Three Dimensional Effects on the Thermal Performance of Insulated Curtain Wall Spandrels

Andrew Dunlap, AIA
[AIA, ASTM, ABAA, NCARB]

Ryan Asava, Assoc. AIA
[AIA]

Katerina Gross, RA
[NCARB]

ABSTRACT HEADING

Current methods of determining the thermal performance of fenestration systems generally include two-dimensional computer modeling and sometimes laboratory testing. While this may be sufficient for typical punched window openings, it may not adequately address the potential for reduced thermal performance of curtain wall systems that incorporate insulated spandrel conditions.

In most curtain walls, vertical mullions extend from a warmer interior environment into a colder insulated spandrel. The mullions function as vertical thermal bridges and may decrease the overall thermal performance of the opaque spandrel area. The impact will vary depending on several factors such as the type of spandrel glazing, IGU spacer type, insulation thickness, location of the insulation, and vapor barrier methodology.

Industry standard evaluation methods do not adequately address this vertical heat transfer. Two-dimensional computer modeling can be used to produce an area weighted average thermal performance. However, since it is only a two-dimensional evaluation, it does not include the linear transfer of heat flow in the third dimension, along the length of the vertical mullions. Laboratory testing such as AAMA 1503, "Voluntary Test Method for Thermal Transmittance and Condensation Resistance of Windows, Doors, and Glazed Wall Sections" is sometimes used to provide measured results of thermal performance. However, manufacturers typically do not include spandrel conditions when testing the performance of a system. Additionally, physical testing is costly and only produces results at one given set of variables. Performing several variations can quickly become cost prohibitive.

This paper will evaluate the three-dimensional effects of heat flow through curtain wall spandrel conditions and the relative impact on thermal performance. Industry standard two-dimensional computer modeling will be used to compare the results with the three-dimensional modeling procedures. Additionally, physical testing of curtain walls with insulated spandrels is planned to be performed at a later date to provide actual results for comparison.

Andrew A. Dunlap, AIA, Principal, Building Technology Studio, SmithGroupJJR, Inc, Detroit, MI, 48226
Ryan Asava, Building Technology Studio, SmithGroupJJR, Inc., Detroit, MI, 48226;
Katerina Gross, RA, Building Technology Studio, SmithGroupJJR, Inc., Detroit, MI, 48226;

BACKGROUND AND INTRODUCTION

The total product thermal performance of curtain wall spandrels is not well understood by many in the building industry. There are often misunderstandings on the prescriptive requirements of the model energy codes and how these areas should be detailed to achieve the required performance. Some believe the spandrel areas can be included as part of the entire fenestration area and that a weighted average of both the spandrel and vision areas can be combined to produce one overall U-factor for the entire system. However, most model energy codes clearly indicate the spandrel area is required to be determined separate from the vision area. Additionally, these codes indicate that spandrels are required to meet the thermal performance for opaque walls. There are select energy codes from individual states that deviate from this requirement. These codes still require the spandrel performance to be determined separately from the vision performance, but the specific thermal performance requirements for spandrels is different from the typical opaque wall requirements. The following are excerpts from ASHRAE 90.1 "Energy Standard for Buildings Except Low-Rise Residential Buildings".

Section 3 Definitions, Abbreviations, and Acronyms

Section 3.2 Definitions

Wall (partial definition): *That portion of the building envelope, including opaque area and fenestration, that is vertical or tilted at an angle of 60 degrees from horizontal or greater. This includes above- and below-grade walls, between floor spandrels, peripheral edges of floors, and foundation walls. For the purposes of determining building envelope requirements, the classifications are defined as follows:*

***steel-framed wall**: a wall with a cavity (insulated or otherwise whose exterior surfaces are separated by steel framing members (i.e., typical steel stud walls and **curtain wall systems**).*

NORMATIVE APPENDIX A "RATED R-VALUE OF INSULATION AND ASSEMBLIY U-FACTOR, C-FACTOR, AND F-FACTOR DETERMINATIONS"

A3 ABOVE GRADE WALLS

A3.3.2 Rated R-Value of Insulation for Steel-Framed Walls

A3.3.2.3 *Opaque mullions in spandrel glass shall be covered with insulation complying with the steel-framed wall requirements*.

The method of achieving the code required thermal performance is also often misunderstood. It is not uncommon for design professionals to provide insulation, installed between the curtain wall framing members, in the thickness required to meet the prescriptive code. For example, if the code requirement was R15 then one might install 4" of mineral wool insulation (approximate R-value of 4.3 per inch) thinking that it will produce an R-value well beyond the R15 requirement. However, the reality of the effectiveness of the insulation is not clearly understood. Similar to vision units, the total product thermal performance of the spandrel must include the effects of the curtain wall framing. There are manufacturers and other enclosure consultants that recognize this and have produced documents and some research on how the curtain wall framing effects the total product thermal performance. Some manufacturers, produce guidance charts that are based on the ratio of the area of spandrel to the ares of the spandrel including the curtain wall framing. **FIGURE 2** illustrates the significant loss of performance of a four-sided captured curtain wall system based on two different frame configurations. The spandrel insulation is installed in a traditional manner, in-filled between the framing.

- 95% Spandrel to Frame Ratio
  - Frame Configuration = 10 ft by 7 ft
  - Center-of-Spandrel R-Value = R16
  - Total Product U-Factor ≈ 0.11 Btu/h·ft²·°F (≈9.1)

- 87% Spandrel to Frame Ratio
  - Frame Configuration = 2 ft by 7 ft
  - Center-of-Spandrel R-Value = R16
  - Total Product U-Factor ≈ 0.19 Btu/h·ft²·°F (≈R5.3)

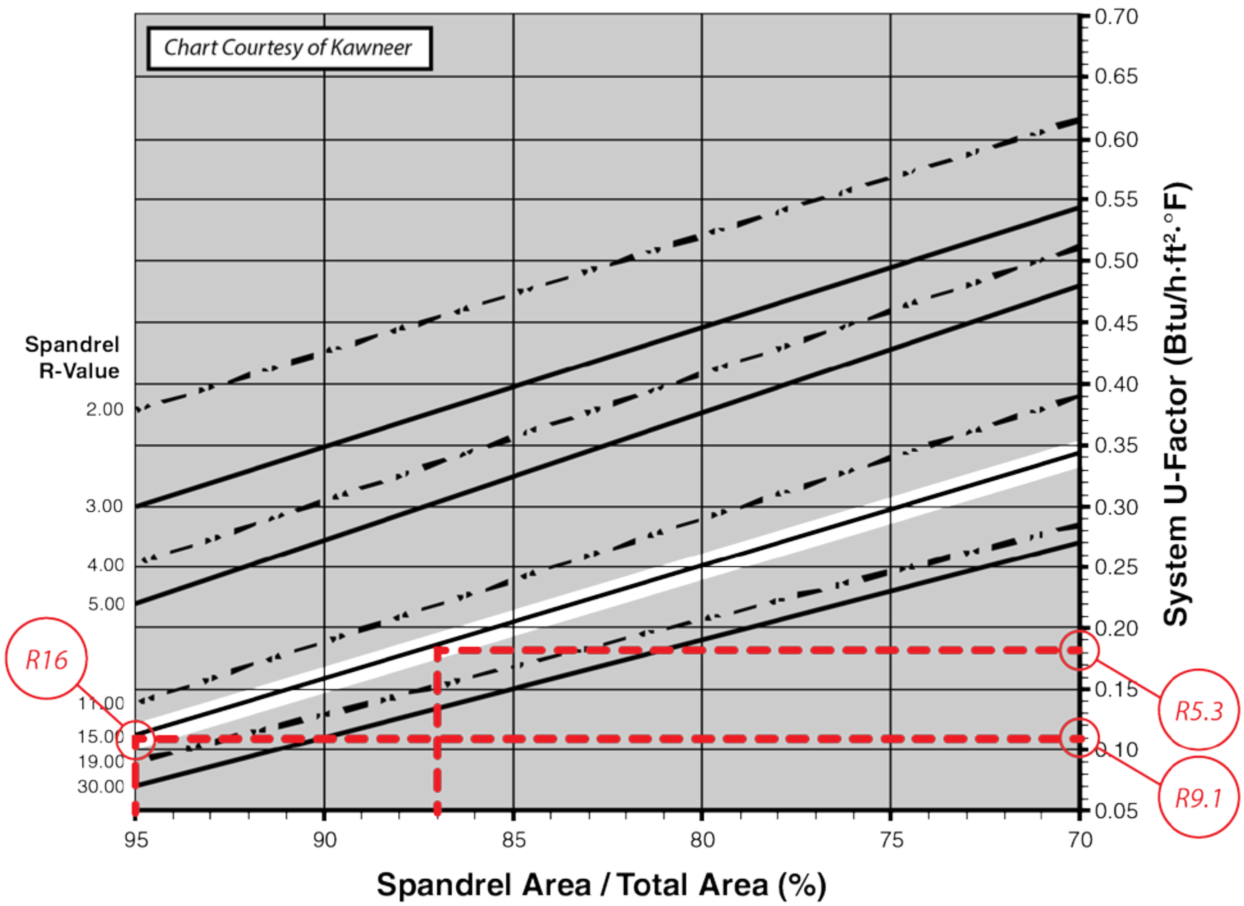

FIGURE 2: Total Product Thermal Perfromance Chart supplied by Curtain Wall manufacturer.

As indicated, the total product thermal performance is significantly degraded by the framing. This is not unique to this curtain wall system. Other curtain wall systems where the insulation is installed between the framing will perform similarly. This is an important point to consider. Far too often, the Center-of-Spandrel thermal performance is used for code compliance and when performing whole building energy modeling. The Total Product Thermal Performance for the spandrel area must be understood, determined, and utilized when proving code compliance or when performing whole building energy models to provide accurate results.

There are methods available within the glass and glazing industry to determine the total product thermal performance. However, they were not specificially developed to address curtain wall spandrels. Current methods include two-dimensional finite element computer modeling and laboratory testing. While there have been some advances in the recent past related to computer simulated thermal modeling, most are still limited to two dimensions. Physical testing is the best method to provide accurate results. However, physical testing is often limited due to the cost and the amount of time/schedule required. It is generally preformed to either validate computer modeling or to determine the performance of a custom glazing assembly that is beyond past similar testing or simulation results.

Thermal performance (U-Factor) of fenestration products is often estimated by utilizing a two-dimensional modeling procedure specified by NFRC 100 "Procedure for Determining Fenestration Product U-factors." This procedure uses multiple two-dimensional models to produce a "Total Product U-Factor". This method was initially developed to determine total product U-Factors for vision units. While this method can be utilized to determine the performance of spandrel areas, it is not common practice. Additionally, since the two-dimensional models do not incorporate three dimensional effects of heat flow parallel with the fenestration system, such as through vertical and horizontal mullions, it is possible that they do not provide accurate Total Product U-Factor results.

This type of industry standard computer analysis calculates heat transfer flowing from a warm interior environment to a cold exterior environment through the frame and insulating glass units, in the direction perpendicular to plane of the fenestration product. This type of analysis may not adequately address the frame effects on the total product thermal performance of the spandrel area.

Typical two-dimensional computer modeling does not consider the complex interfaces at intersections of the jamb/sill and jamb/head conditions. Most modeling procedures evaluate the cross section of the fenestration product and the adjacent construction. However, when evaluating the results of many physical test results one can see that the interface of the various components have an impact on the resultant interior surface temperatures **(Figure 3).**

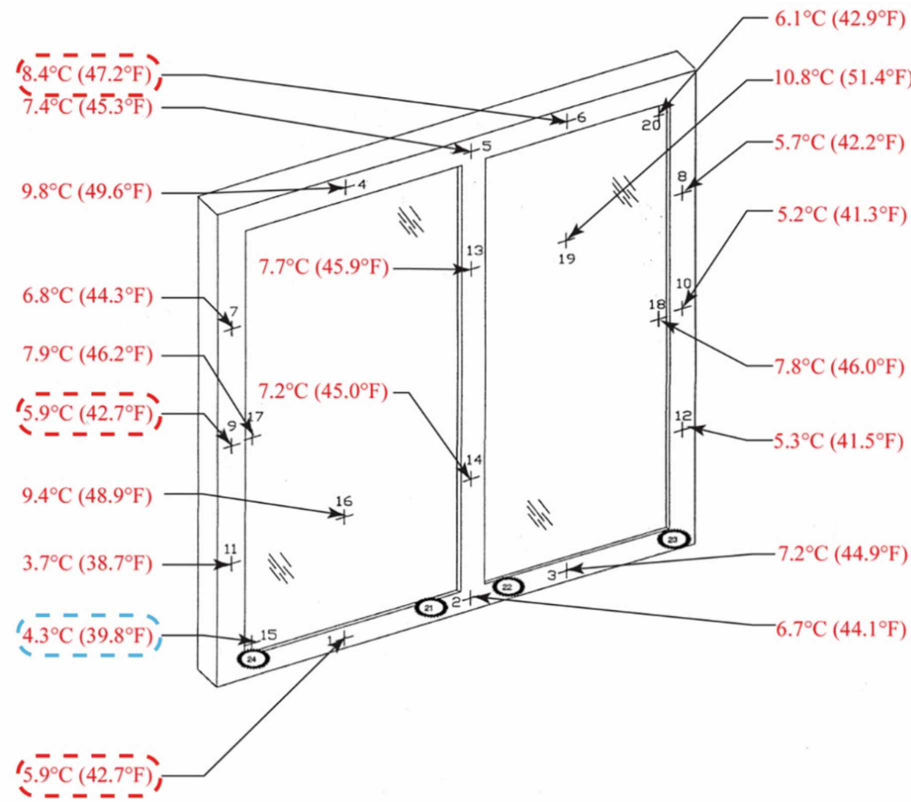

FIGURE 3: Example results of a physical thermal performance test. Note, variations at interfaces of vertical/horizontal mullions.

Just as these differing results can be seen at the interfaces of the tested window in **Figure 3**, similar but potentially more complex conditions can be present within curtain wall construction. Curtain wall systems are typically hung on the outside of a building's structure and often span across one if not several floor lines. At the floor line, many traditional curtain wall systems incorporate the use of spandrel glass and spandrel insulation to increase the energy efficiency of the fenestration system. As a result, some components of the curtain wall system are exposed to two different interior environmental conditions. In particular, vertical mullions span from the vision area up into and through the spandrel condition as a continuous component. This component passes through an interior environmental condition and is completely exposed to the interior conditions, typically 70 degrees Fahrenheit, but it also passes through a much colder spandrel condition that is insulated from the interior environment **(FIGURE 4)**.

FIGURE 4: Vertical mullions run continuously from exposed vision area, through insulated spandrel area, and back into vision area at the next floor.

The environmental conditions the vertical mullion are exposed to are typically colder at the spandrel because the system includes insulation. As the vertical mullions extend from a warmer conditioned interior environment into a colder insulated spandrel, the mullions are essentially vertical thermal bridges (**FIGURE 5**). The overall influence of the thermal bridge will vary depending on several factors such as the type of vision and spandrel glazing, IGU spacer type, insulation thickness, location of the insulation within the system, and vapor barrier methodology.

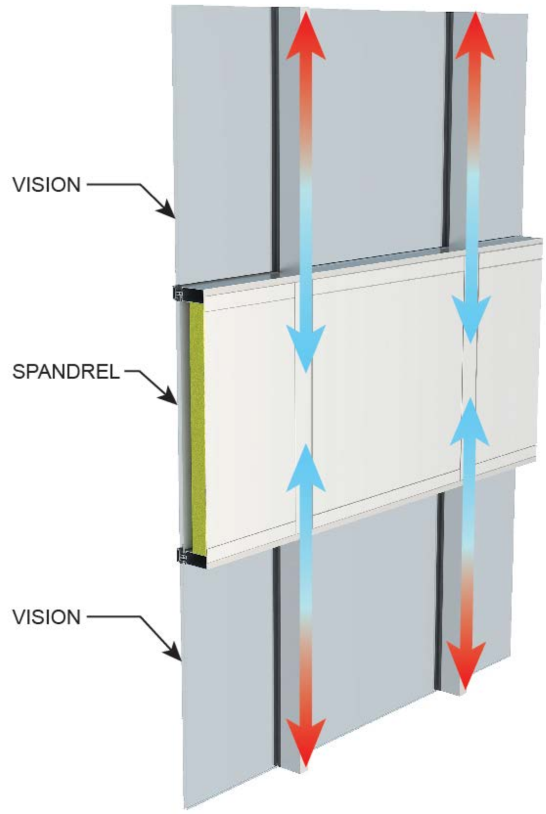

FIGURE 5: Indication of heat flow through vertical mullions that run continuously from exposed vision area, through insulated spandrel area, and back into vision area at the next floor.

It is important to highlight the significance of the potential requirements for fire rated joint assemblies at the floor line. Typically, when a fire rated joint assembly is required, it is often necessary to include “mullion covers”. Mullion covers are typically an 8” wide piece of 2” thick mineral wool insulation that is placed over the vertical mullions in the spandrel areas **(FIGURES 6 - 8)**. This component provides additional insulation to the system.

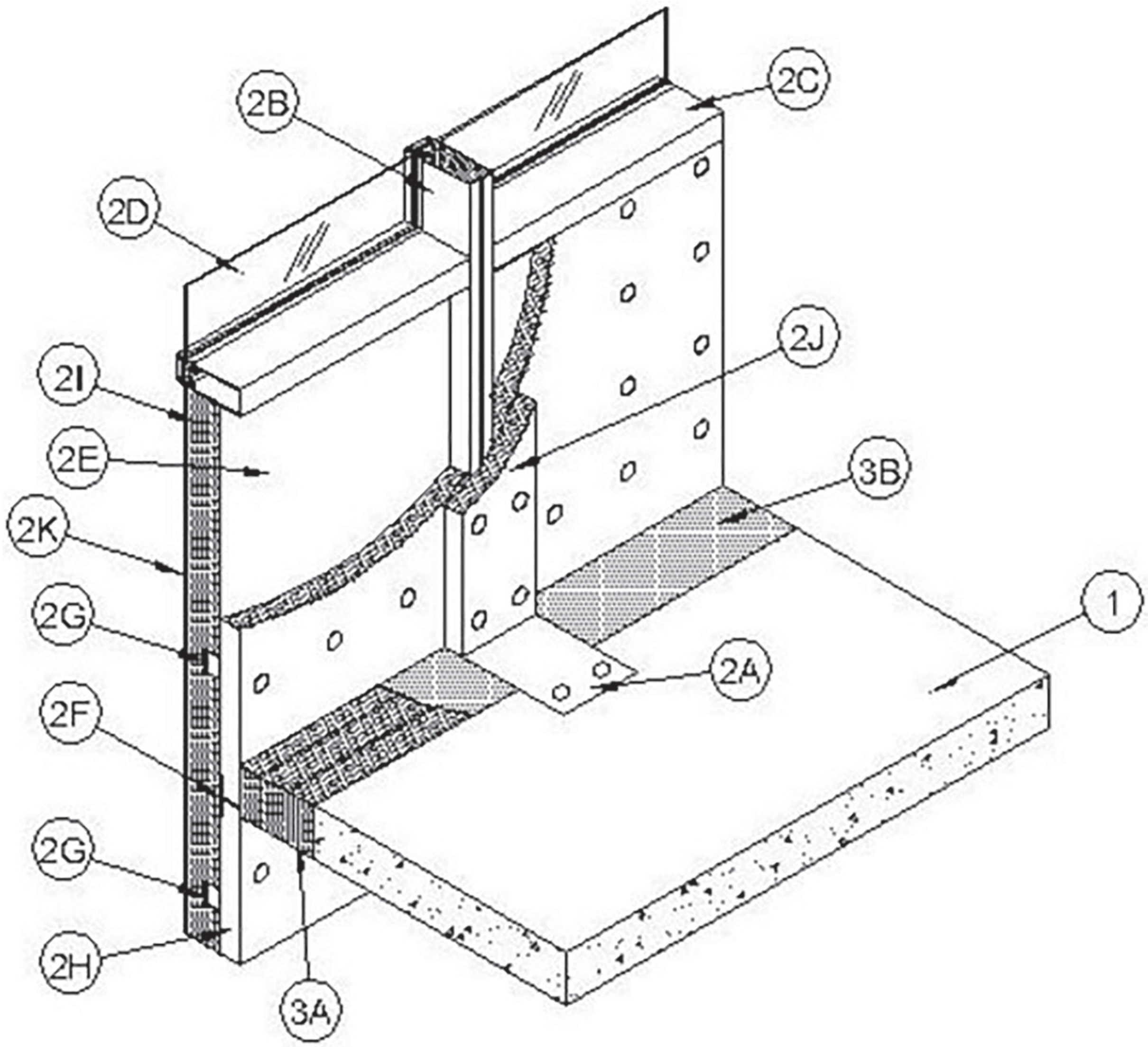

FIGURE 6: Typical fire rated joint assembly. Item 2J is a 2" x 8" foil faced mineral wool mullion cover, which is a common requirement to achieve the fire rating.

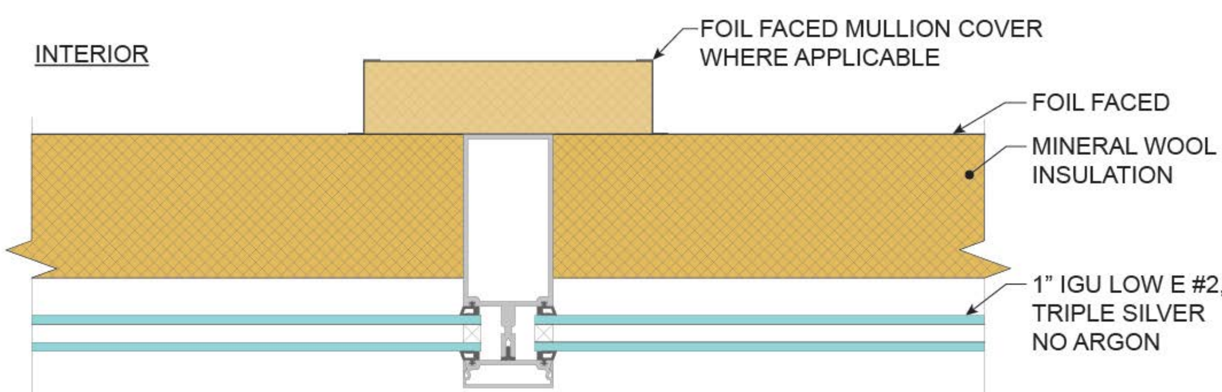

FIGURE 7: Plan detail that indicates a mullion cover at a fire rated joint assembly.

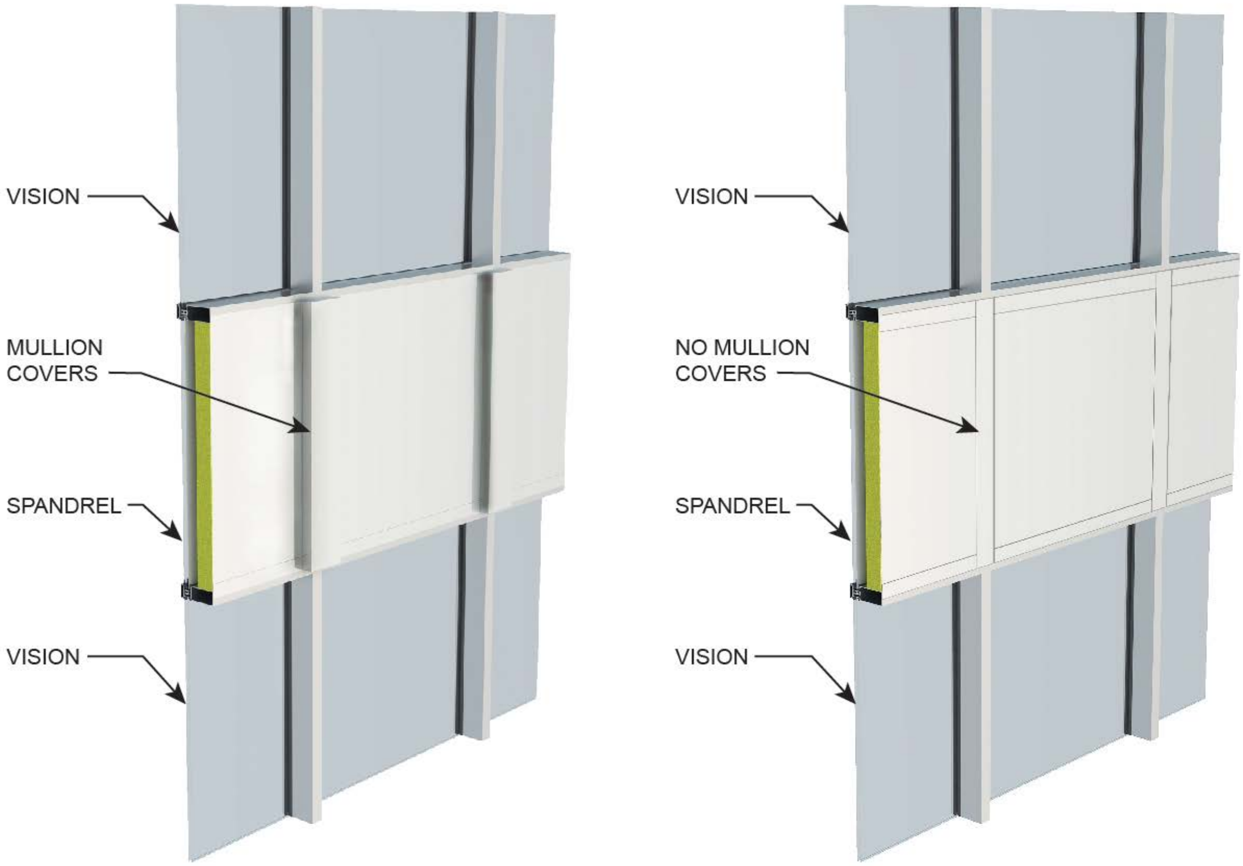

FIGURE 8: Comparison of curtain wall system with and without mullion covers.

Laboratory testing is often used to provide measured results for total product thermal performance. One type of physical testing that manufacturers utilize to determine the performance is AAMA 1503 "Voluntary Test Method for Thermal Transmittance and Condensation Resistance of Windows, Doors, and Glazed Wall Sections", often referred to as the CRF test. However, these tests typically do not include spandrel areas. In fact, the standardized configurations included within the test standard do not indicate or require spandrel conditions. **Figure 9** is a typical configuration of an AAMA 1503 test. Even if a manufacturer elected to include insulated spandrel conditions in a physical test, it is costly and is only accurate at one set of interior and exterior temperatures per test. Performing several variations quickly often becomes cost prohibitive.

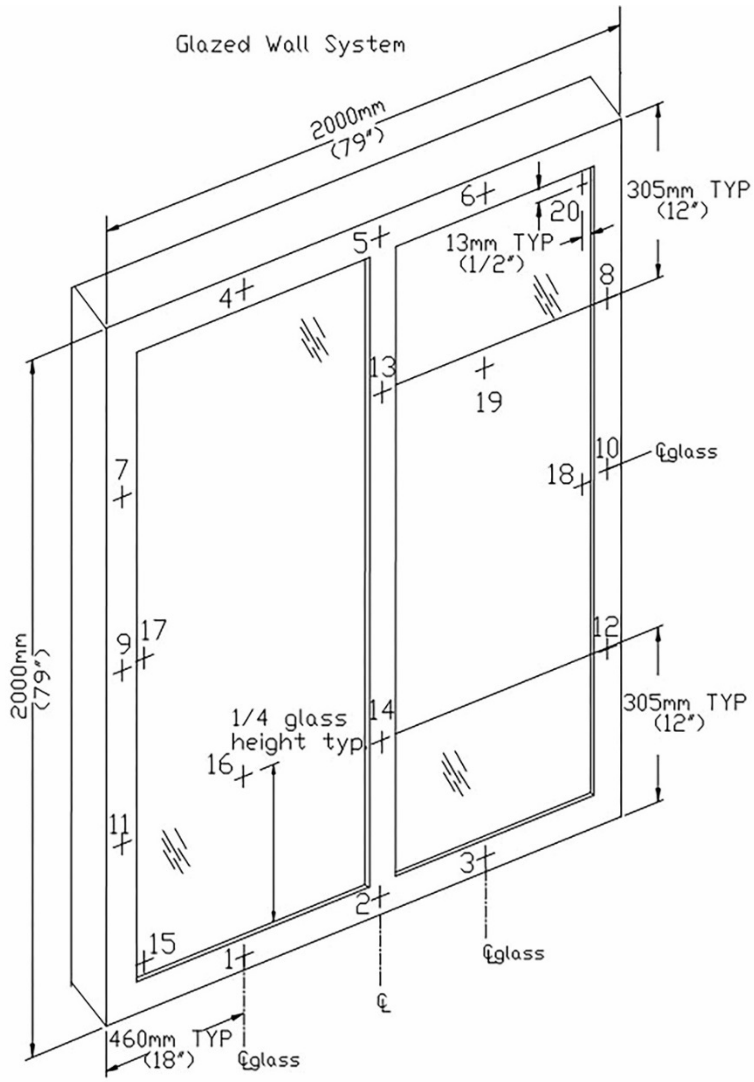

FIGURE 9: Typical AAMA 1503 "Glazed Wall System" test configuration.

Another inherent problem with relying on this test is the standardizing of specimen sizes. Buildings are not designed to standard sized glazing systems. Project specific mullion configurations result in unique individual assemblies. These variables change based on the project specific needs of a building, and contribute to the divergence from the results determined by the standard tests. Proper total product thermal performance prediction must include consideration of the entire glazing system. It evaluates the project specific components, materials, and configurations. This form of analysis requires the design professional to evaluate the specific combination of components to determine the performance.

To address this issue in the fenestration industry, a new method of calculation may be necessary to be developed that includes common installation practices and conditions. This paper will compare, and present results obtained from two different types of total product thermal performance calucalation methods to demonstrate if a new standard method of calculation is required.

The goal of this paper is to evaluate the effects of three-dimensional heat flow through variations of curtain wall vision/spandrel conditions and the relative impact on the themal performance of each. The following methods will be utilized to compare the results of the vision and spandrels conditions.

- Two-dimensional heat flow analysis utilizing THERM 7.5/WINDOW 7.5 per NFRC 100.
- Three-dimensional heat flow analysis utilizing SIEMENS NX

To determine the level of accuracy of each method, the results are planned to be compared to physical testing generally conforming to ASTM C1363 “Standard Test Method for Thermal Performance of Building Materials and Envelope Assemblies by Means of a Hot Box Apparatus” at a later date.

THERM 7.5/WINDOW 7.5

Developed and described by Lawrence Berkley National Laboratory (LBNL), “THERM is a state-of-the-art, computer program for use by building component manufacturers, engineers, educators, students, architects and others interested in heat transfer. THERM models two-dimensional conductive heat-transfer eff ects in building components such as windows, walls, foundations, roofs and doors where thermal bridges are of concern. Heat-transfer analysis, based on the finite element method, allows for evaluation of a product or system’s energy efficiency and local temperature patterns, which can help identify or may relate directly to problems with condensation, moisture damage and structural integrity.” This is the type of software that is most often used when performing NFRC 100 “Procedure for Determining Fenestration Product U-factors.” Again, this procedure uses multiple two-dimensional models to produce a “Total Product U-Factor”.

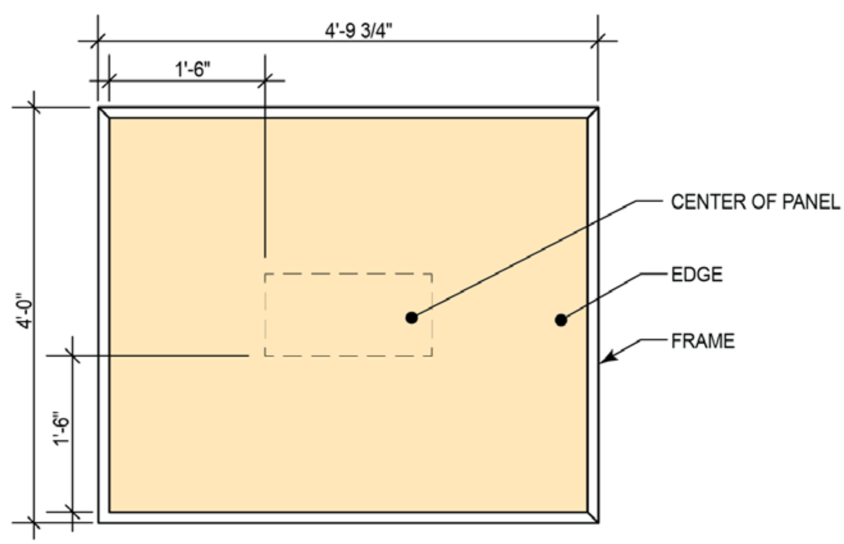

FIGURE 10: NFRC Areas used for calculation

SIEMENS NX (NX)

NX is a widely capable software that allows simulations ranging from 3D finite element modeling heat-transfer effects in building assemblies to Computational Fluid Dynamics. The simulations are conducted on three dimensional models that allow for the interaction of all the components within an assembly or transition. Simulations can be performed over time to demostrate the effects of weather on the heating and cooling of building components, or can be performed as a static simulation showing the "worst case" scenario. This allows for a more accurate understanding of the thermal performance and interactions of the various componets in the assemblies.

Environmental conditions used for analysis.

- Static interior and exterior temperatures.
- Exterior temperature: -18° C (0° F).
- Exterior wind speed: 15mph.
- Interior temperature: 21° C (70° F).

The new component in this evaluation when compared to past studies in the glazing industry is the use of three-dimensional thermal modeling. The following analysis will help determine if this level of modeling is beneficial or necessary to predict the total product thermal performance or if two-dimensional analysis is sufficient. To determine which type of analysis is sufficient the vision/spandrel interface is simulated in two and three-dimensional software. The results from each will be compared and will illustrate how the use of three-dimensional thermal modeling can be readily repeated utilizing multiple project specific variables without the added cost of laboratory testing.

SYSTEM DESCRIPTION AND CONFIGURATIONS

There are numerous variations of curtain wall systems, vision glazing, spandrel glazing, and spandrel insulation thickness that can impact the total product thermal performance. However, this evaluation is limited to variations of the following components. Note, only select combinations of the various components indicated where included in this evaluation.

- Curtain Wall System: Outside glazed, 4-sided captured pressure wall system
  - Pressure Plate Options
    - Aluminum pressure plate
    - Fiberglass pressure plate
  - Thermal Isolation
    - Thermally Improved
    - Thermally Broken

- Vision Glazing: 1" Low E coated Insulating Glass Unit with an aluminum edge spacer.

- Spandrel Glazing: 1" Low E coated Insulating Glass Unit
  - Aluminum Spacer
  - Stainless Steel Spacer

- Spandrel Insulation:
  - Aligned with interior face of mullion
    - 4" mineral wool
    - 3" mineral wool
    - 2" mineral wool
    - 1" mineral wool

- Offset from interior face of mullion towards the exterior
  - 3” offset
  - 1” offset

- Aligned with interior face of mullion with additional 1” thick insulation covering the mullions inside the spandrel cavity.

- Vapor Barrier:
  - Foil Facing on Mineral Wool
  - 22 gauge galvanized metal backpan

- Vertical Mullion Treatment:
  - With Fire-rated Joint Assembly: foil faced mineral wool.
    - 1”x8” mullion cover
    - 2”x8” mullion cover
    - 3”x8” mullion cover
    - 4”x8” mullion cover

  - Without Fire-rated Joint Assembly

- Continuous layer of insulation behind spandrel:
  - 4” unfaced mineral wool with a 4”x8” mullion cover at vertical mullion
  - 3” unfaced mineral wool with a 3”x8” mullion cover at vertical mullion
  - 2” unfaced mineral wool with a 2”x8” mullion cover at vertical mullion
  - 1” unfaced mineral wool with a 1”x8” mullion cover at vertical mullion

COMPUTER MODELING CORRELATION

As previously indicated, two methods of computer modeling are provided in this evaluation. The primary reason to include both two and three-dimensional modeling is to develop confidence in the results of the three-dimensional modeling procedures. Industry standard two-dimensional modeling has been tested and validated numerus times in the past for deterimining the total product u-factor of descrete vision units. However, as three-dimensional modeling is a relatively new procedure in the glazing industry, it is prudent to compare the modeling results from both methods. The first step in this evaluation process included modeling the vertical sections of the curtain wall system with both types of software. This method eliminates the three-dimensional effects of the interfaces at the vertical and horizontal mullions. The results from the two and three-dimensional programs of the following conditions were then compared to determine if correlation was achieved.

As indicated in **Figure 11**, the resultant U-Factor, produced by the two-dimensional and three-dimensional modeling procedures, are within a close margin of error. Based on the minimal deviation of thermal performace, the modeling procedures produces an acceptable level of correlation. Additional coorelation confidence was also obtained from the coorolation proceedures and information gained from a previous study “Three Dimensional Condensation Risk Analysis of Insulated Curtain Wall Spandrels”, recently published in ASTM STP 1599, “Advances in Hygrothermal Perfromance of Building Envelopes.”

Figure 11 illustrates the results of both the two-dimensional and three-dimensional computer modeling procedures side by side for ease of comparison**.**

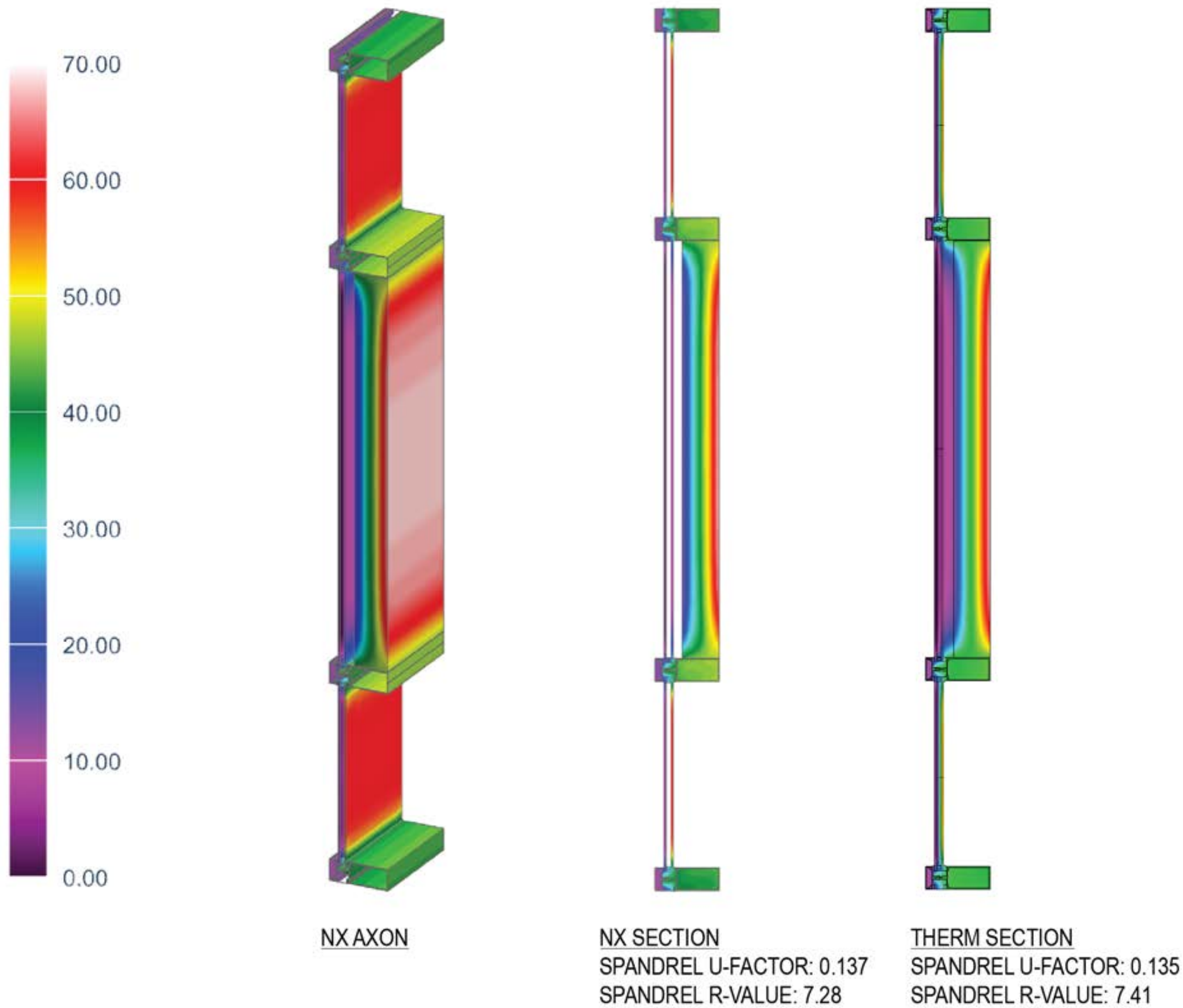

FIGURE 11: Full section through the baseline model in two dimensions and three dimenstions.

SYSTEMS MODELED

Since acceptable correlation between the two modeling procedures is achieved, the three-dimensional modeling procedure can now be used to evaluate the three-dimensional influences of vertical/horizontal mullion interfaces on total product thermal performance. The total product thermal performance of several combinations of componets was determined both in NX and as calculated per NFRC 100. The results were then compared to determine if the three-dimensional effects of the mullions had impact on the overall performance of the system. **TABLE 1** summarizes the combination of components that were included in this evaluation. **Figures 12-16** provide graphic illustration of the curtain wall configuration and of the various combinations.

	Spandrel Insulation Thickness	Continuous layer of insulation	Mullion Cover Thickness	Spandrel Insulation Placement	Spandrel insulation return	Vapor Retarder Type	Thermal Break Size	IGU Spacer Material	Pressure Plate Material
System 1	1"	No	No	Interior	No	Metal Backpan	0.09"	Aluminum	Aluminum
System 2	2"	No	No	Interior	No	Metal Backpan	0.09"	Aluminum	Aluminum
System 3	3"	No	No	Interior	No	Metal Backpan	0.09"	Aluminum	Aluminum
System 4	4"	No	No	Interior	No	Metal Backpan	0.09"	Aluminum	Aluminum
System 5	4"	1"	1"	Interior	No	Metal Backpan	0.09"	Aluminum	Aluminum
System 6	4"	2"	2"	Interior	No	Metal Backpan	0.09"	Aluminum	Aluminum
System 7	4"	3"	3"	Interior	No	Metal Backpan	0.09"	Aluminum	Aluminum
System 8	4"	4"	4"	Interior	No	Metal Backpan	0.09"	Aluminum	Aluminum
System 9	4"	No	1"	Interior	No	Metal Backpan	0.09"	Aluminum	Aluminum
System 10	4"	No	2"	Interior	No	Metal Backpan	0.09"	Aluminum	Aluminum
System 11	4"	No	3"	Interior	No	Metal Backpan	0.09"	Aluminum	Aluminum
System 12	4"	No	4"	Interior	No	Metal Backpan	0.09"	Aluminum	Aluminum
System 13	1"	No	No	Exterior	No	Metal Backpan	0.09"	Aluminum	Aluminum
System 14	1"	No	No	Interior	Yes	Metal Backpan	0.09"	Aluminum	Aluminum
System 15	4"	No	No	Interior	No	Foil	0.09"	Aluminum	Aluminum
System 16	4"	No	2"	Interior	No	Foil	0.09"	Aluminum	Aluminum
System 17	4"	No	No	Interior	No	Metal Backpan	0.25"	Aluminum	Aluminum
System 18	4"	No	No	Interior	No	Metal Backpan	0.09"	Stainless Steel	Aluminum
System 19	4"	No	No	Interior	No	Metal Backpan	0.09"	Aluminum	Fiberglass

TABLE 1: Summary of the various combinations of curtain wall components that were evaluated.

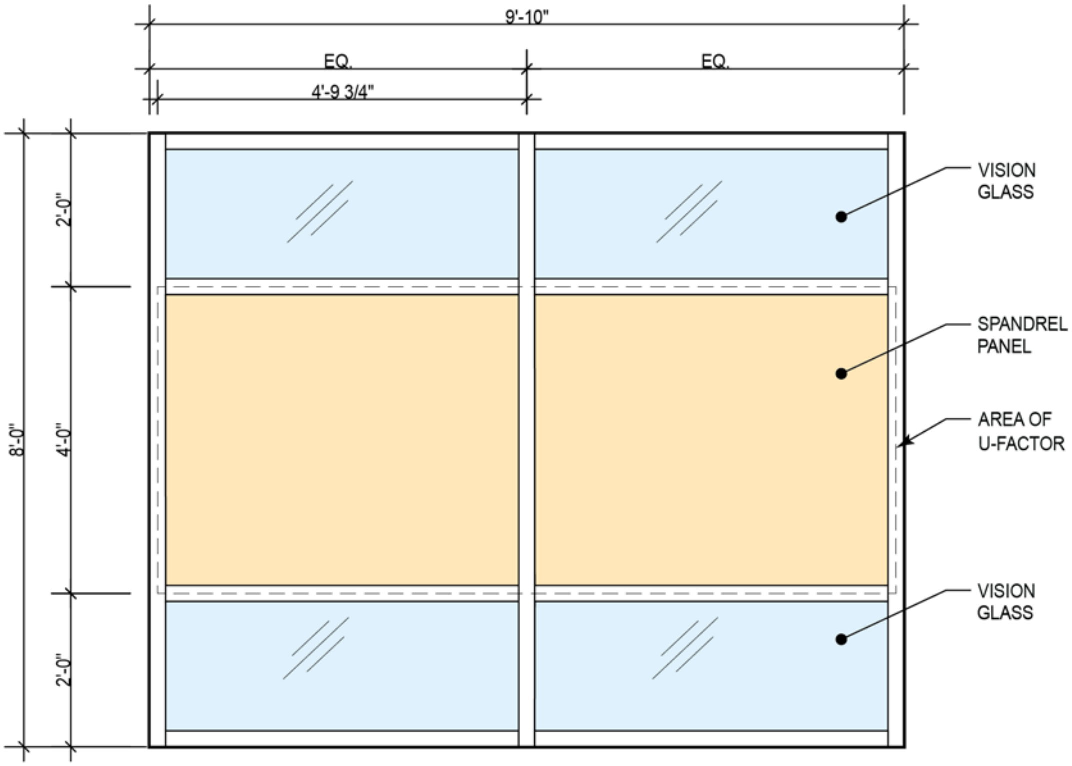

FIGURE 12: Typical curtain wall system configuration.

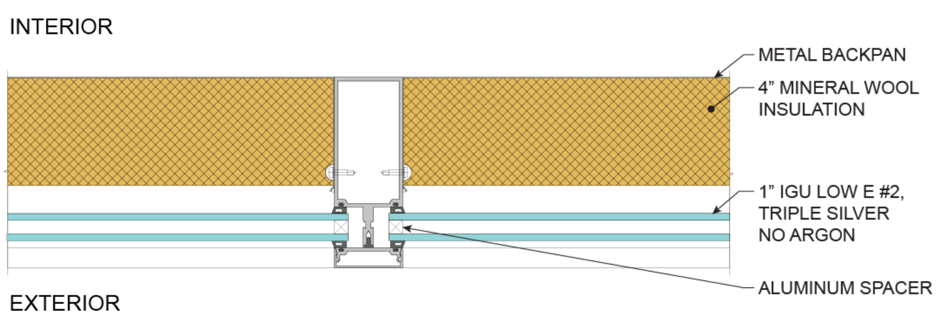

FIGURE 13: Plan detail of baseline model.

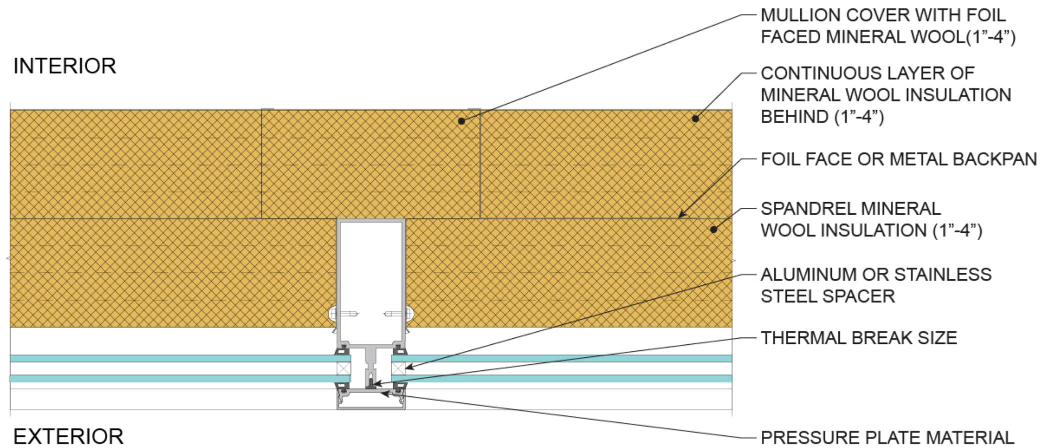

FIGURE 14: Plan detail of model variables.

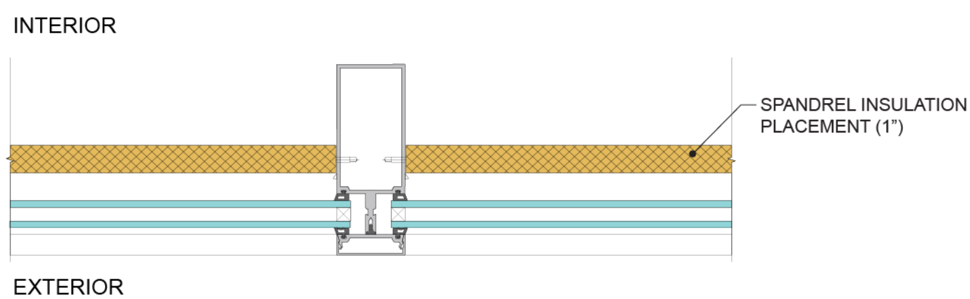

FIGURE 15: Plan detail of 1” mineral wool insulation at spandrel , offset 1” from interior glazing surface.

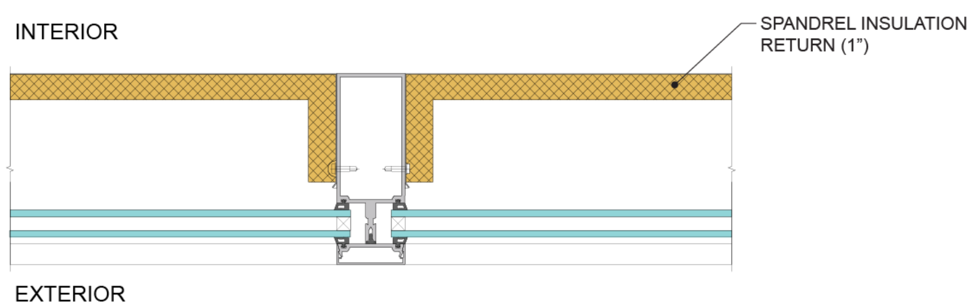

FIGURE 16: Plan detail of 1” mineral wool insulation at spandrel returned at mullion.

RESULTS COMPARISON

Upon comparison, the three-dimensional analysis method consistently produces the total product thermal performance lower than the results produced by the NFRC 100 method. Additionally, the deviation between the two methods continues to increase as the amount of insulation used increases. **Table 1 and Figure 17** summarizes the results for both analysis methods.

	Spandrel Insulation Thickness	Continuous layer of insulation	Mullion Cover Thickness	Spandrel Insulation Placement	Spandrel insulation return	Vapor Retarder Type	Thermal Break Size	IGU Spacer Material	Pressure Plate Material	3-D Calculation Results	2-D Calculation Results	Center of Panel R-Value
System 1	1"	No	No	Interior	No	Metal Backpan	0.09"	Aluminum	Aluminum	3.94	4.19	8.36
System 2	2"	No	No	Interior	No	Metal Backpan	0.09"	Aluminum	Aluminum	Not Calculated	4.77	12.56
System 3	3"	No	No	Interior	No	Metal Backpan	0.09"	Aluminum	Aluminum	Not Calculated	5.18	16.78
System 4	4"	No	No	Interior	No	Metal Backpan	0.09"	Aluminum	Aluminum	4.78	5.52	20.96
System 5	4"	1"	1"	Interior	No	Metal Backpan	0.09"	Aluminum	Aluminum	7.11	11.26	25.19
System 6	4"	2"	2"	Interior	No	Metal Backpan	0.09"	Aluminum	Aluminum	Not Calculated	14.41	29.41
System 7	4"	3"	3"	Interior	No	Metal Backpan	0.09"	Aluminum	Aluminum	10.16	16.98	33.56
System 8	4"	4"	4"	Interior	No	Metal Backpan	0.09"	Aluminum	Aluminum	10.71	19.14	37.74
System 9	4"	No	1"	Interior	No	Metal Backpan	0.09"	Aluminum	Aluminum	3.52	5.35	20.96
System 10	4"	No	2"	Interior	No	Metal Backpan	0.09"	Aluminum	Aluminum	Not Calculated	5.89	20.96
System 11	4"	No	3"	Interior	No	Metal Backpan	0.09"	Aluminum	Aluminum	3.54	6.23	20.96
System 12	4"	No	4"	Interior	No	Metal Backpan	0.09"	Aluminum	Aluminum	3.55	6.48	20.96
System 13	1"	No	No	Exterior	No	Metal Backpan	0.09"	Aluminum	Aluminum	2.71	3.11	8.33
System 14	1"	No	No	Interior	Yes	Metal Backpan	0.09"	Aluminum	Aluminum	3.48	4.21	8.36
System 15	4"	No	No	Interior	No	Foil	0.09"	Aluminum	Aluminum	3.16	6.17	20.96
System 16	4"	No	2"	Interior	No	Foil	0.09"	Aluminum	Aluminum	3.61	7.62	20.96
System 17	4"	No	No	Interior	No	Metal Backpan	0.25"	Aluminum	Aluminum	4.87	5.97	20.96
System 18	4"	No	No	Interior	No	Metal Backpan	0.09"	Stainless Steel	Aluminum	4.78	5.58	20.96
System 19	4"	No	No	Interior	No	Metal Backpan	0.09"	Aluminum	Fiberglass	5.94	6.78	20.96

TABLE 2: Results summary of the various combinations of curtain wall components.

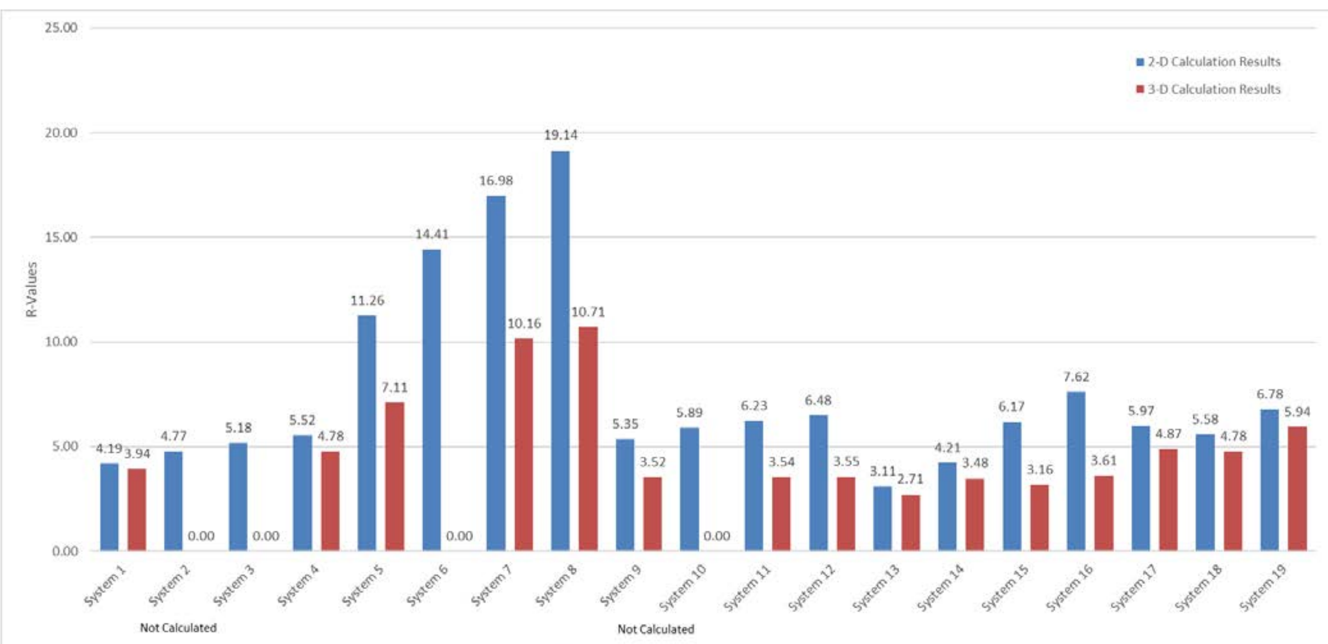

FIGURE 17: Total product thermal performance results summary for spandrel only.

SUMMARY AND CONCLUSIONS

The purpose of this study was to determine if there is a significant difference in the anticpated thermal performance of insulated spandrels based on the type of calculation method used. The current industry standard method used to calculate the total product thermal performance does not address the three-dimensional heat flow through thermal bridging of vertical mullions that pass through insulated spandrel areas. This study illustrates that the current method is potentially producing results that are better than they actual inservice conditions. Design professionals need to be aware of this discreptancy as it can have an impact whole building enegy modeling and energy code compliance. Note, this evaluation is limited to a specific curtain wall system. Results will likely vary when utilizing systems that include additional thermal enhancements.

The evaluation illustrated that three-dimensional modeling may provide more accurate results than two-dimensional modeling, which is currently the common practice employed in the industry. This study also proved that three-dimensional modeling is an effective method to evaluate various conditions. Prior to being able to produce three dimensional models of these conditions, one would require costly physical testing or might rely on potentially inaccurate calculation methods. The process can produce results more rapidly and less expensive than physical testing. While, the three-dimensional modeling is more accurate than two-dimensional modeling, it takes time and experience to gain necessary confidence in the results. Additional work should be undertaken to develop a standardized process to ensure a reasonable level of confidence can be obtained on a consistent basis. This might include a correlation process similar to what is outlined in this paper that involved comparing partial three-dimensional models with two dimensional models that have a known and trusted level of accuracy.

To validate and provide additional confidence in the three-dimensional modeling procedures, physical testing generally conforming to ASTM C1363 “Standard Test Method for Thermal Performance of Building Materials and Envelope Assemblies by Means of a Hot Box Apparatus” is planned to be performed. Once the results of the testing is available, they will be compared with the two and three dimensional results.

There are several other complex conditions on buildings that include significant thermal bridges that cannot be adequately evaluated with two-dimensional modeling. Conditions such as curtain walls that extend past the roof line to function as a parapet, sunshades that are anchored to curtain walls or that penetrate other opaque wall assemblies, curtain walls that extend beyond adjacent walls (wing walls), curtain walls that extend beyond soffit conditions, and structural steel that is used to support canopies or balconies all include thermal bridging from the interior to the exterior **(Figures 16-17)**. Three-dimensional thermal modeling can provide a method to evaluate these conditions without the need to incorporate physical testing.

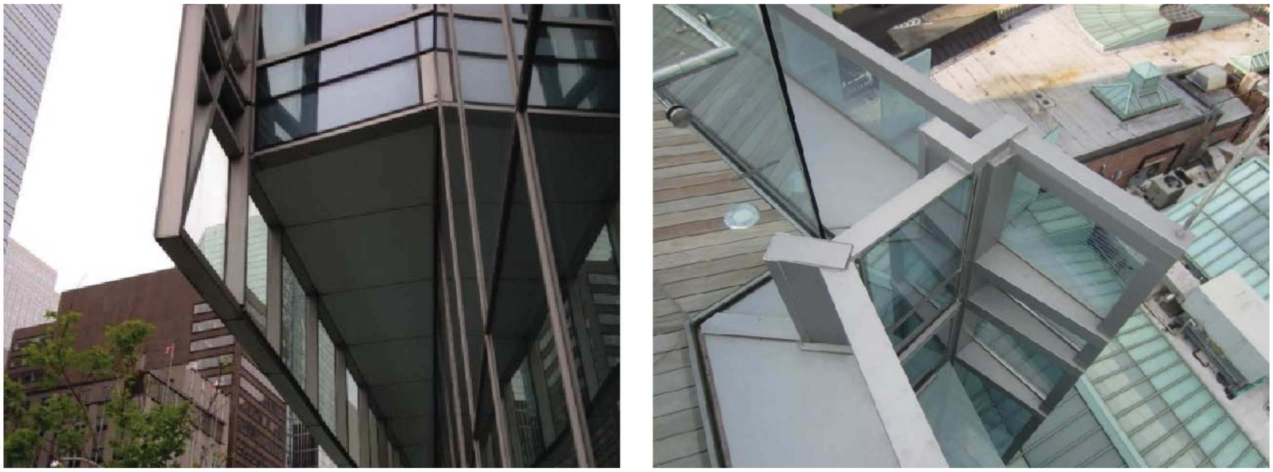

FIGURE 16: Examples of curtain wall wing wall at adjacent wall, soffit and parapet.

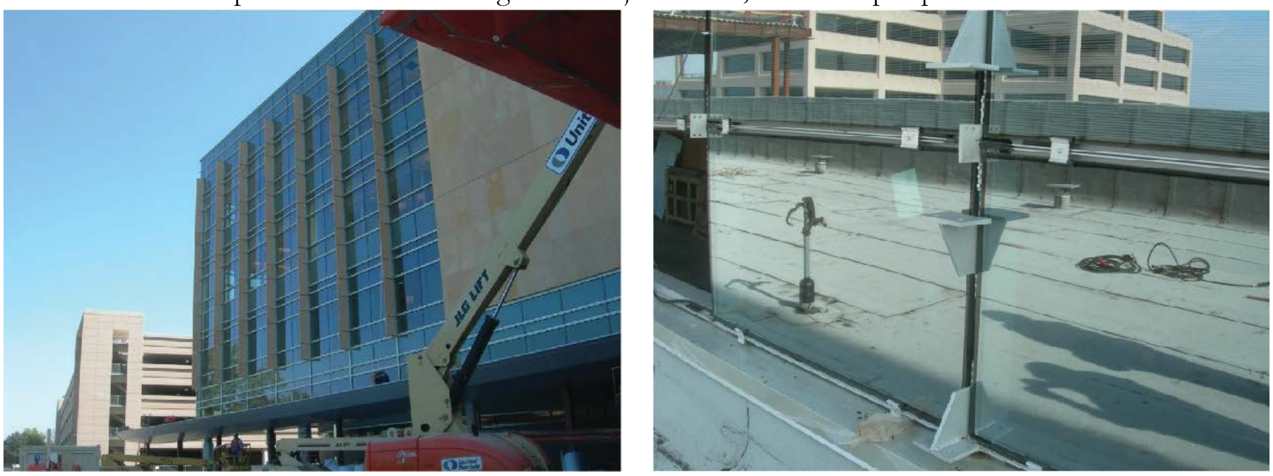

FIGURE 17: Example of sun shade and brackets at curtain wall system.

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