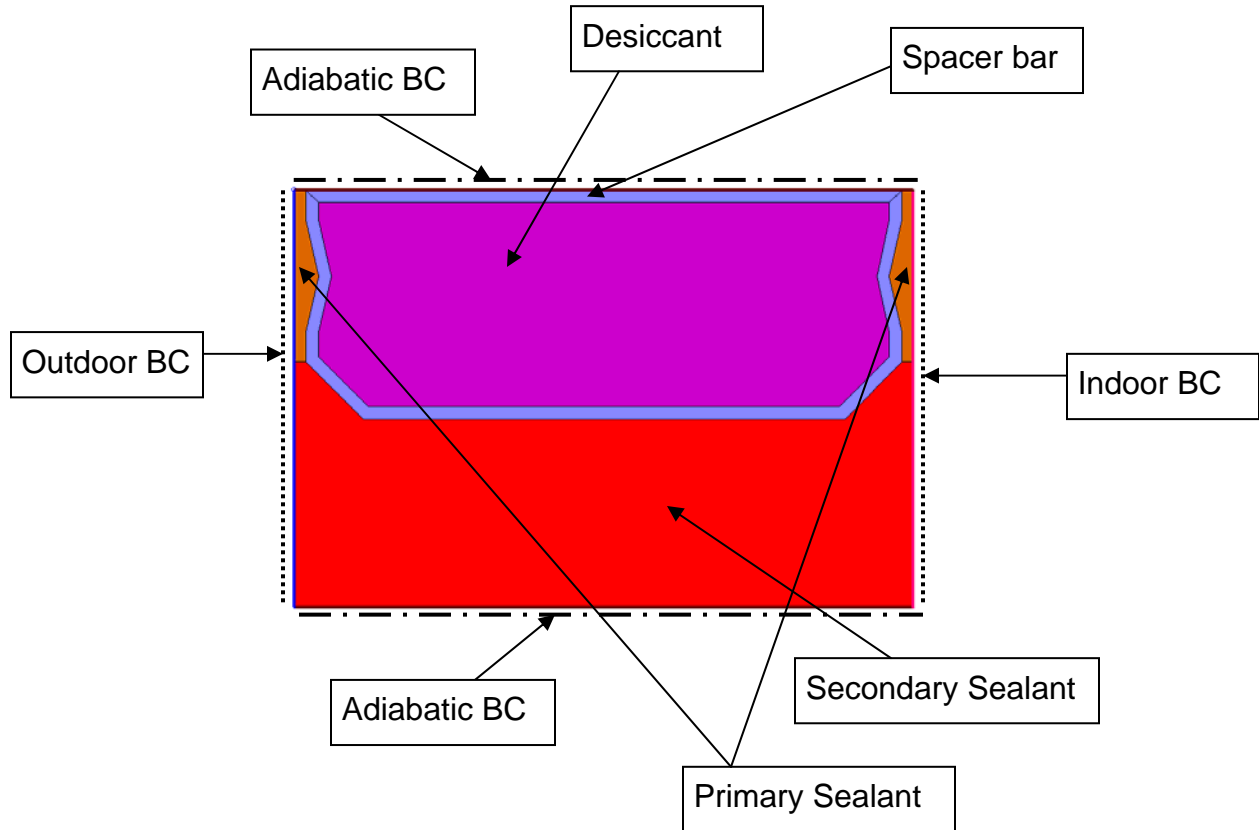


Figure 1. Typical Spacer Assembly and Boundary Conditions for Calculating k_{eff}

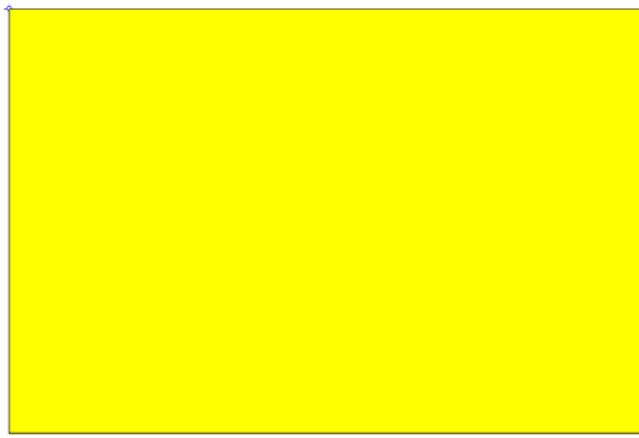


Figure 2. Solid Block with Effective Conductivity k_{eff}

Example:Input:

Spacer bar: Stainless steel; $k = 14.30 \text{ W/(m}\cdot\text{K)}$
 Primary Sealant: Polyisobutylene (PIB); $k = 0.20 \text{ W/(m}\cdot\text{K)}$
 Secondary Sealant: Polysulphide; $k = 0.40 \text{ W/(m}\cdot\text{K)}$
 Desiccant: Silica Gel (loose fill); $k = 0.03 \text{ W/(m}\cdot\text{K)}$
 $L = 16.51 \text{ mm (0.01651 m)}$
 Spacer bar height: $6.10 \text{ mm (0.0061 m)}$
 Spacer bar width: $15.88 \text{ mm (0.01588 m)}$
 Primary sealant thickness: $0.315 \text{ mm (0.000315 m)}$
 Primary sealant height: $4.58 \text{ mm (0.00458 m)}$
 Secondary sealant height: $6.54 \text{ mm (0.00654 m)}$

Results:

$$U = 5.5668 \text{ W/(m}^2\cdot\text{K)}$$

$$R_{\text{TOT}} = 0.1796 \text{ m}^2\cdot\text{K/W}$$

$$k_{\text{eff}} = \frac{0.01651}{0.1796 - \frac{1}{30} - \frac{1}{8}}$$

$$k_{\text{eff}} = 0.776 \text{ W/(m}\cdot\text{K)}$$

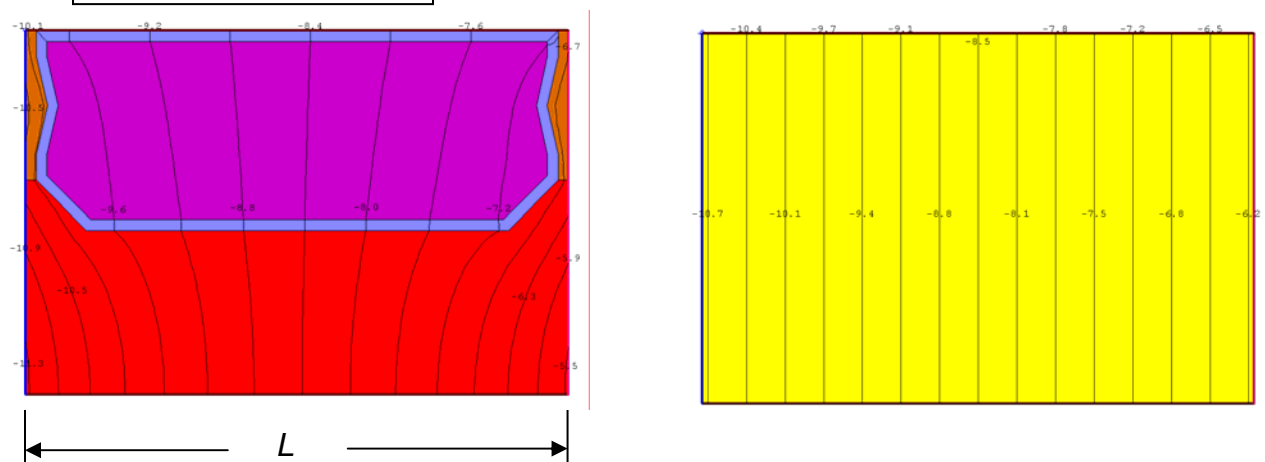


Figure 3. Temperature Distribution in Actual and “Solid Block” Spacer Assembly