CHARLES PANKOW FOUNDATION
Building Innovation through Research

THERMAL PERFORMANCE OF SPANDREL ASSEMBLIES IN GLAZED WALL SYSTEMS

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Phase 1 Report
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- Testing Laboratory: Oak Ridge National Laboratory
- Research Team: Lawrence Berkeley National Laboratory
- Industry Champion: Birch Point Consulting

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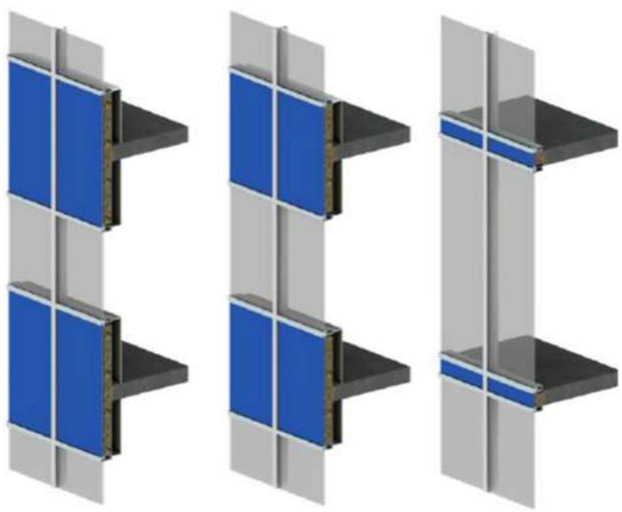
EXECUTIVE SUMMARY

Introduction

Glazed wall systems, such as curtain walls or window walls, form part of the building envelope and are commonly used in modern buildings. They comprise transparent, translucent, and opaque areas. While the opaque areas are often used to hide building components such as slab edges, mechanical equipment, and suspended ceilings, they are increasingly being used to target higher levels of thermal performance. Known as spandrel assemblies, these opaque areas are typically insulated with the intent of improving their thermal performance relative to the transparent portions of the glazed wall system. However, because of the complex arrangement of materials and structural components which bridge the insulation, spandrel assembly thermal performance is often lower than assumed. This can contribute to building energy loss, condensation, and other performance issues.



Various Spandrel Assembly Conditions (Blue) at Slab Edges

Since spandrel assemblies are commonly insulated, there is a general notion that their performance has less impact on whole-building energy performance compared to vision glazing. As a result, spandrels have, until recently, generally not been subjected to the same level of scrutiny or analysis as other segments of the building envelope. Thermal performance calculations have been largely oversimplified, and building energy codes and industry standards do not fully address how to account for the presence of spandrel assemblies. With a lack of guidance on how to accurately calculate thermal performance, designers often unknowingly overestimate the thermal performance of spandrel assemblies (e.g., assuming spandrel assemblies can meet the thermal performance requirements of other opaque exterior wall assemblies). Similarly, the lack of an accurate and enforceable calculation methodology results in limited incentives for technological innovation. As awareness of whole-building energy performance continues to grow and building energy codes and standards become more stringent, the industry will inevitably recognize the impact of spandrel assembly thermal performance on whole-building energy performance and will seek accurate values for their designs.

Problem Statement

Thermal bridging within spandrel assemblies, such as the aluminum framing running continuously through vision glazing and opaque spandrels, represents a potential source of considerable heat loss and condensation risk. Despite this, there is no consensus on how to perform thermal simulations of spandrels, and current codes and standards do not adequately address how to determine the thermal performance of spandrel panel systems. This has slowed the innovation required to improve spandrels to meet the increasingly stringent building energy code targets. There is a need for a standardized calculation procedure to allow manufacturers and designers to improve spandrel thermal performance and to promote research and technological innovation.

Program Goals

The overall goal of this program is to provide the industry with a repeatable and accurate procedure for estimating the thermal performance of spandrel panel systems. Based on this physically validated simulation procedure, jurisdictions may choose to recognize the performance of spandrels in different ways, including requiring use of the procedure when reporting performance or by setting targets independent from those of other opaque wall assemblies. With a standardized approach that can be implemented in future building energy codes and standards, these performance standards can be tightened over time (e.g., Step Codes, Passive House) to improve energy performance. Additionally, the program aims to promote energy-enhancing changes to materials, details, and systems. The program provides an evaluation baseline and an incentive for system suppliers to innovate for improved energy performance to allow owners to prescribe and obtain desired performance levels.

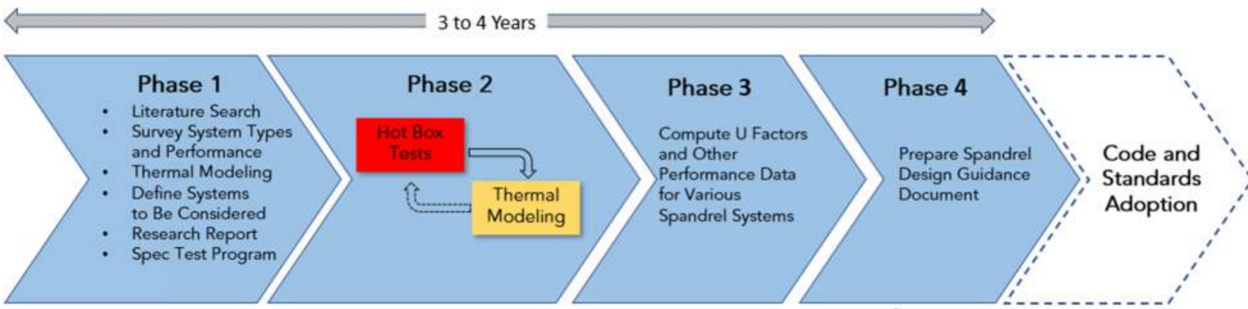
Program Objectives

The program objectives in the short- to mid-term are to provide research findings that lead to publication of a design guide: "Design Guidance for Thermal Performance of Spandrel Assemblies in Glazed Wall Systems." The goals of the Design Guidance Document are to provide shorter-term guidance to improve existing practice and to inform codes and standards changes over a ten-year time horizon. The Design Guidance Document will provide best practices for testing and analytical modeling of spandrel assemblies and relevant adjoining construction in glazing systems, will recommend procedures for rating thermal performance of spandrel assemblies in glazing systems and will suggest assembly configurations and details for improved thermal performance. In the longer term, there is an expectation that relevant standards would adopt the recommendations produced in this program.

Project Phases

The overall project is divided into the following four phases:

- **Phase 1:** Design Test Program
- **Phase 2:** Perform Physical Testing and Analysis
- **Phase 3:** Define Spandrel Thermal Performance Requirements
- **Phase 4:** Prepare Design Guidance Document



Project Phasing Plan

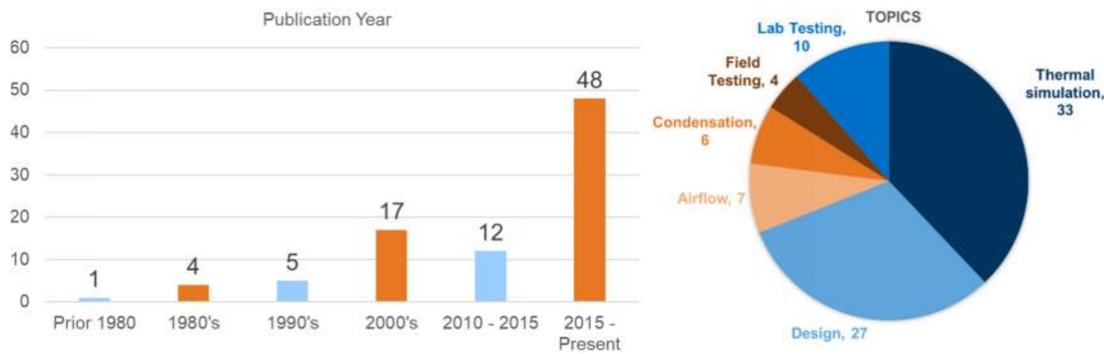
This report is for **Phase 1: Design Test Program**, and includes the following sections:

- **Section 1.1 – Literature Review:** A literature review of current studies and practices related to spandrel thermal performance.
- **Section 1.2 – Industry Survey:** An industry survey to assess the prevalence of specific spandrel types and industry knowledge/expectation of spandrel thermal performance.
- **Section 1.3 – Current State of Use:** In-depth phone interviews with key glazing system manufacturers to identify barriers to future development of spandrels and to identify opportunities for innovation. This section also includes a summary of current codes and standards.
- **Section 1.4 – CFD Modeling:** Computational fluid dynamics (CFD) modeling to explore the effect of airflow within spandrel panels on thermal performance.
- **Section 1.5 – Test Program:** Development of a laboratory testing program to validate computer simulation methods against measured empirical data to develop a set of simulation guidelines to evaluate the thermal performance of spandrels.
- **Section 1.6 – Summary:** Summary of scope and key findings of Phase 1 and next steps for Phase 2.

A summary of the scope and key results of these sections are presented below.

Section 1.1 – Literature Review

The objective of the literature review was to discern the current state of understanding and current research on spandrel thermal performance, including current research methods, evaluation standards and practices, and on problems with spandrel design and associated solutions. The literature review included eighty-seven research papers, codes, standards, industry articles, and guidelines focusing on thermal simulation, condensation risk, airflow, and laboratory testing.



Breakdown of Reviewed Documents by Publication Year and Topic from Literature Review

Findings from this literature review have identified gaps in the industry knowledge as it relates to accurate evaluation of spandrel thermal performance. The knowledge gaps include the following:

- What is the impact of adjacent assemblies on spandrel thermal performance?
- What is the impact of intermediate floor connected to window wall spandrel assemblies?
- How can the accuracy of two-dimensional (2D) thermal simulation methods, when compared to physical test results, be improved?
- How do size and configuration impact spandrel thermal performance?
- What is the accuracy of current industry standards and guidelines on simulating thermal performance compared to physical testing?
- What are the impacts of various spandrel components on thermal performance?
- What are the impacts of accurate spandrel thermal performance values on weighted U-factor (UA) calculations and envelope backstop calculations for building energy code compliance?
- What are the impacts of contact resistance of components on thermal performance?

The Engineering Team used literature review findings to inform the development of the Test Program and to focus the research on areas where additional industry guidance is required.

Section 1.2 – Industry Survey

The purpose of the industry survey was both to assess the prevalence of specific spandrel types and to assess industry knowledge/expectation of spandrel performance. The industry was surveyed to understand the scope and prevalence of different and most relevant spandrel assembly types and details, including what percentage of buildings use the different systems. This survey was also performed to understand what systems and details are most challenging from the standpoints of thermal performance as well as to understand potential opportunities for innovation. The survey reached thirty-five industry professionals in various roles, including fourteen Designers, sixteen Contractors, and five Industry Organization representatives.

Grouped into categories, the key takeaways from the survey results are as follows:

Prevalence of Glazed Wall Systems

- High prevalence of glazed wall systems in modern construction.
- Glazed wall systems are used in all eight ASHRAE Climate Zones (CZs).
- The most common glazing type is double-glazed insulated glazing units (IGUs) with a low-e coating on the #2 surface.
- Unitized curtain wall is the most common type of glazed wall construction.
- The most common average height of glazed wall systems is greater than twelve stories.
- Glazing systems account for more than half of the exterior wall area in most projects. Of the glazed areas, spandrel assemblies account for 40% to 60% for most projects.

Prevalence of Spandrel Panels and Common Characteristics

- Spandrel panels are generally chosen for aesthetic reasons, followed by their speed/constructability.
- The most common average spandrel dimensions are between 24 in. and 79 in. (609 mm and 2,000 mm) tall, and between 24 in. and 39 in. (609 mm and 1,000 mm) wide.
- Vented spandrel panels are more often specified by designers than fully sealed panels. In contrast, vented and fully sealed spandrel panels are equally specified among Contractors.
- Metal panel is the most typical spandrel panel cladding, followed by IGU shadow box, IGU with opaque coating, and other opaque cladding types.
- Most spandrel panel designs include semi-rigid mineral wool insulation.

Spandrel Panel Concerns and Innovation

- The most common issues are aesthetics, condensation, and glass breakage.
- Thermal performance, code compliance, and lack of industry-accepted analysis techniques are of concern.
- Common concerns on future projects include thermal performance and embodied carbon.
- Insufficient market demand for higher performing products, industry education, and lack of industry-accepted analysis techniques are the top three barriers to spandrel innovation.

Spandrel Panel Thermal Performance

- Most are aware of the difference in thermal performance required of spandrel panels compared to transparent glazing.
- The average thermal performance of spandrels varies widely in the industry from R-3 (RSI-0.53) to R-10 (RSI-1.76).
- Based on current technologies, most believe that a spandrel R-value between R-5 (RSI-0.88) to 10 (RSI-1.76) or higher is achievable.
- Most generally follow the procedures outlined by ANSI/NFRC 100 (2D), some follow prescriptive requirements for metal-framed wall or fenestration systems from the codes, and some utilize one-dimensional (1D) or three-dimensional (3D) analyses.
- Most rely on simulation reports to support the manufacturer's reported spandrel panel U-factor.

Section 1.3 – Current State of Use

Recognizing the importance of manufacturers' role in advancing the state of the industry and in providing solutions for higher performing spandrels, the Engineering Team conducted a series of phone interviews with glazing system manufacturers. The focus of the interviews was to identify barriers to future development of spandrel panels and to identify opportunities for innovation. While the interview format was open to a general discussion, the following questions were asked to all interviewees:

- What type of spandrel do you see as most common? Highest and lowest performing?
- What do you think is the most poorly understood characteristic of spandrel panels?
- What is your experience with 2D and 3D thermal modeling as well as guarded hot box testing?
- What does 2030 look like for your team and your products?
- What does your development cycle look like?
- What technologies have you considered to reduce thermal bridging in spandrel panels?
- Where would you like to see building and energy codes go with respect to spandrel panels?

Note that interviews were limited to those with relatively large manufacturers of spandrel assemblies. The following sections highlight common themes that emerged from ten interviews.

Industry Knowledge

- Generally, knowledge of thermal modeling standards, processes, and resources specific to spandrel panels is considered very poor across the industry, even for major manufacturers.

- There is still a common misunderstanding of the difference between 1D center-of-spandrel performance and the effective thermal performance of spandrel panels that account for the 3D complexities of the system.

2D vs. 3D Modeling

- All the interviewed manufacturers use 2D thermal simulation to assess the thermal performance of their spandrel assemblies and the majority were familiar with 3D modeling.
- Manufacturers identified access to 3D performance data as a market differentiator but acknowledged the improved accuracy (and decreased R-value) as a risk when approaching markets or teams with a poor understanding of the results.

Codes and Standards

- Impediments to innovation include current code language, which allows and sometimes requires less accurate 2D thermal simulation, and inconsistent enforcement of the existing performance documentation process.
- Suggested solutions included code updates to recognize spandrels as a unique wall construction type and a standardized modeling procedure.

Innovative Technologies

- The most common areas of product development are limited to internal system components (e.g., thermal breaks).
- Achieving an "all-glass" visual intent is cited as a significant constraint when considering other areas of improvement (e.g., exterior insulation).

In addition to the information gathered from the interviews, the Engineering Team analyzed the prevalence of glazed wall systems in North America. Seven of the largest cities in North America were selected to review the prevalence of glazed versus non-glazed buildings in downtown commercial areas. The cities reviewed include New York, Phoenix, Houston, Chicago, Columbus, Jacksonville, Los Angeles, and Vancouver. The cities are all located in ASHRAE Climate Zones 2 – 5.

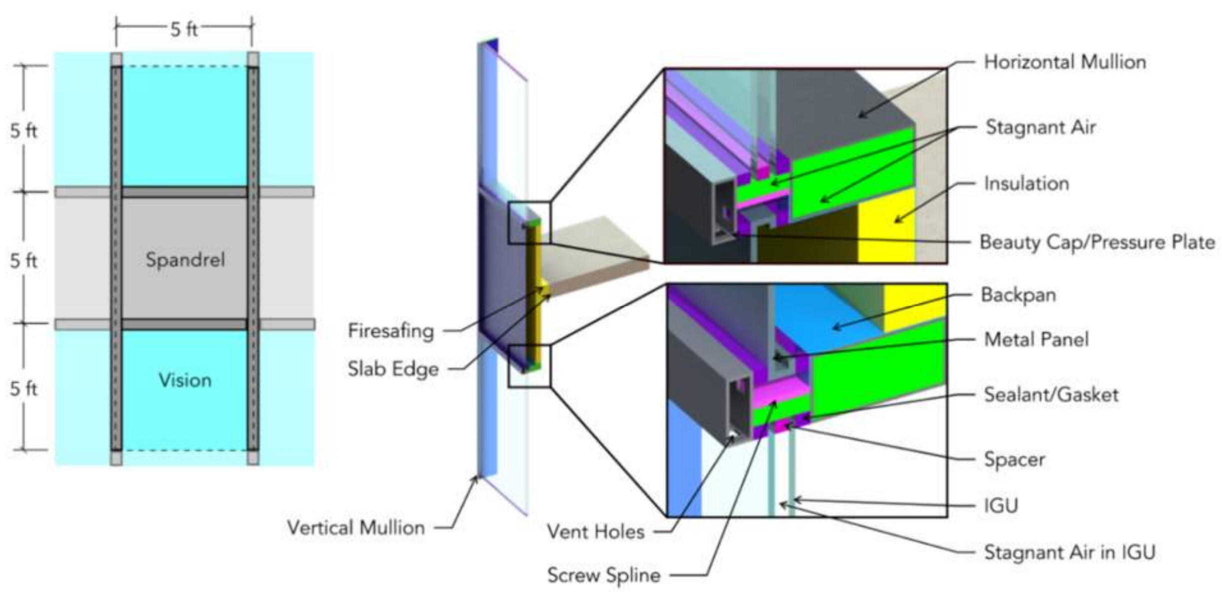
Results show that glazed wall systems represent roughly 40% of the building facade systems, which varies slightly depending on the climate zone. Results also show that high-rise and mid-rise glazed buildings are dominated by curtain wall systems rather than window wall systems.

In summary, the industry appears to recognize that a 3D modeling procedure would produce more accurate results when compared to 2D modeling, but is waiting for building codes and standards to "raise the bar." In the absence of a more accurate and enforceable standard, it is likely that the industry will continue to proceed with "business-as-usual."

Section 1.4 – CFD Modeling

One of the objectives of the CFD study was to explore the effect of airflow within the spandrel panel on the thermal performance of the assembly. While the Engineering Team anticipated that this effect would be minimal based on previous studies of ventilated rainscreens, 3D CFD simulations were performed to quantify the potential impact of varying certain ventilation parameters and to examine the need, if any, to adjust the Test Program design.

The Engineering Team performed 3D CFD simulations to evaluate the impact of airflow on spandrel panel thermal performance. The simulations studied the impact of vent openings, air volume modeling assumptions, and film coefficients. Other variables that can influence airflow include spandrel panel size, cavity depth, frame type, backpan profile, insulation type, roughness of surfaces enclosing the air cavity, and emissivity. However, these variables were all deemed secondary compared to vent openings and exterior air velocity. The 3D CFD simulations were compared to 2D finite element analysis (FEA) thermal simulations more commonly used by practitioners.



3D CFD Simulation Geometry (Excerpts from CFD Model)

Based on the results of these simulations, the following conclusions were drawn:

- Discrete vent openings in spandrel assemblies have a marginal effect on the average velocity and air temperature in the spandrel cavity and have little to no effect on the overall heat transfer across the spandrel assembly.
- Simulated spandrel cavity temperatures using 2D FEA and 3D CFD simulations differ by as much as 19°F (10.5°C), notably near vent openings.

- Interior convective film coefficients vary from floor to ceiling and are higher below the slab edge than above the slab edge. The common practice of using a single interior film coefficient does not account for such variations. In addition, the interior film coefficients vary with exterior air velocity, but are much less pronounced.
    - The CFD-calculated film coefficients in this study reflect an approximation of laboratory testing conditions, not real-world conditions. They should not be compared to standard values, which are derived using different air velocities.
- Overall thermal performance (i.e., U-factors) varies minimally (0% to 6%) when calculated using 2D FEA thermal simulations versus 3D CFD simulations.

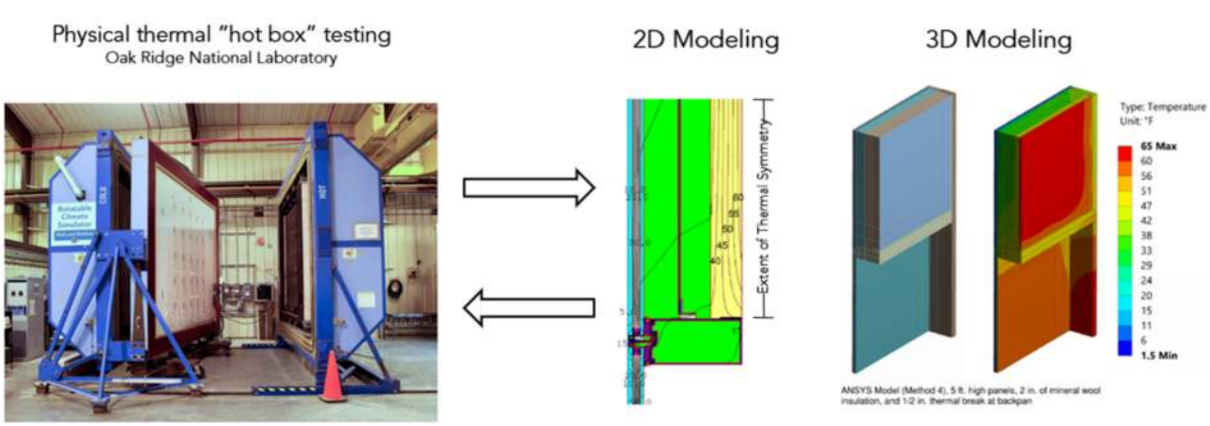
The primary differences between the 2D FEA and 3D CFD simulations are the geometry simplifications, radiative film coefficients, and air volume modeling assumptions used in the 2D FEA thermal simulations.

Different levels of convective heat transfer exist within spandrel cavities depending on exterior wind velocity, but differences between ventilated and sealed panels are negligible even at high wind velocities. Therefore, spandrel panel ventilation will not be considered in the laboratory testing program and in future simulations.

The 3D CFD simulations in this study focused primarily on convection at two exterior air velocities. Additional study should be performed to evaluate the variability of interior convective air film coefficients based on geometric surface configurations and mechanical systems. In addition, future work on the subject should study the effect of radiative film coefficients and solar radiation (heat flux to simulate the solar heat gain).

Section 1.5 – Test Program

The objective of laboratory testing is to validate computer simulation methods against measured data to develop a set of simulation guidelines to evaluate the thermal performance of spandrel assemblies.



Left: "Hot Box" Testing Image Courtesy of Oak Ridge National Laboratory
Right: 2D and 3D Computational Models

The laboratory tests are designed to cover multiple systems and configurations that are intended to capture conditions typically found in commercial buildings. These configurations include the impacts of:

- Spandrel panel size.
- Adjacent assemblies (e.g., transparent vision glazing sections, non-spandrel opaque assemblies).
- Intermediate floor attachments and anchorages.
- Spandrel construction (e.g., backpan configuration, insulation type, cladding type, interior wall construction).
- Airflow in and around the spandrel assembly.

The impacts of the above factors have been missing from previous and current industry standards and research. As a result, there is little guidance on how to consider these factors when evaluating spandrel thermal performance through thermal simulations; this lack of guidance has led to confusion and improper evaluations in the industry.

The Engineering Team seeks to test both curtain wall and window wall systems with various configurations and spandrel construction components through multiple rounds of hot box testing at steady-state conditions. A total of six test articles and eighteen variations will be tested.

Proposed Curtain Wall and Window Wall System Test Articles and Variations

Description	Description
Stick-Built Curtain Wall • Thermally broken aluminum captured system. • Commonly used in industry. • Individual components installed on site.	Unitized Curtain Wall • Thermally broken aluminum structural glazed (SSG) system. • Commonly used in industry. • Prefabricated panels shipped to and assembled on site.
Window Wall (US) • Thermally broken aluminum captured system. • Supported on slab edge; mullion above and below slab. • Greater integration with intermediate floor slab, less space available for insulation leading to greater heat loss.	Window Wall (Canadian) • Thermally broken aluminum captured system. • Significant integration with intermediate floor slab (more than U.S. window wall systems). • More space for insulation outboard of slab, but still high heat loss.
Veneer System • Captured system with wood or steel mullions. • Alternative to typical curtain wall systems with potentially less heat loss. • Individual components installed on site.	Next Generation High Performance System • Industry state-of-the art high-performance systems. • Thermally broken aluminum systems with insulation (R-40+).

The laboratory tests will be carried out at the Oak Ridge National Laboratory (ORNL) in Oak Ridge, Tennessee using hot box equipment capable of testing large articles at steady-state conditions. To evaluate the impact of various components on spandrel thermal performance, variations to the spandrel panel construction will be made to the test articles for multiple rounds of testing. These variations will consist of discrete modifications of key components and will not impact the common panel layout of all tested systems. Temperature and air speed sensors will be placed on, within, and adjacent to each test article to capture data that can be compared to simulations.

All laboratory testing will be carried out as part of Phase 2 of the research project.

Section 1.6 – Summary

The following is a brief outline of the scope and key findings in Phase 1 of the research.

Section 1.1 – Literature Review: A literature review of current studies and practices related to spandrel thermal performance.

- The Engineering Team used literature review findings to inform the development of the Test Program and to focus the research on areas where additional industry guidance is required.

Section 1.2 – Industry Survey: An industry survey to assess the prevalence of specific spandrel types and to assess the industry knowledge/expectations of spandrel thermal performance.

- The most common issues are aesthetics, condensation, and glass breakage.
- Thermal performance, code compliance, and lack of industry-accepted analysis techniques are of concern.
- Methods for calculating thermal performance of spandrel assemblies vary widely.

Section 1.3 – Current State of Use: In-depth phone interviews with key industry members (e.g., glazing system designers) to identify barriers to future development of spandrels and to identify opportunities for innovation.

- Generally, knowledge of thermal modeling standards, processes, and resources specific to spandrel panels is considered very poor across the industry, even for major manufacturers.
- Most use 2D thermal simulation to assess the thermal performance of spandrel assemblies.
- Main impediments to innovation include current code language allowing less accurate 2D thermal simulation of spandrels and inconsistent enforcement of the performance documentation process.

Section 1.4 – CFD Modeling: CFD modeling to explore the effect of airflow within spandrel panels on thermal performance.

- Discrete vent openings in spandrel assemblies have a marginal effect on the overall spandrel assembly U-factor. Spandrel ventilation will not be considered in laboratory testing and future simulations.
- Simulated spandrel cavity temperatures using 2D FEA and 3D CFD simulations differ by as much as 19°F (10.5°C), notably near vent openings.
- Interior convective film coefficients vary from floor to ceiling and are higher below the slab edge than above the slab edge. The common practice of using a single interior film coefficient does not account for such variations.
- Overall thermal performance (i.e., U-factors) varies minimally (0% to 6%) when calculated using 2D FEA thermal simulations versus 3D CFD simulations.
- The primary differences between the 2D FEA and 3D CFD simulations are the geometry simplifications, radiative film coefficients, and air volume modeling assumptions used in the 2D FEA thermal simulations.
- Additional studies should be performed to evaluate radiative film coefficients, solar radiation, and differing interior air film coefficients based on differing geometries and mechanical systems.

Section 1.5 – Test Program: Development of a laboratory testing program to validate computer simulation methods against measured empirical data to develop a set of simulation guidelines to evaluate the thermal performance of spandrels.

- The Engineering Team seeks to test both curtain wall and window wall systems with various configurations and spandrel construction components through multiple rounds of hot box testing at steady-state conditions.
- A total of six test articles and eighteen variations will be tested.
- To evaluate the impact of various factors on spandrel thermal performance, variations to the spandrel panel construction will be made to the test articles for multiple rounds of testing.

The Engineering Team has developed a detailed plan for Phase 2 in collaboration with the Research Team, Test Laboratory, and Industry Champion that includes testing and modeling of the six test articles each with three variations for a total of eighteen variants. Supplementing the measurements with 2D and 3D simulations will enable the development of procedures that can be universally applied, developed into standards, and adopted by codes. Specifically, Phase 2 will include the tasks noted below:

- Test Program Specification: Prepare a "Test Program Specification Package," including drawings/details of the test articles/variants and fabrication and testing schedule requirements.

- Pre-Construction Coordination: Coordinate with manufacturers and select final systems/materials to be tested, including coordination with the testing facility, ORNL.
- Submittals: Review manufacturer's shop drawings, product data, etc., to confirm final details of test articles prior to fabrication.
- Construction: Observe construction and instrumentation of the test articles, documenting observations.
- Testing: Collect laboratory test results and compare with 2D and 3D simulations. Prepare a summary package including relevant documentation and measurements so that independent researchers or professionals may conduct additional investigations or calibrate future 2D and 3D simulation techniques/software.
- Simulation: Construct 2D and 3D simulations of select details. Compare simulated and measured test results of select details.
- Report: Prepare a report of the Test Program results and the simulation calibration and validation process, and include findings for discrepancies between 2D and 3D software programs and recommendations for modifications to calculation methodologies.
- Whole-Life Carbon Study: Construct whole-building life-cycle assessment of archetypal buildings in multiple locations and compare two test articles to determine the impacts on global warming potential. Construct whole-building energy models of the same archetypal buildings in the same locations to determine impacts on operational carbon emissions. Compare the carbon "investment" of higher-performing spandrel assemblies, including trade-off between high and low embodied carbon systems, on operational carbon.

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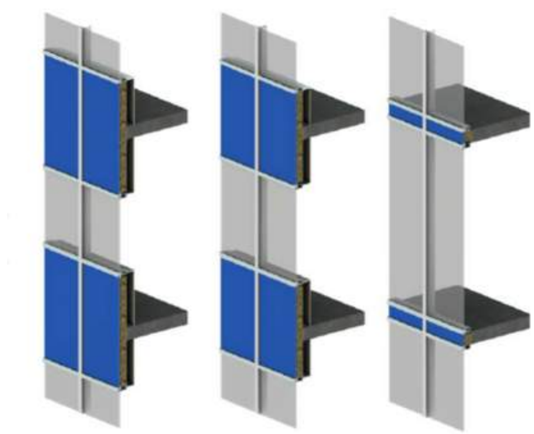
1.0 INTRODUCTION

Buildings accounted for 40% of the energy consumed in the United States in 2020 according to the U.S. Energy Information Administration. Understanding energy loss attributed to the building envelope is of great importance to rationally mitigating the losses and upgrading energy performance. Glazed wall systems, such as curtain walls or window walls, form part of the building envelope and are commonly used in modern buildings. They comprise transparent, translucent, and opaque areas. While the opaque areas are often used to hide building components such as slab edges, mechanical equipment, and suspended ceilings, they are increasingly being used to target higher levels of thermal performance. Known as spandrel assemblies, these opaque areas are typically insulated with the intent of improving their thermal performance relative to the transparent portions of the glazed wall system. However, because of the complex arrangement of materials and structural components which bridge the insulation, spandrel assembly thermal performance is often lower than assumed. This can contribute to building energy loss, condensation, and other performance issues.



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- **Phase 3:** Define Spandrel Thermal Performance Requirements
- **Phase 4:** Prepare Design Guidance Document

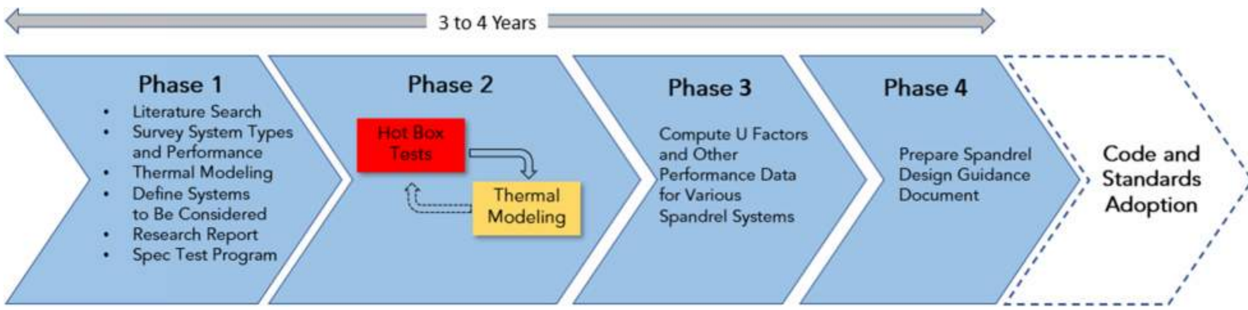


Figure 2: Project Phasing Plan

This report is for **Phase 1: Design Test Program**, and includes the following sections:

- **Section 1.1 – Literature Review** includes an extensive literature review of current studies and practices related to spandrel panel systems, including thermal simulation, lab testing, design improvement strategies, and more. The literature search is compiled in a bibliography of findings that includes papers, codes, standards, guidance documents, and tools relevant to the program.
- **Section 1.2 – Industry Survey** includes key takeaways from the industry outreach survey that was completed as part of the program, separating results based on prevalence of glazed wall systems, prevalence of spandrel panels and common characteristics, spandrel panel concerns and innovation, and spandrel panel thermal performance.
- **Section 1.3 – Current State of Use** includes takeaways from a series of phone interviews with key glazing system manufacturers, focusing on identifying current barriers to further development of spandrel assemblies and on opportunities for innovation. This section also includes a summary of current codes and standards.
- **Section 1.4 – CFD Modeling** describes the CFD analysis used to explore the impact of airflow on spandrel thermal performance and to examine whether varying ventilation parameters in the laboratory Test Program was necessary.
- **Section 1.5 – Test Program** provides a laboratory Test Program designed to validate computer simulation methods against measured data. The Test Program defines materials and specimens, laboratory setup, testing procedures, and data collection.

- **Section 1.6 – Summary** presents a brief outline of scope and key findings in Phase 1 of the research program and provides guidance for next steps leading into Phase 2.

Spandrel Assembly (Panel) Definition and Common Types

For the purposes of this program, we have defined spandrel assemblies, or panels, as a non-vision application of a fenestration product consisting of fixed framing, an opaque infill, and an exterior opaque or transparent panel. Examples of exterior panels used in spandrel assemblies include monolithic glass, insulated glass units (IGUs), semi-transparent glass (e.g., ceramic frit-coated glass), opacified spandrel glass, metal panels, terra cotta, and stone. The framing system can be unitized or stick-built and can span floor-to-floor (i.e., window wall) or across multiple floors (i.e., curtain wall). Spandrels typically incorporate the following components, listed from exterior to interior:

- **Exterior Panel:** Transparent (e.g., monolithic glass, insulating glass unit), semitransparent (e.g., ceramic frit-coated glass) or opaque panels (e.g., opacified spandrel glass, metal panel, terra cotta, stone).
- **Air Cavity:** Either fully sealed or vented/pressure-equalized to the exterior.
- **Insulation:** Typically, semi-rigid mineral wool.
- **Backpan:** Either a foil-faced membrane laminated to the interior surface of the insulation or a metal backpan. The backpan is commonly detailed to be the air, water, and vapor barrier by taping the foil-faced membrane to the perimeter framing or by sealing the metal backpan.

When the exterior panel is transparent, it is common to introduce an intermediate opaque panel layer set back from glazing to conceal the insulation and to provide an all-glass look to the facade. This spandrel panel configuration is known as a shadow box (Figure 3). Variations on a typical shadow box include a touch-mullion shadow box (Figure 4) where the adjacent glazing extends from the vision area into the spandrel zone and an open shadow box where the air space behind the exterior panel is open to the interior (essentially, no spandrel). A description of the major features and challenges of glass spandrels and shadow boxes is provided in *Jackson, 2021*.

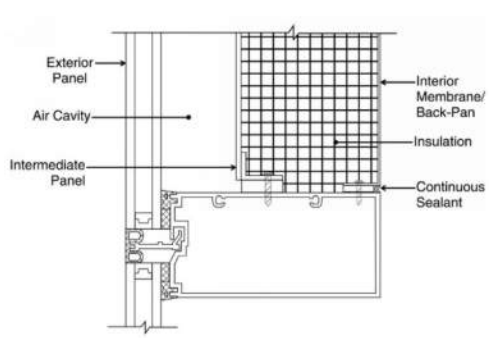


Figure 3: Typical Shadow Box Assembly Components

Illustration Courtesy of Oldcastle Building Envelope and SGH

Figure 4: Touch-Mullion Shadow Box as Part of Unitized Curtain Wall

Illustration Courtesy of Enclos (with Annotations)

The laboratory test articles developed as part of this research program include representative variations in spandrel framing, insulation, backpan, and exterior panel types including shadow box configurations. In addition to the comprehensive assessment of thermally distinct system parameters, the laboratory Test Program included a representation of a concrete floor slab to permit testing of slab bypass conditions. Using CFD simulations, some factors such as the ventilation of spandrel air spaces were determined not necessary to include in laboratory testing (refer to Section 1.4).

1.1 LITERATURE REVIEW

A literature review of current studies and practices was conducted. A complete bibliography of the literature review is included in Appendix A. The objective of the literature review was to discern the current state of understanding and current research on spandrel thermal performance, including current research methods, evaluation standards and practices, and problems with spandrel design and associated solutions. Findings from this literature review have identified gaps in the industry knowledge as it relates to accurate evaluation of spandrel thermal performance and has informed the focus of the current research program.

Literature Review Statistics

A total of eighty-seven research papers, codes, standards, and guidelines were reviewed. Of the documents, the majority were research papers that were published between 2015 and July 2022. Most of the papers focused on thermal simulation, condensation risk, and laboratory testing. Figure 5 provides a breakdown of the documents reviewed.

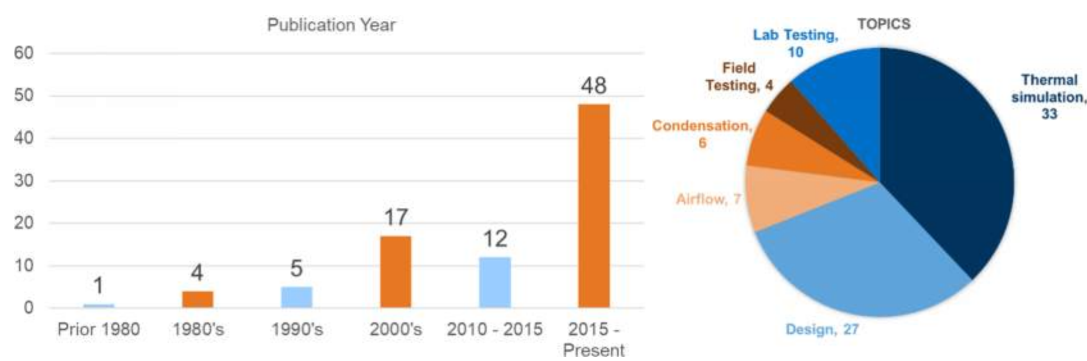


Figure 5: Breakdown of Reviewed Documents by Publication Year and Topic

The reviewed documents were selected and characterized based on the following topic categories:

- Thermal simulation.
- Physical testing, including laboratory and field testing.
- Designs to improve spandrel thermal performance.
- Airflow.
- Condensation.

The following are brief summaries of each topic reviewed that is relevant to the objectives of this program.

Thermal Simulation

Thermal analysis through finite element analysis (FEA) computer simulation is commonly used to evaluate thermal performance of spandrel assemblies both in the industry and in research. While most commercial thermal analysis simulation software used has been validated extensively in the industry for total product U-factors of discrete vision units (U-factor validation error is within 10% per ANSI/NFRC 100), typically in isolation of adjacent components and assemblies, the accuracy of the simulated results compared to lab measurements varies for spandrel assemblies depending on the analysis methodology. For example, several differences between two-dimensional (2D) and three-dimensional (3D) analysis methodologies are identified in Table 1.

Table 1: Differences between 2D and 3D Analysis Methodologies

Model Type	Description
2D	• Typically follows ANSI/NFRC 100 and ISO 10599 standards. • Simulated results are within 20% to 30% of thermal transmittance values calculated from guarded hot box measurements (Norris 2015, Bettenhausen 2015). • Simulated results get closer to hot box results when edge distances are extended (Norris 2015), consistent with FenBC procedure and ANSI/NFRC 100-2020 [E0A2]. • Difficult to predict accurate surface temperatures using this method.
3D	• Typically follows ISO 10211 standard and simulation procedures from ASHRAE 1365 RP and CSA Z5010. • Simulated results within 5% of thermal transmittance values calculated from guarded hot box measurements (*Norris 2015, Boafo 2019*). • Simulated surface temperatures are more closely aligned with hot box measurements than in 2D simulations.

Many of the reviewed papers note that, while 2D thermal simulations can provide insight into spandrel thermal performance, simulated results should be compared to physical testing as 2D simulations may not provide accurate results of thermal transmittance values and surface temperatures (*Dunlap 2018, Jackson et al 2018*). In addition, many of the published thermal simulation studies are based on heat loss through spandrel panel assemblies only and do not consider the impact of adjacent assemblies such as vision areas. These configurations do not represent the real-world installed conditions commonly found on buildings and may result in inaccurate heat loss values.

The Engineering Team speculates that heat loss between spandrel and vision areas is greater than the spandrel-only sections that are commonly simulated. This speculation arises from a comparison of surface temperatures of simulated spandrel to those of vision areas of various curtain wall and window wall systems using 2D and 3D analysis methodologies. This is supported by findings from *Bettenhausen 2015* which showed higher simulated spandrel U-factors for sections with adjacent vision glazing compared to spandrel-only sections. This additional heat loss may lead to greater building envelope heat loss and energy consumption.

Physical Testing

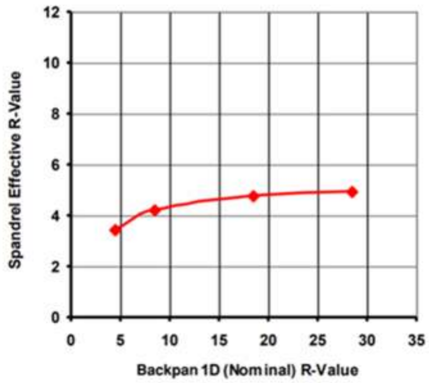
The scope of the research reviewed related to physical testing varied from studying condensation risk in spandrel panels (*ASTM 2014, Walsh 2018*) to studying spandrel glass breakage due to thermal stress (*Schwartz 2017, Walsh 2018*), to measuring surface film coefficients (*Ge 2006*) and heat flow with various spandrel insulation materials (*Bettenhausen 2015*).

Key findings from these studies related to spandrel heat flow and surface temperatures include:

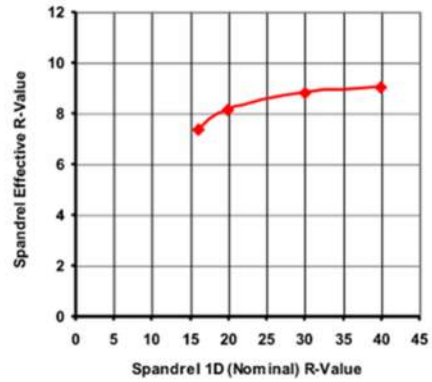
- Differences between simulated and measured heat flows depend on the size and configuration of the panel (*Bettenhausen 2015*).
- Larger differences between simulated and measured heat flows were observed for scenarios with more insulation in the spandrel assembly (*Bettenhausen 2015*).
- Differences between surface temperatures are larger than the differences between calculated assembly U-factors when comparing simulations to physical tests (*Bettenhausen 2015*).
- Lower surface temperatures found around spandrel and framing component junctions indicate greater heat flow (*Ge 2006*).
- Surface temperatures near vision glazing areas are highly sensitive to film coefficients. Careful measurements of localized airflow in areas around glazing, framing, and spandrel assemblies may be required to minimize surface temperature measurement errors during testing (*Ge 2006*).

Design Improvement Strategies

Most of the research available related to improvements to spandrel performance is focused on reducing heat loss through the center of the spandrel panel using vacuum insulated panels (VIPs). Although VIPs are effective at reducing heat flow through the center of the panel, they do not address heat loss through thermal bridging around the spandrel panel framing which has always been a major factor in thermal performance. Figure 6 shows the impact of 1D spandrel insulation R-value on the overall spandrel effective R-value from ASHRAE 1365RP.



Conventional curtain wall spandrel with uninsulated steel frame backup wall.



Conventional curtain wall spandrel with spray foam insulation behind backpan and steel frame backup wall.

Figure 6: Spandrel Panel Insulation and Thermal Performance (ASHRAE 1365RP)

While the scenarios shown only test mineral wool and spray foam insulation, both show similar trends in that the overall spandrel thermal performance does not change significantly with different levels of spandrel insulation.

Aside from a few mentions of potentially using larger thermal breaks in the framing, there is limited publicly available research on reducing heat flow through curtain wall and window wall framing. The Engineering Team recognizes that there could be a gap in the literature due to competition between glazing system manufacturers who may be reluctant to share thermal improvements of their proprietary framing systems.

Airflow and Condensation

The effect of airflow around (e.g., film coefficients) and through the spandrel panel, from ventilation through the spandrel assembly or air leakage through the system (infiltration or exfiltration), on spandrel thermal performance is an area of research that currently does not have sufficient available information. Most of the research is focused on the impact of venting spandrel panels to prevent heat buildup and thermal stress (*Apogee Advance Glazing Group 2004, Boswell et al 2005, and Walsh 2018*) and the ability for the spandrel assembly to dry out incidental moisture within the assembly (*Behr 1995*). Much of this research is for shadow boxes.

Only a few papers discussed the use of CFD simulations to study the impact of venting and airflow around the spandrel on thermal performance and condensation risk (*Almeida 2019, Schwartz 2017*). Research from *Almeida 2019* showed that CFD simulations were effective at determining film coefficients for glazing systems under both natural convection and forced convection conditions. Similarly, *Schwartz 2017* demonstrated correlation between measured and simulated temperatures with CFD simulations for spandrel assemblies for a range of ventilation designs.

Other Categories

Although durability is not a focus of this program, it is worth noting that this topic was very common in literature. There have been many studies on spandrel glass breakage from overheating, particularly in shadow boxes, with some studies dating back to 1995. The strategies for reducing thermal stress include venting behind the spandrel panel and switching from double- to single-glazed spandrel panels. In addition, heat-treated glass is often used in spandrel assemblies to withstand these thermal stresses.

Gaps in Literature

In addition to summarizing the current literature, the Engineering Team identified shortcomings and gaps in the current research. These topics will be used to inform the Test Program being developed and to focus the research on areas where additional industry guidance is required. The gaps in current research include:

- **What is the impact of adjacent assemblies on spandrel panel thermal performance?** Assemblies such as steel frame walls and vision glazing adjacent to spandrel assemblies may have an impact on spandrel surface temperatures and heat flow due to lateral heat flow paths in aluminum curtain wall and window wall systems. There is very little research on this topic despite how common this condition is in many buildings.
- **What is the impact of intermediate floor connected to window wall spandrel assemblies?** There is no physical testing and very little simulated information on the thermal performance of window wall spandrels, particularly at key thermal bridging details such as the slab bypass at floor slabs.
- **How can the accuracy of 2D thermal simulation methods when compared to physical test results be improved?** There is limited information on what factors impact error in thermal simulations. Some studies have suggested there is greater error for 2D simulations with higher levels of spandrel insulation (*Bettenhausen 2015*). However, there is limited information on what modifications to current 2D simulation methods are needed to reduce this error.
- **How does size and configuration impact spandrel thermal performance?** Most of the research available evaluated different spandrel assembly designs rather than the impact of the spandrel configuration on thermal performance. This is a key aspect in quantifying thermal performance, as spandrel panel sizes and spandrel configurations usually differ from project to project.

- What is the accuracy of current industry standards and guidelines on simulating thermal performance compared to physical testing? While there are published guidelines for 2D and 3D thermal simulation methods, there is limited information and research on validating the accuracy of these methods compared to lab measurements. The newly published CSA Z5010 standard and the upcoming version of ANSI/NFRC 100 will provide guidance on how to simulate spandrel assemblies; however, both standards do not have information on how these simulation methods compare to physical testing.
- What are the impacts of various spandrel components on thermal performance? There is limited research available on the impact of components within spandrel assemblies, such as metal backpans, on spandrel thermal performance. It is speculated through thermal simulations that the connection between the spandrel backpan to the mullions can have an impact on surface temperatures and U-factor; however, this has not been verified with lab measurements.
- What are the impacts of accurate spandrel thermal performance values on weighted U-factor (UA) calculations and envelope backstop calculations for building energy code compliance? There is limited research on the impact of using accurate spandrel thermal performance values on building energy code and standard compliance paths such as envelope backstops. This could be a blind spot for both policy makers and practitioners in the industry.
- What are the impacts of contact resistance of components on thermal performance? There is limited research on the impact of contact resistance between adjacent components in spandrel assemblies on thermal performance in thermal simulations. Most current 2D simulation programs, like THERM, assume contact resistance between adjacent materials have very little impact on thermal performance and ignore it. However, this was confirmed to be false for steel frame walls through guarded hot box measurements for ASHRAE 1365 RP. *Norris 2015* included contact resistance in 3D thermal simulations, but this result was only compared to one spandrel assembly rather than to a range of systems with different configurations.

1.2 INDUSTRY SURVEY

The purpose of the industry survey was to both assess the prevalence of specific spandrel types and assess industry knowledge/expectation of spandrel performance. The industry was surveyed to understand the scope and prevalence of different and most relevant spandrel assembly types and details, including what percentage of buildings use the different systems. This survey was also performed to understand what systems and details are most challenging from the standpoint of thermal performance as well as to understand potential opportunities for innovation. The survey reached thirty-five industry professionals in various roles, including fourteen Designers, sixteen Contractors, and five Industry Organization representatives. Note that some participants responded with 'n/a' or skipped questions; therefore, the percentages may not always sum to 100%.

The key takeaways from the survey results are separated into the following categories: prevalence of glazed wall systems, prevalence of spandrel panels and common characteristics, spandrel panel concerns and innovation, and spandrel panel thermal performance. The survey can be found in Appendix B and the full list of survey results can be found in Appendix C.

Prevalence of Glazed Wall Systems

- About 90% of the Designers and Contractors specify/install a glazed wall system in half or more of their projects, reflecting the prevalence of glazing systems in modern construction.
- Glazed wall systems are used in all eight ASHRAE Climate Zones (CZs), with most respondents having projects located in CZ-4 (mixed) and CZ-6 (cold) regions. However, this distribution may be reflective of the locations of the respondents and not only of where glazed wall systems are most commonly used.
- The most common glazing type for the adjacent vision areas is double-glazed IGUs with low-e coating on the #2 surface, non-air gas (e.g., argon) fill, and warm-edge spacers.
- Unitized curtain wall is the most common type of glazed wall construction among the respondents. About half of the Contractors never work with window wall or veneer systems, whereas most of the Designers work with window walls on 25% to 50% of their projects and with veneer systems on less than 25% of their projects.
- The most common average height of the respondents' projects which utilize glazed wall systems is greater than twelve stories, followed by five to twelve stories. Only one respondent works with glazed systems on buildings that are less than five stories on average. This shows that glazed systems are almost exclusively used on mid- to high-rise buildings. However, it should be noted that the results may be influenced by the type of projects that the respondents work on, for example, single-family homes may not have Designer involvement.

- The percentage of glazing area at exterior walls is typically between 40% to 60% for the Designers, versus between 80% to 100% for Contractors. In general, glazing systems account for more than half of the exterior wall area in most projects. Of the glazed areas, spandrel assemblies account for 40% to 60% for most projects.

Prevalence of Spandrel Panels and Common Characteristics

- Almost all of the Designers (twelve out of thirteen) said that they chose spandrels for aesthetic reasons, followed by their speed/constructability. Most of the Designers indicated that they will very likely specify spandrel panels on their next projects, but there is less agreement on the expected relative proportion of spandrel areas in these future projects. More than one-third of the Designers indicated that their decision on spandrel use is independent of the glazed wall systems used on their projects.
- Currently, the most common average spandrel dimensions are between 24 in. and 79 in. (609 mm and 2,000 mm) tall, and between 24 in. and 39 in. (609 mm and 1,000 mm) wide, although most respondents work with spandrels of all sizes on their projects.
- Vented spandrel panels are more often specified by designers than fully sealed panels. In contrast, vented and fully sealed spandrel panels are equally specified among Contractors.
- Metal panel is the most typical spandrel panel cladding, followed by IGU shadow box, IGU with opaque coating, and other opaque cladding types. Single-glazed cladding types are less common. Backpan sealed to mullion with return is the most common configuration of the spandrel backpan. This may have been skewed by limited respondents in cooling-dominated climates, which typically use foil-faced insulation in lieu of a metal backpan.
- Of the respondents, 71% of designers and contractors include insulation within spandrel panels. Backpan insulation is almost exclusively semi-rigid mineral wool, which is used by twenty-four of twenty-six respondents, excluding blank responses. Outside of the backpan, interior insulation is sometimes or always included by 70% of respondents, and mullion wrap is sometimes or always included by 59% of respondents. Insulation within the mullion is more polarizing, as it is never included by 67% of respondents and always included by 22% of respondents. Fins are the most common shading element compared to shades, or others.

Spandrel Panel Concerns and Innovation

- The most common spandrel issues experienced by the respondents are, in order, aesthetic issues, condensation, and glass breakage. Of the Designers, 36% cited that they have experienced water and air leakages with spandrel panels; however, these leakages were not common among Contractors. Of all respondents, 26% did not cite any issues.
- Thermal performance, code compliance, and lack of industry accepted analysis techniques are considered the greatest challenge or concern faced by the respondents on current projects that involve spandrel panels.
- Common concerns that prevent Designers' use of spandrels on future projects include spandrel thermal performance and embodied carbon, though more than half of the Designers did not cite any concerns.
- Insufficient market demand for higher performing products, industry education, and lack of industry-accepted analysis techniques are the top three barriers to spandrel innovation cited by the respondents. The cost of current materials/solutions is another significant barrier cited by Contractors. Of the Designers, 75% agree that more stringent code requirements are the biggest motivator to advancing spandrel design.

Spandrel Panel Thermal Performance

- Of the respondents, 64% of the Designers and 92% of the Contractors/Manufacturers indicated that they are aware of the difference in thermal performance required of spandrel panels compared to transparent glazing.
- The average thermal performance of spandrel products in today's market seen by most of the representatives from Industry Organizations is less than R-5 ft^2-°F-hr/BTU (RSI-0.88 m^2-K/W), while more than half of the Designers specify R-3 (RSI-0.53) to R-7 (RSI-1.23) for spandrel assemblies in their projects. In comparison, 75% of the Contractors indicated that they typically work with R-5 (RSI-0.88) to R-10 (RSI-1.76) spandrels, with some Contractors working with even better assemblies. This difference in expectation is also true for the anticipated code-required spandrel R-value in 2030, with most Designers expecting R-7 (RSI-1.23) to R-15 (RSI-2.64) to be required and most Contractors expecting R-10 (RSI-1.76) to R-20 (RSI-3.52) to be required.
- Based on current technologies, most Designers think that the highest achievable spandrel R-value is between R-5 (RSI-0.88) to R-7 (RSI-1.23), while most Contractors think that R-7 (RSI-1.23) to R-10 (RSI-1.76) or higher is achievable.

- Given that many energy codes and standards (e.g., IECC, ASHRAE 90.1) do not include prescriptive U-factors specifically for spandrels, one-third of Designers follow the procedures outlined by ANSI/NFRC 100 with modified edge zone values using 2D finite element modeling results. The next most common methods to account for spandrel thermal performance are to follow prescriptive requirements for metal-framed wall or fenestration systems, and some of the Designers utilize 1D or 3D analyses. None of the respondents indicated that they use manufacturers' published data – it is unclear whether this is due to limited published data or if this is a choice by the Designers.
- About 60% of the respondents indicate that they rely on simulation reports to support the manufacturer's reported spandrel U-factor. Most respondents expect thermal simulation results to have less than 10% error, with the Contractors generally expecting less accuracy than the Designers and Industry Organization representatives. If available, 96% of all respondents indicated that they would use 3D over 2D simulation results.

1.3 CURRENT STATE OF USE

Recognizing the importance of manufacturers' role in advancing the state of the industry and providing solutions for higher performing spandrels, the Engineering Team conducted a series of phone interviews with glazing system manufacturers. The focus of the interviews was to identify barriers to future development of spandrel panels and to identify opportunities for innovation. While the interview format was open to a general discussion, the following questions were asked of all interviewees:

1. What type of spandrel do you see as most common? Highest and lowest performing?
2. What do you think is the most poorly understood characteristic of spandrel panels?
3. What is your experience with 2D and 3D thermal modeling as well as guarded hot box testing?
4. What does 2030 look like for your team and your products?
5. What does your development cycle look like?
6. What technologies have you considered to reduce thermal bridging in spandrel panels?
7. Where would you like to see building and energy codes go with respect to spandrel panels?

The following sections highlight common themes that emerged from ten interviews.

Industry Knowledge

Generally, knowledge of thermal modeling standards, processes, and resources specific to spandrel panels was considered poor across the industry. One interviewee noted that the general confusion in the industry about how to properly treat spandrel panels deters manufacturers from doing the right thing, saying that it is "easy to lose a sale if you ask too many questions."

Misunderstandings persist as to the difference between 1D center-of-spandrel performance and the effective thermal performance of spandrel panels that account for the 2D and 3D complexities of the systems.

2D vs. 3D Modeling

All the interviewed manufacturers use 2D thermal simulation to assess the thermal performance of their spandrel assemblies and the majority were familiar with 3D modeling. However, only a few noted that they currently have 3D thermal performance data for their systems, and of these only two manufacturers noted that they currently offer 3D modeling results as a standard document in the submittal process.

Manufacturers identified access to 3D performance data as a market differentiator but acknowledged that the improved accuracy (and decreased R-value [RSI-value]) is a risk when approaching markets or teams with a poor understanding of the results.

Codes and Standards

Current code language allowing, and sometimes requiring, less accurate 2D thermal simulation or use of default values for spandrels was viewed as an impediment to innovation. Similarly, manufacturers identified inconsistent enforcement of the performance documentation process as a reason for continuing with the status quo.

When asked what changes they would like to see, there was a general consensus amongst manufacturers that they would like to see future codes recognize spandrels as a separate assembly type from other opaque wall assemblies. For some, the reason was to permit setting achievable performance targets. For others, the reason was to define the calculation procedures more clearly.

Other topics that were raised included updated default spandrel U-factors based on physical testing and a reconsideration of the use of combustible materials in taller buildings (e.g., wood or fiberglass framing).

Product Development

The average product development cycle reported by manufacturers was two to three years, with planning cycles stretching out to five to ten years. When asked about the driving factors, the majority of respondents cited code changes and increases in prescriptive performance targets as the key factor in deciding to pursue development of higher performance systems.

Several manufacturers referenced state-level stretch codes requiring project-specific size performance and accounting of thermal bridging at interfaces as current areas of interest.

Innovative Technologies

The most common areas of development for improved glazed wall system performance were:

- Thermal breaks (material, size, location), and
- Low thermal conductivity accessories for perimeter interface detailing.

A limited number of the manufacturers were looking at more insulative claddings (e.g., vacuum insulated panels) and/or exterior insulation. However, the manufacturers also recognized that designers often select spandrels in part to achieve a specific visual intent, such as alignment of the opaque facade with the vision glazing. This aesthetic limitation was noted as a key factor in the historic focus on components within the system profiles (e.g., thermal breaks).

Key Takeaways

In all, the industry seems to recognize that a 3D modeling procedure would produce more accurate results when compared to 2D modeling, and that they are entertaining methods for improving the overall thermal performance of spandrel assemblies. However, the industry appears to be waiting for codes and standards to "raise the bar," as one manufacturer described it.

The interviews targeted relatively large manufacturers of spandrel assemblies. While the interviewed manufacturers appeared ready to adopt 3D modeling for spandrels, often the responsibility for preparing these models falls on a glazing contractor with more limited resources. There are an estimated 26,000 glazing contractors in the US (https://www.ibisworld.com/industry-statistics/number-of-businesses/glass-glazing-contractors-united-states/), and additional education and resources will be needed to support any changes to the status quo.

Glazed Wall System Prevalence

To understand the prevalence of glazed wall systems in large North American cities, the Engineering Team selected seven of the largest cities in the U.S. based on population and Vancouver, Canada to review the representative percentage of glazed buildings versus non-glazed buildings. The reviewed cities include New York, Phoenix, Houston, Chicago, Columbus, Jacksonville, Los Angeles, and Vancouver. The cities are all located in ASHRAE Climate Zones 2 – 5.

Using Google Maps' Street View, downtown city blocks were scanned and relevant data of facade characteristics for each building was collected. Figure 7 is a sample location for Chicago where an approximately three-block-by-four-block area was reviewed.

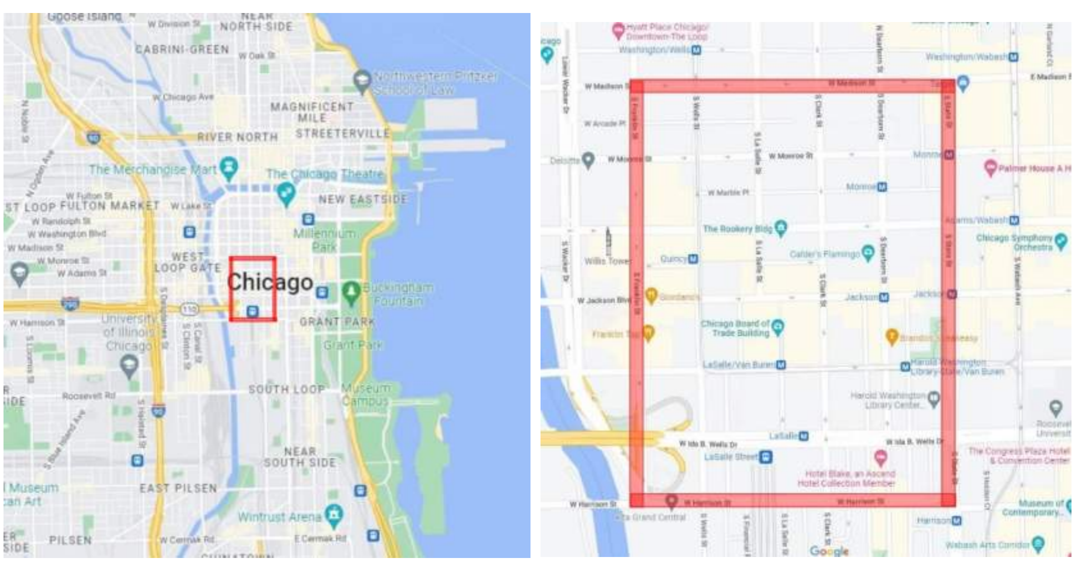


Figure 7: Example of Sample Location for Chicago

Results from the analysis show that glazed wall systems represent roughly 40% of the building facade systems used in the downtown core of several major U.S. cities. The prevalence was higher in colder climates (Figure 8). Results also showed that curtain wall was significantly more prevalent than window wall in mid- to high-rise construction of glazed wall facades. Based on the city survey, more than 80% of the glazed buildings were curtain wall (Figure 9). Interestingly, low-rise glazed buildings were observed to be evenly split between curtain wall and window wall type systems.

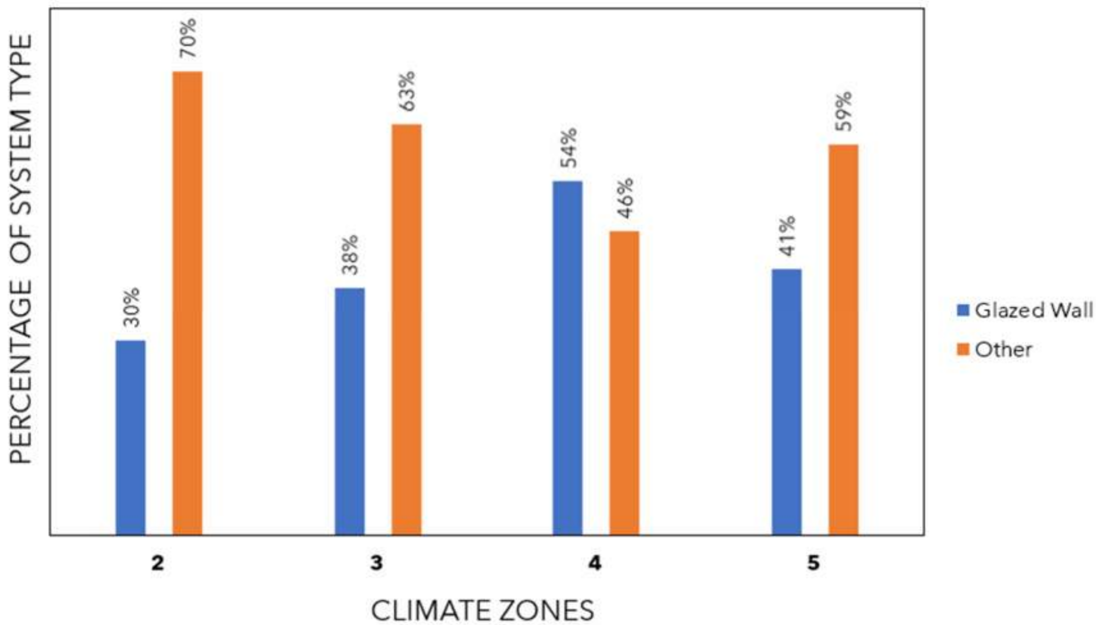


Figure 8: Percentage of Glazed vs. Other Wall Systems by ASHRAE Climate Zone

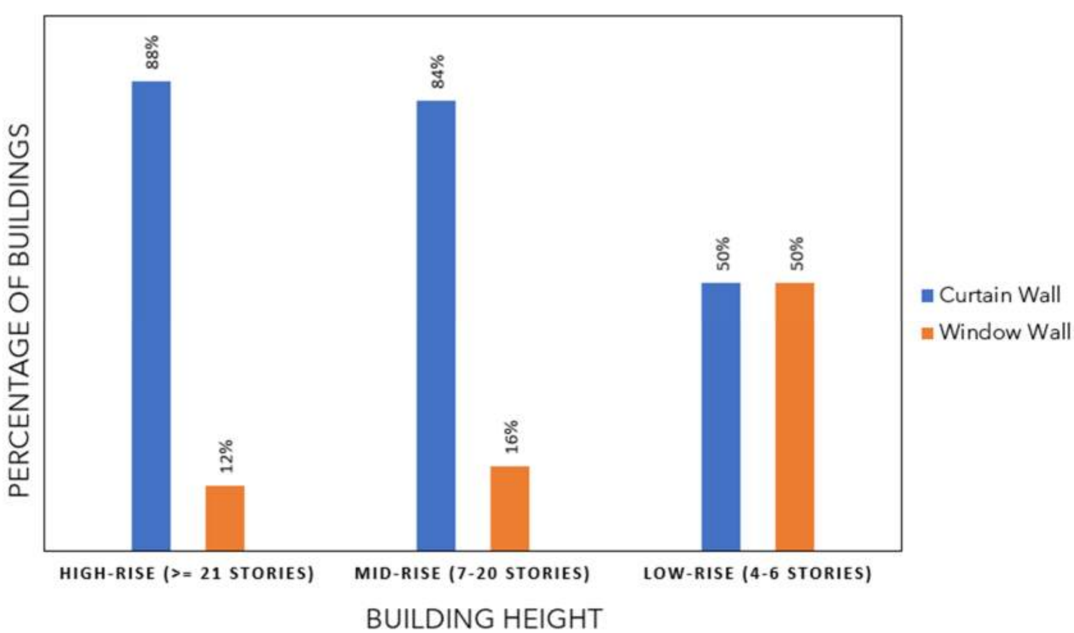


Figure 9: Building Height vs. Glazed System Sub-Type

Current Energy Codes

Although widely used in the building industry, there is currently no consensus on the calculation methods used to determine the thermal performance of spandrel panels.

With few exceptions (e.g., California Title 24), state and national energy codes do not separately define spandrels from other opaque wall elements. As a result, the insulation requirements of above-grade framed walls are assumed to apply. This implicit classification of spandrels has a profound impact on the performance targets as well as on the referenced calculation methodologies.

Table 2 summarizes the classification of spandrels in the two most common national energy codes (ASHRAE and IECC) along with a selection of state energy codes. The table also includes a description of the approved calculations methodologies.

The ASHRAE 90.1 and NECB (Canadian) standards explicitly permit the use of 2D and 3D thermal simulation for the determination of opaque assembly U-factors. Others, including the IECC and numerous state codes, permit thermal simulation indirectly by referencing ASHRAE 90.1.

However, until the recent release of CSA Z5010:21, a North American consensus standard for performing thermal simulation of opaque assemblies did not exist. For this reason, North American designers and manufacturers have historically cited ASHRAE Handbook – Fundamentals or ANSI/NFRC 100 as the simulation procedure for spandrels. This lack of direct guidance has likely contributed to the development of tabulated default performance values for spandrel assemblies, which have been included in several state-level energy codes (e.g., California, Washington, New York).

Current Thermal Simulation Standards and Procedures

Current thermal simulation standards and reference procedures which apply to 2D and 3D thermal simulation of spandrel panels include:

- ANSI/NFRC 100-2020 [E0A2] – Procedure for Determining Fenestration Product U-Factors
- AAMA 515-19 – Voluntary Procedure for Determination of Fenestration Surface Temperatures by THERM Finite Element Modeling
- Fenestration Association of British Columbia (FenBC) – Reference Procedure for Simulating Spandrel U-Factors
- ASHRAE RP-1365 –Thermal Performance of Building Envelope Details for Mid- and High-Rise Buildings
- CSA Z5010 – Thermal Bridging Calculation Methodology

Internationally, several other standards exist, including ISO 10077, ISO 10211, and ISO 13788. While these standards differ from the referenced North American standards in several ways (e.g., material aspects, boundary conditions, frame cavity models, etc.), they do not specifically address the unique characteristics of spandrels beyond the referenced North American standards.

ANSI/NFRC 100, the FenBC Reference Procedure, and AAMA 515 describe procedures for 2D simulation. ASHRAE RP-1365 and CSA Z5010 provide procedures for 3D simulation. The section below provides an overview of each.

ANSI/NFRC 100

ANSI/NFRC 100 is published by the National Fenestration Rating Council (NFRC) and is widely accepted in the industry as the standard for 2D thermal simulation of glazed wall systems including glazed spandrels. The ANSI/NFRC 100 definition of a spandrel panel system is:

> A non-vision application of a fenestration product; typically used to hide or obscure features of the building structure or used for visual effect. A spandrel panel system consists of an exterior exposed glazing layer with an interior insulated opaque panel.

Significantly, the ANSI/NFRC definition of a spandrel panel system limits the applicability of ANSI/NFRC 100 to spandrels that include a glazing layer. All other spandrels (e.g., metal panel clad) are excluded from the scope of ANSI/NFRC 100 and the rating program.

Consistent with the objective of determining product ratings, ANSI/NFRC 100 identifies standard configurations and sizes for fenestration products. While the list of product types has historically included spandrel panels separate from curtain wall and window wall, the procedure for simulating and testing spandrels has been identical to transparent glazed wall systems.

The ANSI/NFRC simulation procedure for glazed wall systems involves 2D thermal simulation of intermediate vertical frame sections and either an intermediate or a standard head/sill frame section for curtain wall and window wall products, respectively. Each frame section is divided into a frame, edge, and center-of-glass area to permit determination of U-factors at different overall product sizes. A schematic of this approach is provided in Figure 10.

Table 2: Classification of Spandrels in Select North American Energy Codes and Approved Calculation Methods

Standard	Classification	R_{min}*		Calculation Methods	Notes
		Low	High		
ASHRAE 90.1-2019	Walls, above-grade (other)	11.3	31.2	2D/3D Thermal Simulation or Physical Testing *(Ref: A9.2)*	*"...spandrel panels are considered opaque wall elements and need to be insulated to those requirements."*
IECC-2021	Above-grade Wall (other)	15.6	31.3	References ASHRAE 90.1 Appendix A (Ref: C402.1.4)	*"ABOVE-GRADE WALL. A wall…enclosing conditioned space. This includes between-floor spandrels..."*
WA Commercial Energy Code 2018	Above-grade Wall (other)	18.5	19.6	Default table (C303.1.5) OR ASHRAE 90.1 Appendix A	*Based on IECC 2018 with amendments* *"VERTICAL FENESTRATION…opaque areas such as spandrel panels are not considered vertical fenestration"*
2019 California Title 24	Exterior Wall	12.2	16.1	Tabulated values in Joint Appendix JA4 (Table 4.3.8) or Physical Testing	Spandrels recognized as a unique wall construction type with its own mandatory U-factor requirement, R-3.6 (Ref: 3.2.5.1).
2020 New York City Energy Conservation Code	Exterior Wall	16.4	16.4	Tabulated values (C402.1.4.2 or 5.5.3 in Appendix CA)	"…Opaque assemblies within fenestration framing systems…" Tabulated values are from 2019 California Title 24. Table cannot be used if system includes metal backpan.
2023 Massachusetts Stretch Energy Code	Glazed Wall System	12	12	Tabulated values (C402.7.4.1), Reference values from Building Envelope Thermal Bridging Guide (C402.7.4.2) or modeled values (C402.7.4.3)	"Glazed Wall System" classification includes any fenestration framing system with vision and opaque spandrel assemblies. Thermal performance prescriptive requirements have been introduced specifically for "…opaque assemblies within fenestration framing systems…." Minimum R-values are for insulation infill within opaque assemblies. Weighted U-factor calculations are required to include thermal bridging effects.
National Energy Code of Canada for Buildings (NECB) 2020	Above-ground Opaque Building Assembly	19.6	34.4	2D/3D Thermal Simulation or Physical Testing (Ref: A-3.1.1.5)	No differentiation between wall construction types.

* *R-values based on maximum U-factor approach and varies by climate zone.*

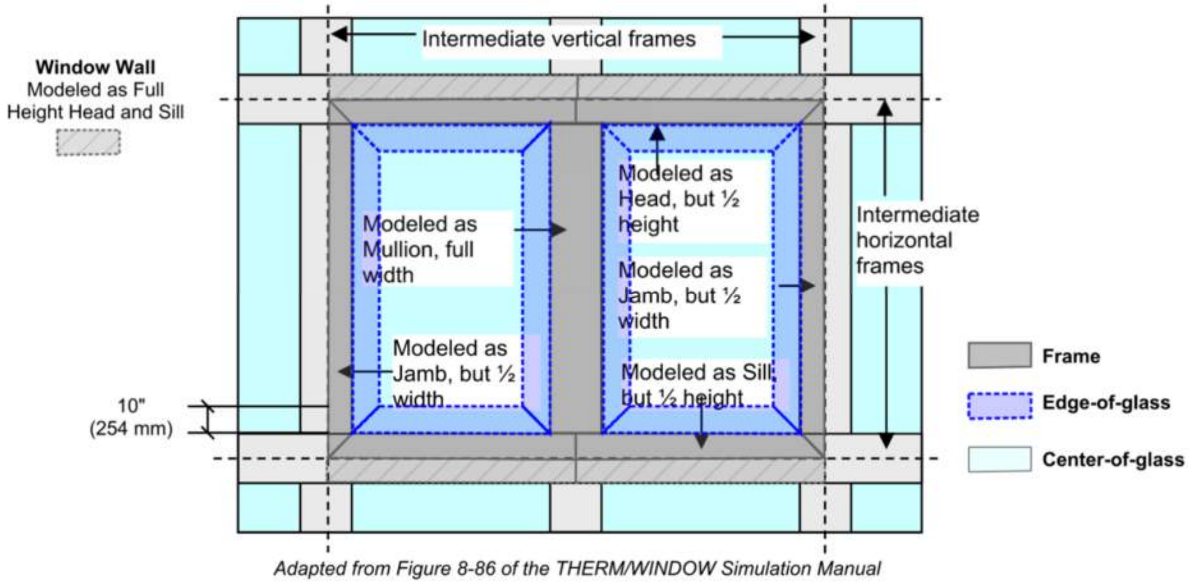


Figure 10: Elevation of Frame, Edge of Glass, and Center of Glass Areas per ANSI/NFRC 100

Beginning with ANSI/NFRC 100–2020, the simulation procedure requires that the edge-of-glass dimension for spandrels be increased from the standard 2.5 in. (63.5 mm) to 10 in. (254 mm). The edge distance is measured from the point where the spandrel assembly becomes one-dimensional as illustrated in Figure 11. This change was the result of several years of work by the ANSI/NFRC Spandrel Panel System Task Group and the calibrated thermal modeling of a limited number of test articles. The model calibration was based on the overall product U-factor, and the Task Group determined that increasing the edge distance was required to capture the 2D heat flow effects more completely at the frame-to-backpan interface and to achieve an accuracy within 10% of the measured results.

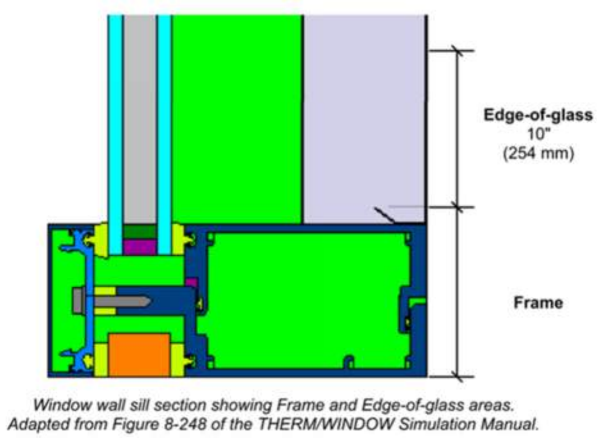


Figure 11: Window Wall Sill Section Showing Extent of Edge of Glass and Frame Areas

Although outside the scope of this research program, the ANSI/NFRC rating system and technical documents also provide a procedure for estimating the solar heat gain through glazed spandrel assemblies.

<u>FenBC Reference Procedure</u>

Similar to the ANSI/NFRC Spandrel Panel System Task Group, the intent of the FenBC Reference Procedure was to extend the ANSI/NFRC 100 simulation procedure to provide a more accurate estimate of spandrel U-factors. The authors of the procedure similarly noted that increasing the edge distance was required to capture the 2D heat flow effects at the frame-to-backpan interface. However, the reference procedure also identified thermally distinct spandrel configurations which were not accurately represented by the single product type configuration included in ANSI/NFRC 100.

In summary, the FenBC Reference Procedure differs from ANSI/NFRC 100 in two ways. The FenBC Reference Procedure:

- Requires a minimum edge distance of 6 in. (152 mm) as opposed to 2.5 in. (63.5 mm).
- Includes two additional spandrel configurations: window wall and slab bypass (Figure 12).

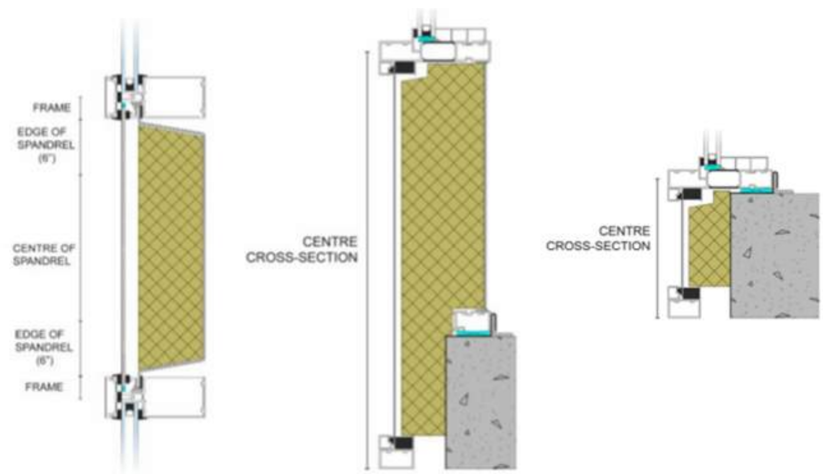


Figure 12: FenBC Spandrel Configurations

To accommodate the additional spandrel configurations, a procedure and calculator were developed to determine an overall product U-factor outside of ANSI/NFRC's WINDOW program. The FenBC Reference Procedure references ANSI/NFRC 100 for all material, modeling details, and boundary condition assumptions.

AAMA 515

AAMA 515 provides a detailed procedure for predicting interior surface temperatures of fenestration products. It is generally based on ANSI/NFRC 100, but extends the simulation methodology by:

- Providing a method for adjusting interior and exterior boundary conditions to match project-specific conditions.
    - The interior boundary condition assigns variable temperature only. It assumes a fixed convection film coefficient based on the frame type (per ANSI/NFRC 100) and an automatic enclosure model for radiation.
    - The exterior boundary condition assigns variable temperature and convective film coefficient. Unless otherwise specified, the convective film coefficient assumes forced convection and is based on the mean coincident wind speed corresponding to the ASHRAE 99.6% dry bulb temperature. No method is provided to account for variations in project height relative to the elevation of the measurement (typically 32.8 ft or 10 m). Radiative heat transfer is based on a blackbody radiation model per ANSI/NFRC 100.
- Requiring the reporting of the coldest point on the frame and glass.
    - In contrast, ANSI/NFRC 500 requires measurement 1/2 in. (13 mm) and 1 in. (25 mm) away from the glass-to-frame junction for the frame and edge-of-glass temperatures respectively.
    - Requiring inclusion of adjacent construction (i.e., installation details) up to a point of thermal symmetry or to a point determined by the simulator so as to be representative of the point of interest.

AAMA 515 also includes several important considerations when comparing simulations to testing (i.e., ASTM C1199) including:

- Measurement accuracies ± 0.5°F (0.3°C).
- Local variations in edge-of-glass and corner temperatures on the order of 17°F (9°C) (Figure 13).
- A 10% accuracy in U-factor (per ANSI/NFRC 100) results in a surface temperature tolerance on the order of ± 3.1°F (1.7°C), based on a frame U-factor of 0.6 BTU/hr-ft^2-°F (3.42 W/m^2-K).

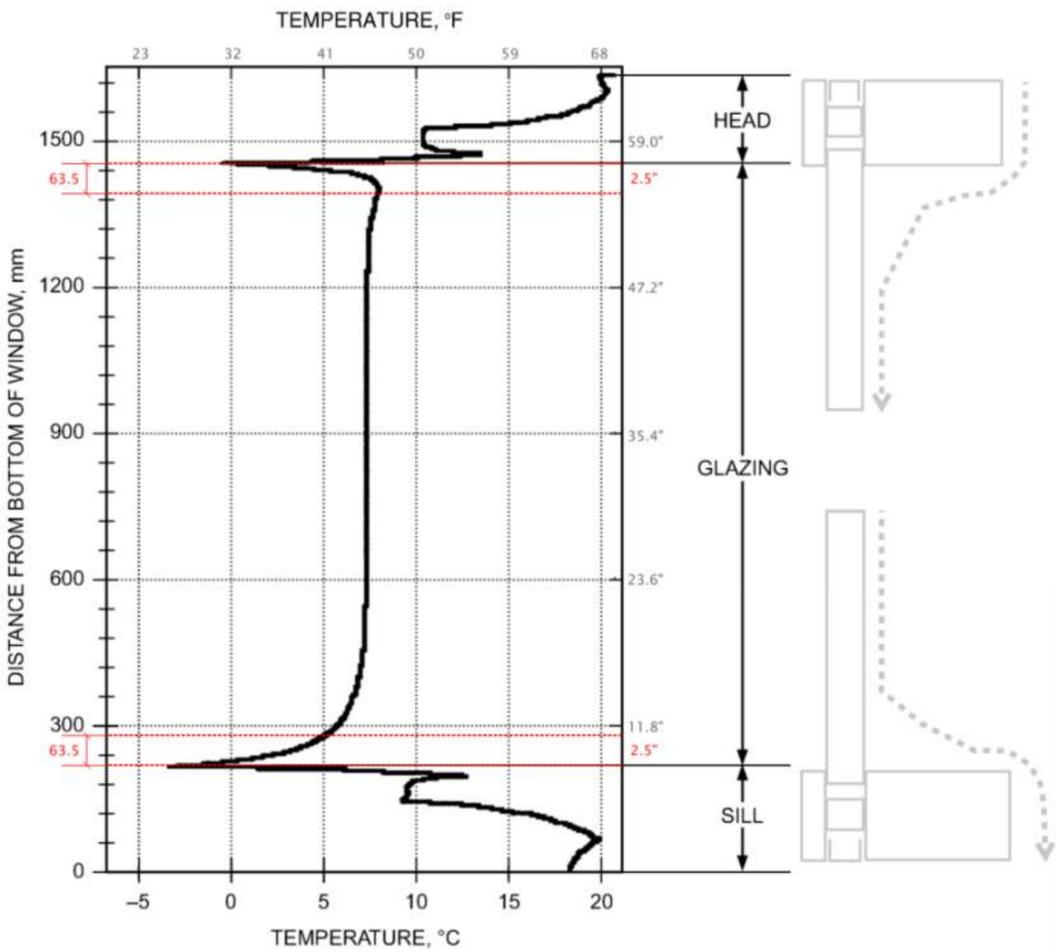


Figure 13: Temperature Distribution on Indoor Surfaces of Glazing Unit

(ASHRAE Handbook – Fundamentals Chapter 15 Figure 26)

<u>ASHRAE RP-1365</u>

Published in 2011, ASHRAE Research Project RP-1365 developed a 3D thermal simulation procedure specifically for building envelope details. The research project also led to the development of a catalog of forty common building envelope details and assemblies that has since grown to over six hundred. To validate the procedure, the authors calibrated the simulations against guarded hot box testing. Key elements of the simulation procedure include:

- Cut-off planes located at symmetry planes or a minimum of 36 in. (915 mm) away from the point of interest.
    - CSA Z5010 and ISO 10211 define a distance of 39.4 in. (1,000 mm).
- Boundary condition and material properties based on the 2009 ASHRAE Handbook – Fundamentals.

- A constant thermal resistance of 0.91 hr-ft^2-°F/BTU (0.16 m^2-K/W) applied to unventilated plane air spaces.
    - Air cavities within frame cavities per ISO 10077.
- Inclusion of contact resistances.

The 3D thermal simulation procedure described in ASHRAE RP-1365 was shown to predict the measured U-factor within 5% for the majority of the test articles. However, variations in the simulated and measured surface temperature, specifically at fasteners and other highly conductive heat flow paths, were higher.

ASHRAE RP-1365 informed later versions of the ASHRAE Handbook – Fundamentals and CSA Z5010 standards.

CSA Z5010

Published in 2021, CSA Z5010 combines the simulation procedures of ASHRAE RP-1365, ISO 10211, and AAMA 515. Similar to ASHARE RP-1365, the referenced source for materials and boundary conditions is ASHRAE Handbook – Fundamentals. Several important aspects of the modeling procedure as it relates to spandrels include:

- Requiring 3D thermal simulation of assemblies and details with intermittent thermal bridges or thermal bridging in multiple planes. This includes spandrels due to the perimeter framing.
- Locating model boundaries at symmetry planes or the greater of three times the thickness of the flanking element and 39.37 in. (1,000 mm).
- Conservatively recommending a reduced interior heat transfer coefficient of U-0.70 BTU/hr-ft^2-°F (USI-4.0 W/m^2-K) when assessing surface temperatures for condensation risk.

1.4 COMPUTATIONAL FLUID DYNAMICS (CFD) MODELING

The extent to which energy is lost through airflow in a vented spandrel panel cavity is not well understood. The current literature on this issue is limited and focuses on the effectiveness of CFD models in determining film coefficients on the interior and exterior surfaces of the panel which affect overall thermal performance (*Almeida 2019, Schwartz 2017*). The research to date has not addressed the effect of interstitial airflow on overall panel performance (see "Airflow" in Section 1.1 – Literature Review).

There is notably insufficient guidance in the reference standards with respect to calculating the thermal performance of spandrel assemblies. As described in Section 1.3, the lack of a recognized reference methodology led to the development of the FenBC reference procedure, which modifies the standard simulation procedure (ANSI/NFRC 100) for obtaining U-factors for spandrel assemblies. The FenBC reference procedure will be used in this study to calculate spandrel U-factors using 2D FEA thermal simulation.

One of the objectives of this study was to explore the effect of airflow within the spandrel panel on the thermal performance of the assembly. While the Engineering Team anticipated that the effect would be minimal, CFD simulations were performed to quantify the potential impact of varying certain ventilation parameters and to examine the need, if any, to adjust the Test Program design.

Background

Airflow can impact the thermal performance of spandrel panels in the following ways:

1. Airflow through the spandrel assembly (i.e., air leakage) leads to increased levels of heat transfer and changes in system temperatures.
2. Airflow within the spandrel cavity (or cavities) influences the convective heat flow across spandrel layers.
3. Airflow adjacent to surface boundaries influences the heat transfer rate between the surrounding environment and the spandrel panel (i.e., film coefficients). This applies both within the spandrel cavity and along the exterior surfaces of the spandrel assembly.

Air leakage is outside the scope of this study, as it is driven primarily by joint detailing and workmanship rather than by conductive, convective, and radiative heat flow across the spandrel assembly materials and air spaces. This section summarizes three factors related to spandrel features that impact airflow (both within the spandrel panel and adjacent to surface boundaries) and thermal performance: vent openings, air volume modeling assumptions, and film coefficients.

Vent Openings

Spandrels can be sealed, vented only at the top or bottom, or ventilated at both the top and bottom of a panel. Vent openings can vary in size and shape, which controls the amount of air that flows into and out of the spandrel.

The rate of air exchange between the spandrel cavity and the exterior will not only affect heat transfer but will also dictate the extent to which condensate can form within or evacuate from the cavity. There are no design standards or guidelines that provide direction on ventilation requirements for differing climates. Industry stakeholders offered dissenting opinions on whether to vent, ventilate, or seal a spandrel panel airtight to mitigate heat buildup or condensation. The thermal performance impact of adding vent openings is even less understood.

A ventilated spandrel assembly is analogous to a rainscreen wall system, as shown in Figure 14. Both have cladding panels, an air cavity, insulation, and an air/vapor barrier.

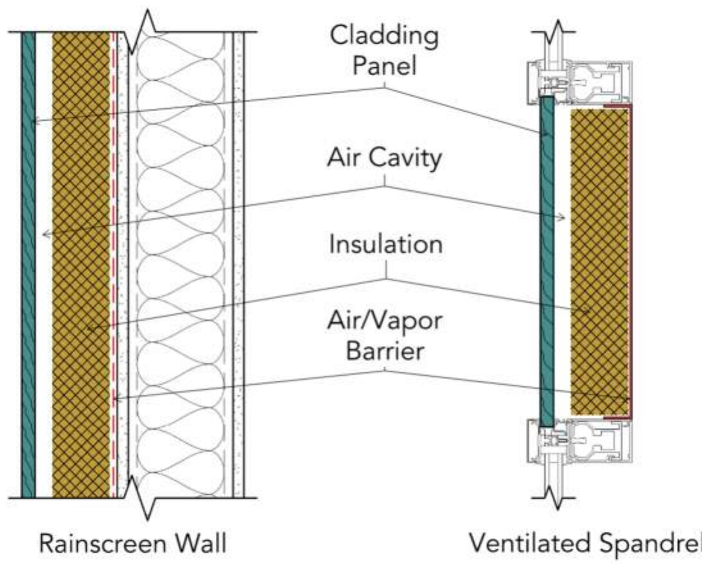


Figure 14: Comparison of a Rainscreen Wall and a Ventilated Spandrel

Based on rainscreen wall ventilation studies (*Garden 1963, Baskaran 1992*), relatively large vent openings (at least 3/8 in. by 1 in. or 10 mm by 25 mm) at the top and bottom of an air cavity can enhance airflow at temperature ranges typically seen in buildings. However, the impact on the overall thermal performance of the wall assembly is subtle because the insulation is at the inboard side of the air cavity. This rainscreen condition is similar to a ventilated spandrel assembly, and we would expect similarly marginal effects on thermal performance.

Air Volume Modeling Assumptions

In 2D FEA thermal simulations, enclosed air spaces such as those within fenestration mullions are modeled as solid materials that approximate air behavior based on empirical studies of similar, small-scale configurations and conditions. Practitioners assume it is appropriate to use this air volume material for larger spandrel air cavities. This approach may inappropriately extrapolate the thermal performance of air cavities in 2D FEA thermal simulations. Through comparing CFD and FEA results, our study intends to evaluate these air volume modeling assumptions as they apply to larger spandrel air cavities.

Air Volume Modeling Assumptions

Film Coefficients

Film coefficients quantify the rate of heat transfer between an environment and a surface. In 2D FEA thermal simulation software tools, practitioners use film coefficients to account for convective and radiative heat transfer on the interior and exterior model surfaces. In most building applications, convection from airflow is much higher than radiative effects.

- Interior: Radiative effects at the interior are minimal because the interior space and surface temperatures are similar. The mechanical systems and air distribution ductwork will drive air movements adjacent to the spandrels.
- Exterior: Simulations are assumed during nighttime winter conditions. Radiation to the night sky (where there is a direct line of sight) may influence radiative heat transfer; however, winter wind speed assumptions often govern film coefficient values.

Rather than calculate project-specific conditions, the industry uses film coefficients prescribed by standards based on a fixed set of conditions. A summary of the film coefficients commonly used by the most frequently referenced standards (ANSI/NFRC 100, ISO 100772, ISO 15099, EN 673, CSA Z5010, and AAMA 515) for U-factor simulations is provided in Appendix D. Rather than using the film coefficients from referenced standards, our study intends to take film coefficients from CFD simulations and use those to calculate the U-factors. It is important to note that the film coefficients from the 3D CFD simulation in this study reflect an approximation of laboratory testing conditions, not real-world interior conditions.

Airflow Simulation Study

The Engineering Team performed an airflow simulation study to review the effect of vent openings, air volumes, and film coefficients on spandrel thermal performance. A commercial CFD software tool was used to simulate the behavior of air explicitly. This tool calculates air temperature and velocity within the simulated air volume based on the initial temperature of the air volume and the airflow conditions (e.g., heat flow, velocity, pressure) at the model boundaries.

Spandrel airflow is primarily driven by pressure and temperature differences between the air cavity and the surrounding environment. Other variables that can influence airflow include spandrel panel size, cavity depth, frame type, backpan profile, insulation type, roughness of surfaces enclosing the air cavity, emissivity, and vent opening size and configuration. To avoid performing laboratory testing of all possible configurations and flow conditions, CFD simulations were used to:

- Examine the impact of key variables (e.g., vent openings) on internal spandrel air flow to determine if they significantly impact spandrel thermal performance.
- Compare the properties of the spandrel cavity air volume in a 3D CFD simulation of a spandrel assembly to that of a traditional 2D FEA thermal simulation with the same setup.
- Compare U-factor calculations following the FenBC reference procedure using 2D FEA thermal simulations and those determined directly using CFD simulations.

<u>CFD Simulation Setup</u>

The CFD simulation is based on a typical stick-built curtain wall system and is modeled explicitly in 3D. While there are many frame types available, a stick-built system can have the most direct airflow path between the spandrel air cavity and the exterior relative to unitized assemblies. Using this system type obviates the need to test other less direct airflow path systems (e.g., unitized curtain wall, window wall, etc.). If airflow does not impact thermal performance on this system, it is unlikely to impact thermal performance on systems with more convoluted or restricted airflow paths.

Figure 15 shows the model extents in elevation, consisting of a spandrel panel with glazed vision areas above and below. The model extends to a plane of thermal symmetry at the centerline of the vertical mullions and at the centerline of the vision panel above and below. The model assumes all adjacent materials are in continuous contact with negligible contact resistance.

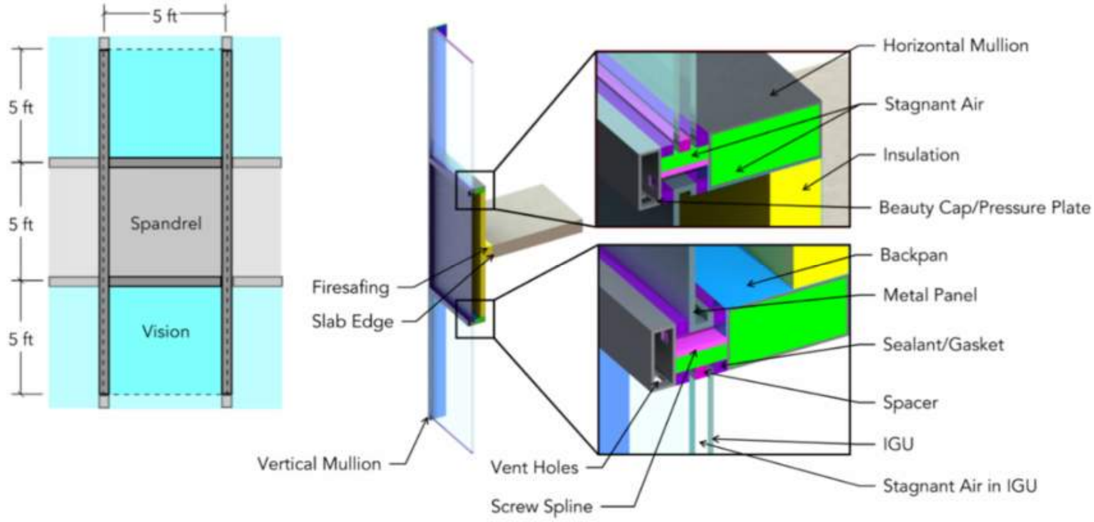


Figure 15: CFD Simulation Geometry

In CFD simulations, the model discretizes air volumes into a finite volume mesh to perform calculations. Unlike 2D FEA thermal simulation models, the air within the spandrel cavity was explicitly modeled, as well as the connecting path through the curtain wall mullions, i.e., through vent openings in the gaskets, openings in the pressure plate, and openings in the beauty cap (Figure 16, ventilated case). For the sealed spandrel cases, the openings were modeled to disconnect the spandrel air volume from the exterior air volume (Figure 16, sealed case). On the exterior and interior side of the assembly, 6 in. (152.4 mm) thick air layers were also simulated. Disconnected fully enclosed air volumes within the mullions and IGUs were modeled as solids with equivalent average effective thermal conductivities to reduce simulation time (solid-colored areas of Figure 16). This approach is adopted in ANSI/NFRC 100 standardized calculations.

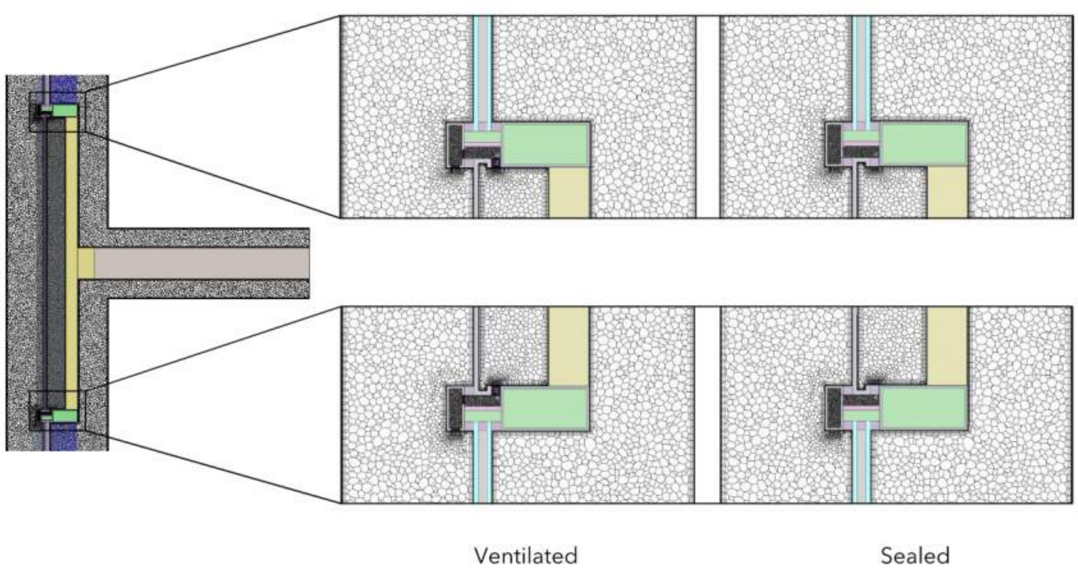


Figure 16: CFD Simulation Air Volumes – Meshed vs. Solid Components

Appendix E includes complete assumptions for the solids, air volumes, and boundary conditions in the CFD simulation.

FEA Simulation Setup

Figure 17 shows the 2D FEA thermal simulation extents. The 2D FEA thermal simulation setup matches the 3D CFD simulation setup in terms of geometry, simulation extents, solid material thermal conductivities, and boundary conditions.

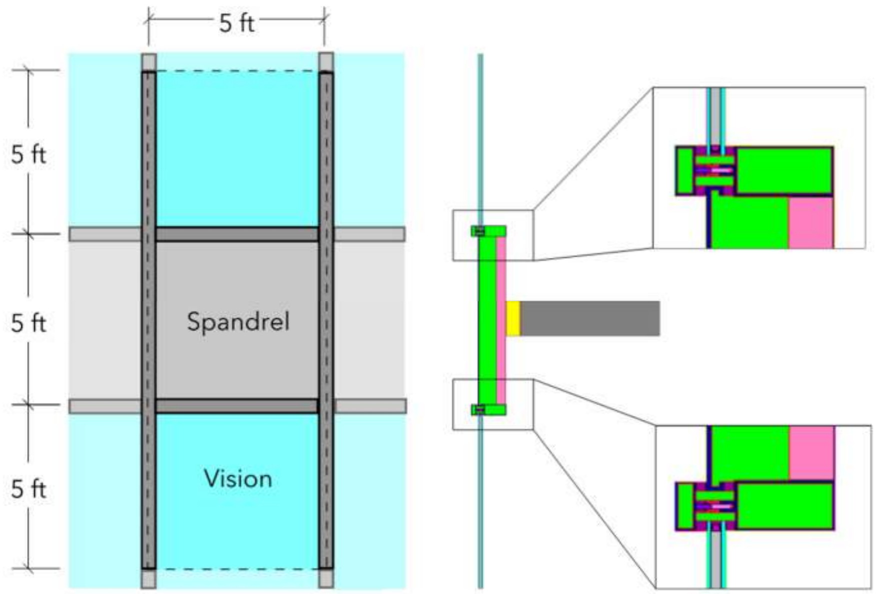


Figure 17: FEA Simulation Extents

The most notable difference is that all air layers in the 2D FEA thermal simulation use the same air cavity solid material, whereas the 3D CFD simulation accounts for air movement with turbulence parameters (meshed areas of Figure 16). Appendix F includes complete assumptions for the 2D FEA thermal simulation.

Variables

The variables in Table 3 influence airflow within spandrel cavities. However, the panel height, cavity depth, exterior air velocity, and vent openings are the four variables most likely to have a significant impact on airflow. The ranges of values shown in Table 3 were compiled based on the Engineering Team's experience, literature review findings, and input from the industry survey and outreach.

Table 3: Variables, Ranges, Influence, Significance, and Selected CFD Inputs

Variables	Range	Influences	Predicted Significance	Selected CFD Input
Cavity Ventilation	Sealed: 0 openings Vented: 2 openings Ventilated: 4 openings Opening Size: 0.5 in. (12.7 mm) dia.	Air exchange between spandrel cavity and exterior.	Primary	Sealed: 0 openings. Ventilated: 4 openings. Opening Size: 0.5 in. (12.7 mm) dia.
Exterior Air Velocity	<1 to 10 mph (<1 to 4.5 m/s)	Volume of air that may enter vent openings.	Primary	Low Velocity: 0.36 mph (0.16 m/s) High Velocity: 10 mph (4.5 m/s)
Panel Height	1 to 5 ft (0.3 to 1.5 m)	Convection loop height.	Primary	5 ft (1.5 m)
Air Cavity Depth (Between Panel and Insulation)	0.5 to 4 in. (12.7 to 101.6 mm)	Convection loop depth.	Primary	4 in. (102 mm)
Backpan Profile	• Taped. • Returned to glazing pocket. • Small return. • Flat panel.	Perimeter thermal isolation.	Secondary	Returned to glazing pocket
Framing Type	• Stick-built. • Unitized curtain wall. • Window wall. • Veneer. • Next generation.	Perimeter thermal isolation and spandrel cavity air flow path.	Secondary	Stick-built
Glazing Support Type	• Pressure plate. • Structural silicone.	Perimeter thermal isolation.	Secondary	Pressure plate
Spandrel Panel Insulation Type	Mineral wool	Thermal isolation.	Secondary	Mineral wool
Exterior Panel Type and Insulation	• Glass panel. • Metal panel. • Insulated metal panel.	Thermal and specular properties.	Secondary	Metal panel
Surface Roughness	0 to 10 nm	Convection current speed and heat exchange.	Tertiary	0 nm

In general, the CFD simulation inputs were selected to allow more air exchange between the spandrel cavity and the exterior to determine the impact of airflow under the most favorable conditions. More detailed descriptions of each variable are included in Appendix G. We have assumed in all cases that the insulation layer is in continuous contact with the backpan and mullions, or is integral to the interior air barrier so that air cannot flow between the insulation and adjacent materials.

Simulation Cases

The following cases were simulated and compared in CFD and 2D FEA thermal simulation software:

- Ventilated (four vent openings, two top and two bottom), low exterior air velocity.
- Sealed, low exterior air velocity.
- Ventilated (four vent openings, two top and two bottom), high exterior air velocity.
- Sealed, high exterior air velocity.

Airflow Simulation Results

The following analysis results for the four simulation cases are presented below:

- Air velocity inside the spandrel cavity.
- Air temperature inside the spandrel cavity.
- CFD versus 2D FEA thermal simulated air cavity temperatures.
- Convective film coefficients extracted from the CFD simulation.
- U-factors calculated from 2D FEA thermal simulations with film coefficients extracted from CFD versus U-factors calculated from CFD simulations directly.

Results are presented as comparisons between sealed and ventilated cases.

Air Velocity

Figure 18 shows the CFD simulated air velocity in the spandrel at a section through the vent openings. The high exterior air velocity case shows higher velocity and increased penetration of exterior air into the spandrel compared to the low exterior air velocity case. While there is a 200% increase of velocity magnitude in the vicinity of the vent openings, this effect quickly dissipates away from the openings. The airflow penetration is more pronounced through the lower vent openings, and marginal through the upper vent openings.

In the sealed cases, air pressure differences do not contribute to the air velocity variations within the air cavity. The increased air velocity adjacent to surfaces within the spandrel cavity is caused by internal natural convection driven by surface temperatures. The internal convection is greater for the high velocity case due to the colder exterior surface temperature generated from the higher exterior air velocity.

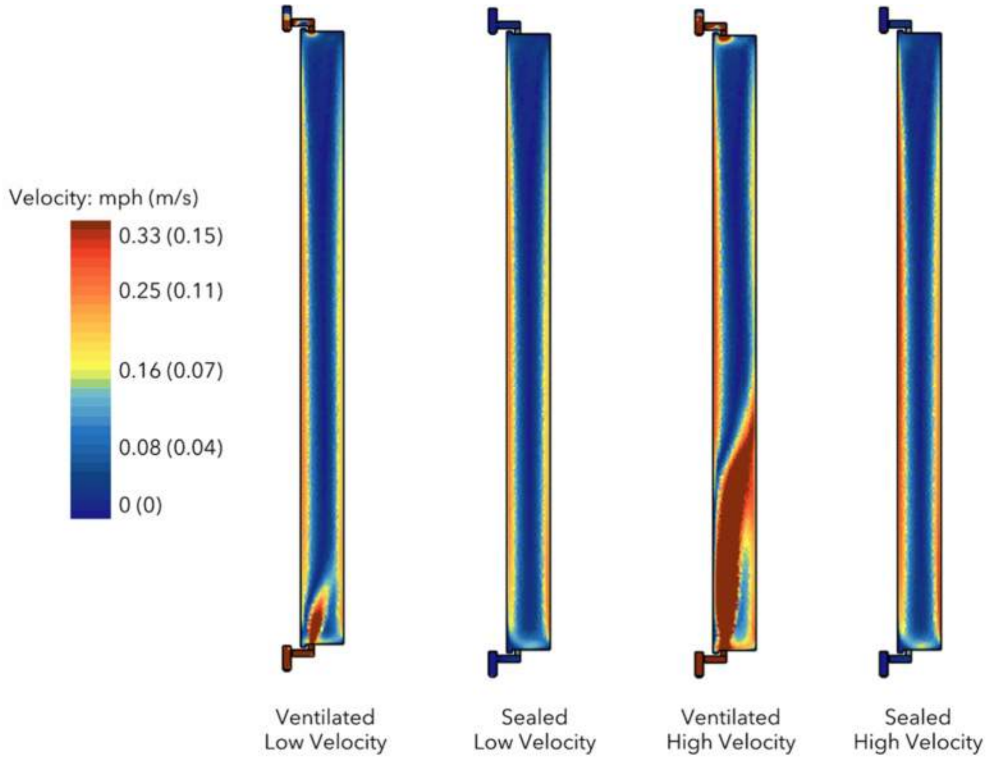


Figure 18: Spandrel Air Velocity at Vent Openings

Air Temperature

Figures 19 and 21 show the CFD simulated insulation surface temperature at the interior side of the spandrel air cavity. Figures 20 and 22 show enlarged sections through the vent openings.

Although there are discernible temperature differences at the lower vent openings, the temperature differences dissipate away from the openings, similar to the velocity results presented above. The temperature differences at the upper vent openings are less pronounced. The difference between the ventilated and sealed cases is negligible when averaged across the insulation surface.

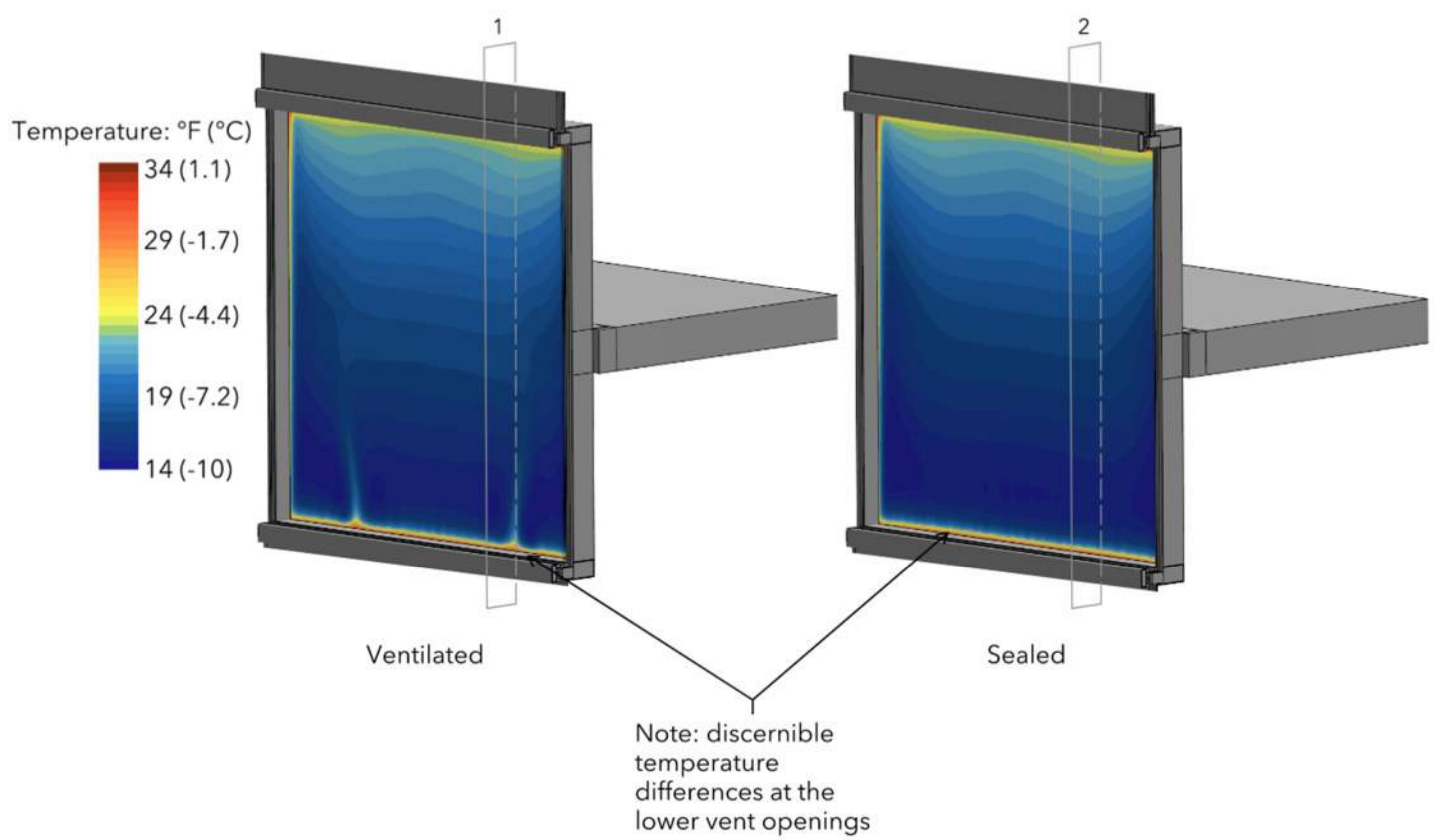


Figure 19: Temperatures at Low Air Velocity (Isometric)

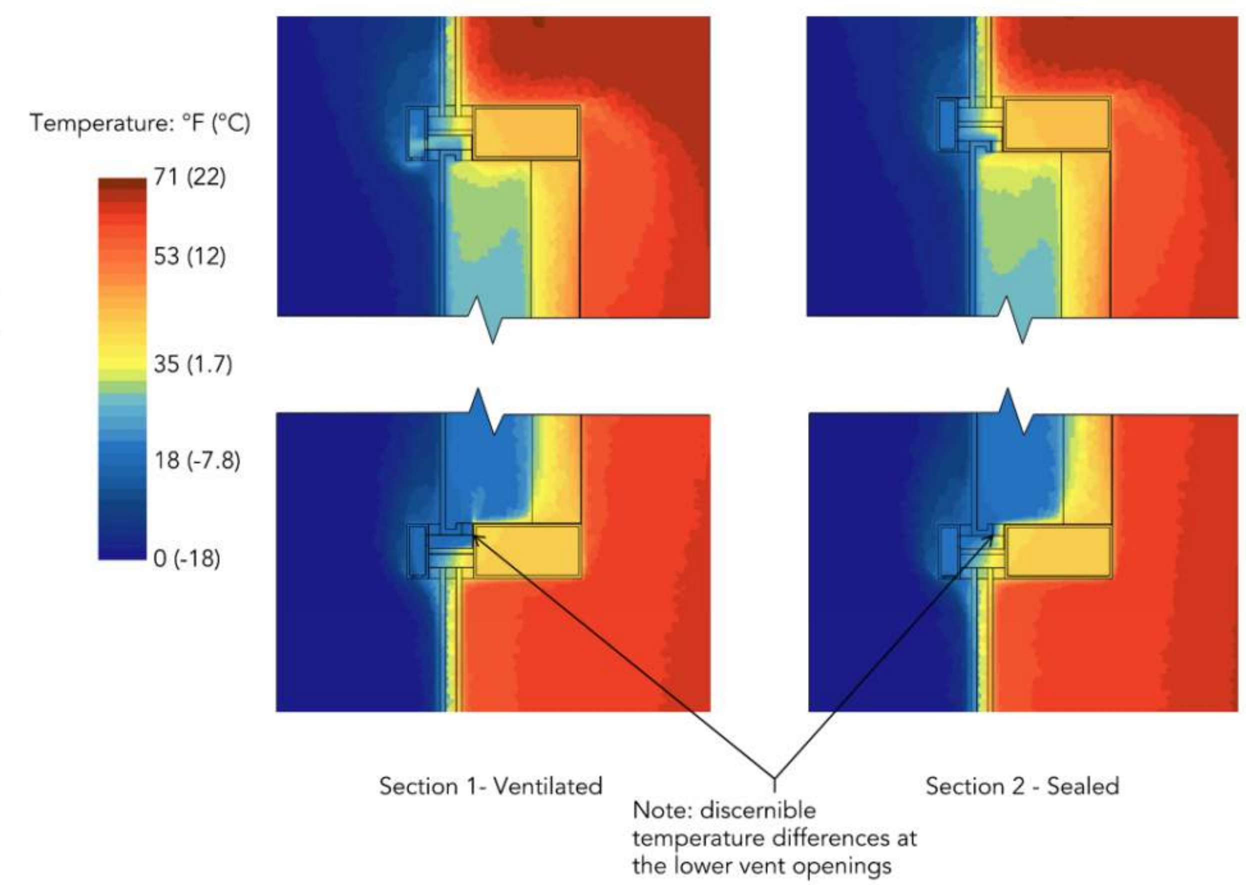


Figure 20: Temperatures at Low Air Velocity (Sections at Vent Openings)

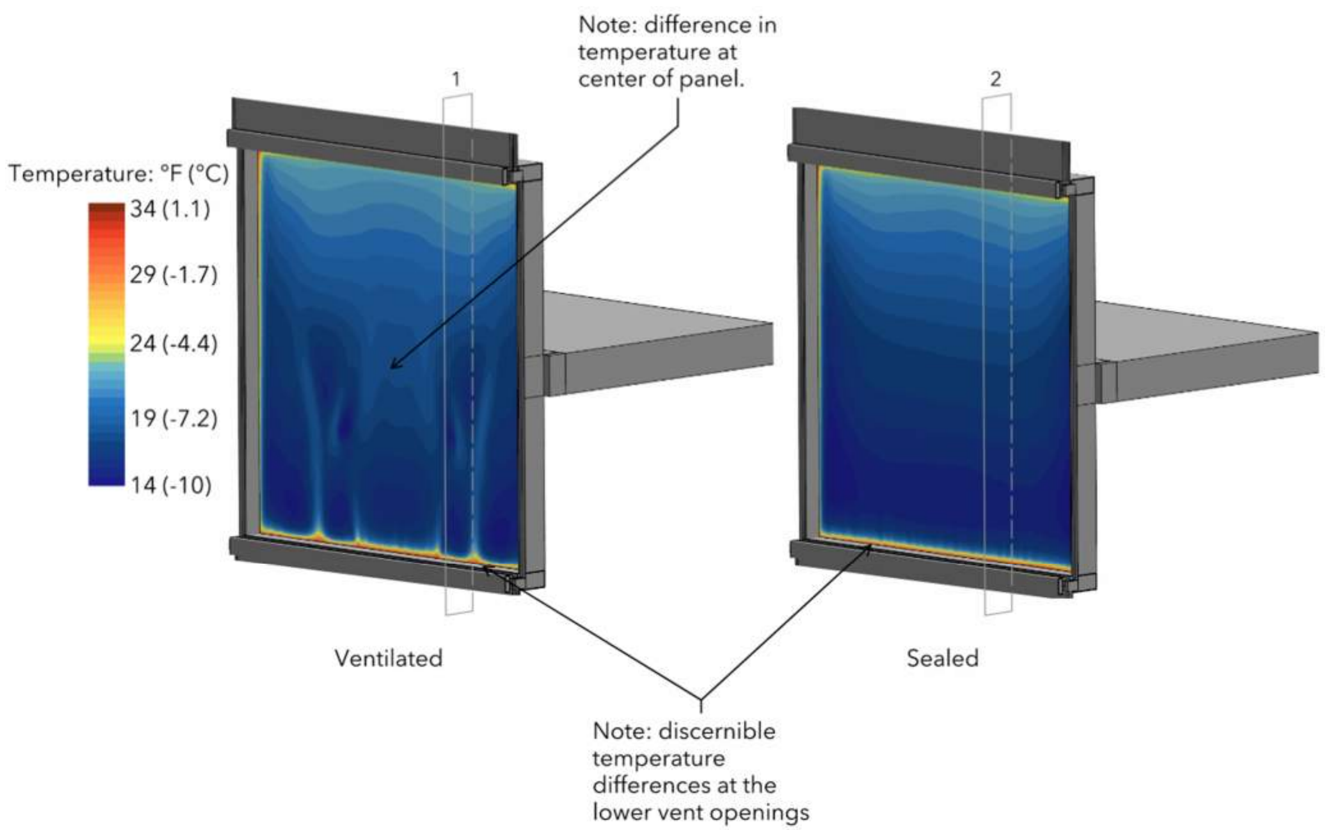


Figure 21: Temperatures at High Air Velocity (Isometric)

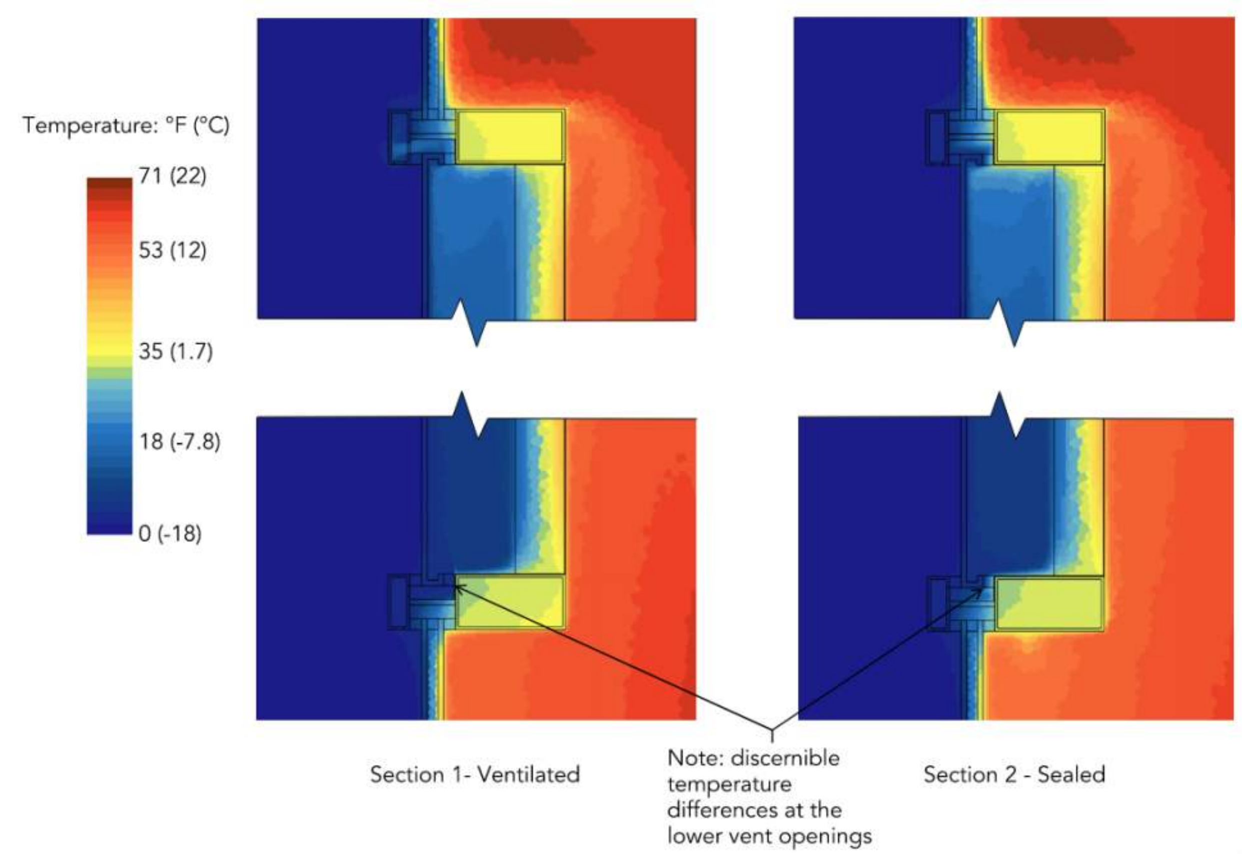


Figure 22: Temperatures at High Air Velocity (Sections at Vent Openings)

Table 4 compares the percent difference in average temperature and air velocity between ventilated and sealed cases for low and high exterior air velocity.

Table 4: Velocity and Temperature Difference Between Ventilated and Sealed Cases

Low Exterior Air Velocity	% Difference between Ventilated and Sealed Cases
Average spandrel air velocity percent difference	1%
Average spandrel air temperature percent difference	1%
High Exterior Air Velocity	**% Difference between Ventilated and Sealed Cases**
Average spandrel air velocity percent difference	1%
Average spandrel air temperature percent difference	1%

FEA vs. CFD Air Volume Temperatures

Figure 23 shows the 3D CFD simulated temperature profiles at a section through the center of the panel. The center of panel section was selected for comparison because it is where a 2D FEA thermal simulation would most closely approximate a 3D CFD simulation. Temperatures at specific points of interest on the section profile are listed in Table 5 to demonstrate the differences between the 3D CFD and 2D FEA thermal simulation results, which can vary significantly. The average temperature difference between 3D CFD and 2D FEA is 7% and 15% for the low- and high-velocity cases, respectively.

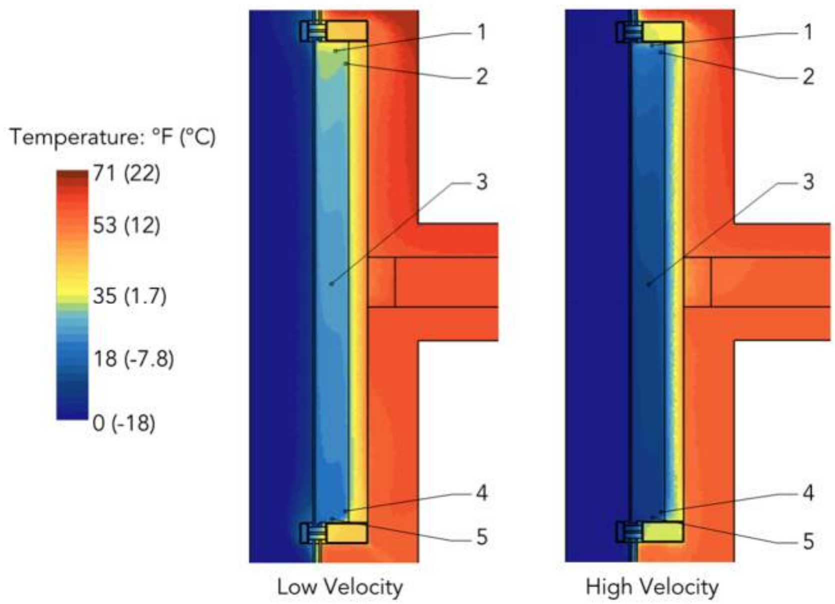


Figure 23: Temperature Probes

Table 5: Simulated 2D FEA Thermal vs. 3D CFD Air Volume Temperatures and % Difference

Location		Ventilated			Sealed		
		CFD	FEA	% Difference	CFD	FEA	% Difference
Low Velocity	Point 1	34°F (1.1°C)	31°F (-0.6°C)	9%	35°F (1.7°C)	31°F (-0.6°C)	12%
	Point 2	35°F (1.7°C)	32°F (0.0°C)	9%	36°F (2.2°C)	32°F (0.0°C)	12%
	Point 3	25°F (-3.9°C)	21°F (-15°C)	17%	25°F (-3.9°C)	20°F (-6.7°C)	22%
	Point 4	28°F (-2.2°C)	39°F (3.9°C)	33%	28°F (-2.2°C)	38°F (3.3°C)	30%
	Point 5	34°F (1.1°C)	40°F (4.4°C)	16%	34°F (1.1°C)	39°F (3.9°C)	14%
	Average	26°F (-3.3°C)	28°F (-2.5°C)	7%	26°F (-3.3°C)	28°F (-2.5°C)	7%
High Velocity	Point 1	33°F (0.6°C)	32°F (0.0°C)	3%	33°F (0.6°C)	32°F (0.0°C)	3%
	Point 2	22°F (-5.6°C)	27°F (-2.8°C)	20%	23°F (-5.0°C)	27°F (-2.8°C)	16%
	Point 3	11°F (-12°C)	5°F (-15°C)	75%	11°F (-12°C)	5°F (-15°C)	75%
	Point 4	15°F (-9.4°C)	34°F (1.1°C)	78%	16°F (-8.9°C)	33°F (0.6°C)	69%
	Point 5	22°F (-5.6°C)	36°F (2.2°C)	48%	23°F (-5.0°C)	36°F (2.2°C)	44%
	Average	12°F (-11°C)	14°F (-10°C)	15%	12°F (-11°C)	14°F (-10°C)	15%

Convective Film Coefficients

Convective film coefficients were calculated from the 3D CFD simulations at every exterior and interior vertical and horizontal surface, as shown in Table 6. Because the ANSI/NFRC 100 film coefficients are based on different velocities from what was included in the 3D CFD simulations, these values should not be directly compared.

Table 6: Convective Film Coefficients from CFD

System Type	Surface Location	Average Convective Film Coefficient BTU/hr-ft^2-°F (W/m^2-K)
Ventilated, Low Velocity	Exterior	0.71 (4.03)
	Interior, Above Slab Edge	0.51 (2.91)
	Interior, Below Slab Edge	0.71 (4.03)
Sealed, Low Velocity	Exterior	0.70 (4.00)
	Interior, Above Slab Edge	0.51 (2.91)
	Interior, Below Slab Edge	0.67 (3.82)
Ventilated, High Velocity	Exterior	4.75 (26.96)
	Interior, Above Slab Edge	0.55 (3.13)
	Interior, Below Slab Edge	0.73 (4.12)
Sealed, High Velocity	Exterior	4.71 (26.73)
	Interior, Above Slab Edge	0.55 (3.13)
	Interior, Below Slab Edge	0.71 (4.02)

The CFD-calculated convective film coefficients at the interior are different above and below the slab edge. In general, the interior convective film coefficients are higher below the slab edge than above the slab edge, and interior film coefficients are higher when calculated at the higher exterior air velocity cases.

U-factor Calculations

Table 7 shows the calculated spandrel U-factors from the 2D FEA thermal simulation software tool using convective film coefficients extracted from the 3D CFD simulation and the U-factors calculated from the CFD simulation directly. The convective film coefficients are identical in the 2D FEA thermal and 3D CFD simulations. In the 2D FEA thermal simulation cases, the FenBC procedure was applied, which uses a 6 in. edge zone, and allows for including a portion of the slab edge inboard of the spandrel assembly.

Table 7: Spandrel U-factors Using CFD Film Coefficients and FenBC Procedures

System Type	Spandrel U-factor BTU/hr-ft^2-°F (W/m^2-K) 2D FEA	3D CFD	% Difference between 2D FEA and 3D CFD
Ventilated, low velocity	0.17 (0.97)	0.16 (0.91)	6%
Sealed, low velocity	0.17 (0.97)	0.16 (0.91)	6%
Ventilated, high velocity	0.22 (1.25)	0.22 (1.25)	0%
Sealed, high velocity	0.22 (1.25)	0.22 (1.25)	0%

As expected, the low velocity cases differ from the high velocity cases, showing the impact of differing convective film coefficients. The U-factors for sealed and ventilated cases are nearly identical, whether calculated using 2D FEA thermal simulation or 3D CFD methods. The U-factors calculated via 3D CFD with airflow explicitly modeled are very similar to those calculated using the 2D FEA thermal simulation methods.

Discussion

Air Movement and Vent Openings

The simulations indicate that exterior air velocity has a significant effect on the insulation surface temperature within the spandrel cavity for both sealed and ventilated cases. In the sealed cases, although there is no air exchange between the cavity and the exterior, the convection from faster-moving exterior air cools the insulation surface. For the ventilated cases, different temperature patterns on the insulation surface emerge from vent openings; however, temperature differences dissipate away from the vent openings. The difference between the ventilated and sealed cases is negligible when averaged across the insulation surface.

When comparing the spandrel air volume average temperatures between 3D CFD and 2D FEA, the difference is 7% and 15% for the low and high velocity cases, respectively. The simulations also show that while there are velocity and temperature changes local to vent openings (up to 200% increase in velocity and 19°F [10.5°C] increase in temperature), the effects dissipate away from vent openings. There is also little to no difference in spandrel U-factors at either the high or low exterior air velocities studied. Based on the study performed, vent openings have negligible impact on spandrel assembly overall thermal performance (i.e., U-factor).

Air Volume Modeling

The air volume temperatures differ significantly between the 3D CFD and 2D FEA thermal simulations, including at the center of panel areas and particularly in the high velocity case near the bottom of the panel. If we were to compare a section of the 3D CFD simulation taken closer to the spandrel edges, then the temperature differences would be even more significant due to the increased influence of 3D heat transfer effects not captured in a 2D FEA thermal simulation.

A primary reason for differences at the center of panel section (where 3D heat transfer effects are reduced) is that the air volume properties in 2D FEA thermal simulations are diffusion-based, while the air volume properties in 3D CFD simulations account for advection. Exterior air velocity is used to derive a uniform film coefficient at the exterior surface of a 2D FEA thermal simulation. However, 2D FEA thermal simulations do not account for temperature changes due to steady-state mass flow through the vent openings whereas this is accounted for in 3D CFD simulations. Based on the study performed, there are meaningful differences between how air volumes are simulated in FEA and CFD software tools.

<u>Film Coefficients</u>

Convective film coefficients were calculated from 3D CFD simulations. Interior film coefficients vary above and below the slab edge and with exterior air velocity. Interior film coefficients are generally higher below the slab edge and when exterior air velocity is higher. This result suggests that using a single standard convection film coefficient (as indicated in industry references) does not necessarily capture all convective behavior, particularly when there are geometric interruptions to airflow such as slab edges.

It is important to note that the film coefficients from the 3D CFD simulation in this study reflect an approximation of laboratory testing conditions, not real-world interior conditions. Further study is needed to achieve more accurate film coefficients, including the impact of the interior mechanical systems. For example, a 3D CFD simulation could be developed using the same velocities as those used in ANSI/NFRC 100 as well as a range of interior air velocities to represent a range of differing mechanical systems in a building. In this study, the CFD-calculated convective film coefficients should not be compared to the standard values included in ANSI/NFRC 100 and FenBC's procedures because they were calculated at different velocities.

The CFD-calculated film coefficients were used in the 2D FEA thermal simulations to calculate U-factors and surface temperatures. These U-factors were compared to U-factors calculated from the 3D CFD simulation directly. As mentioned above, U-factor results for sealed and ventilated cases are nearly identical. Additionally, the U-factor results comparing the 2D FEA thermal simulations and the 3D CFD simulation are also nearly identical (0% to 6%). The main differences between the simulations are that the CFD simulation includes 3D geometry, models the air volume explicitly with turbulence parameters, and does not include radiative film coefficients. The impact of radiative film coefficients on spandrel thermal performance was not evaluated in this study.

This finding aligns with literature (*Ge and Fazio, 2004*) which shows that U-factors can vary by up to 20% when using default film coefficients compared to those measured in a laboratory setup. The U-factors calculated using CFD film coefficients should not be directly compared to the ANSI/NFRC 100-calculated U-factors because the film coefficients were derived using different velocities. This simulation exercise demonstrates that the industry's film coefficient assumptions and assumptions implicit to the software tool chosen significantly impact the calculated U-factors.

Summary

A set of CFD simulations were performed to evaluate the impact of airflow on spandrel panel thermal performance. Based on the results of these simulations, the following conclusions were drawn:

- Discrete vent openings in spandrel assemblies have a marginal impact on the average velocity and air temperature in the spandrel cavity and have little to no effect on the overall heat transfer across the spandrel assembly.
- Simulated spandrel cavity temperatures using 2D FEA and 3D CFD simulations differ by as much as 19°F (10.5°C), notably near vent openings.
- Interior convective film coefficients vary from floor to ceiling and are higher below the slab edge than above the slab edge. The common practice of using a single interior film coefficient does not account for such variations. In addition, the interior film coefficients vary with exterior air velocity, but is much less pronounced.
- The CFD-calculated film coefficients in this study reflect an approximation of laboratory testing conditions, not real-world conditions. They should not be compared to standard values, which are derived from different air velocities.
- Overall thermal performance (i.e., U-factors) varies minimally (0% to 6%) when calculated using 2D FEA thermal simulations versus 3D CFD simulations.

The primary differences between the 2D FEA thermal and 3D CFD simulations are the geometry simplifications, radiative film coefficients, and air volume modeling assumptions used in the FEA thermal simulations.

Different levels of convective heat transfer exist within spandrel cavities depending on exterior wind speed, but differences between ventilated and sealed panels are negligible even at high wind speeds. Therefore, spandrel panel ventilation will not be considered in the laboratory testing program and in future simulations.

Future Work

The CFD simulations in this study focused primarily on convection at two exterior air velocities. Additional study should be performed to evaluate the variability of interior convective air film coefficients based on geometric surface configurations and mechanical systems.

In addition, future work on the subject should study the effect of radiative film coefficients and solar radiation (heat flux to simulate the solar heat gain).

1.5 TEST PROGRAM

Background

The objective of the laboratory testing is to validate computer simulation methods against measured data to develop a set of simulation guidelines to evaluate the thermal performance of spandrel assemblies. The laboratory tests are designed to cover multiple systems and configurations that are intended to capture conditions typically found in the field and push the limits of current simulation methods. These configurations include the impacts of:

- Spandrel panel size.
- Adjacent assemblies (e.g., transparent vision glazing sections, non-spandrel opaque assemblies).
- Intermediate floor attachments and anchorages.
- Spandrel construction (e.g., backpan configuration, insulation type, cladding type, interior wall construction).
- Airflow around the spandrel assembly (e.g., film coefficients).

As previously mentioned in the literature review, the impact of the above factors has been missing from previous and current industry standards and research. As a result, there is little guidance on how to consider these factors when evaluating spandrel thermal performance through thermal simulations; this lack of guidance has led to confusion and improper evaluations in the industry.

The Engineering Team seeks to test both curtain wall and window wall systems with various configurations and spandrel construction components through multiple rounds of hot box testing at steady-state conditions. This section provides a list of proposed spandrel assemblies to test, an overview of the proposed test procedures, and planned layouts and variations. More details can be found in the Laboratory Testing Guideline in Appendix H. The details presented in this section and in the Laboratory Testing Guideline may be subject to change in Phase 2 of the study in coordination with the testing lab and material suppliers.

Spandrel Assembly Types

The proposed spandrel assemblies for laboratory testing encompass system types that are typically found in buildings throughout North America in current practice, as well as progressive systems that the Engineering Team anticipate will become common in the future. Table 8 includes generic curtain wall and window wall systems. Specific manufactured products for each type will be chosen in Phase 2 during the material procurement stage.

Test Article Layout

The test articles consist of curtain wall or window wall systems that are divided into five panels. These articles include four spandrel panel types, one vision panel, and an adjacent insulated steel-frame wall assembly as shown in Figure 24.

Table 8: Proposed Curtain Wall and Window Wall System Types

Description	Description
Stick-Built Curtain Wall • Thermally broken aluminum captured system. • Commonly used in industry. • Individual components installed on site.	Unitized Curtain Wall • Thermally broken aluminum structural glazed (SSG) system. • Commonly used in industry. • Prefabricated panels shipped to and assembled on site.
Window Wall (US) • Thermally broken aluminum captured system. • Supported on slab edge; mullion above and below slab. • Greater integration with intermediate floor slab, less space available for insulation leading to greater heat loss.	Window Wall (Canadian) • Thermally broken aluminum captured system. • Significant integration with intermediate floor slab (more than U.S. window wall systems). • More space for insulation outboard of slab, but still high heat loss.
Veneer System • Captured system with wood or steel mullions. • Alternative to typical curtain wall systems with potentially less heat loss. • Individual components installed on site.	Next Generation High Performance System • Industry state of the art high performance systems. • Thermally broken aluminum systems with insulation (R-40+).

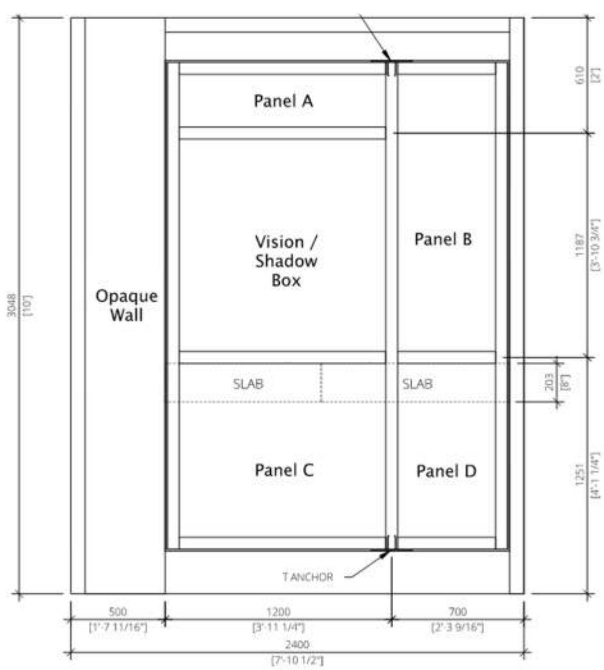


Figure 24: Test Article Layout

The test article includes a truncated intermediate concrete floor slab at Panels C and D. The floor slab will be 8 in. (203 mm) thick, 12 in. (305 mm) in depth, and span across the entire 95 in. (2,400 mm) width of the test article. It will be composed of concrete with a rigid insulation core and will be supported with a steel frame to help secure the slab to the test article as shown in Figure 25. The floor slab will help determine the impact of slab anchorages for curtain wall systems and deflection header frames for window wall systems on spandrel thermal performance.

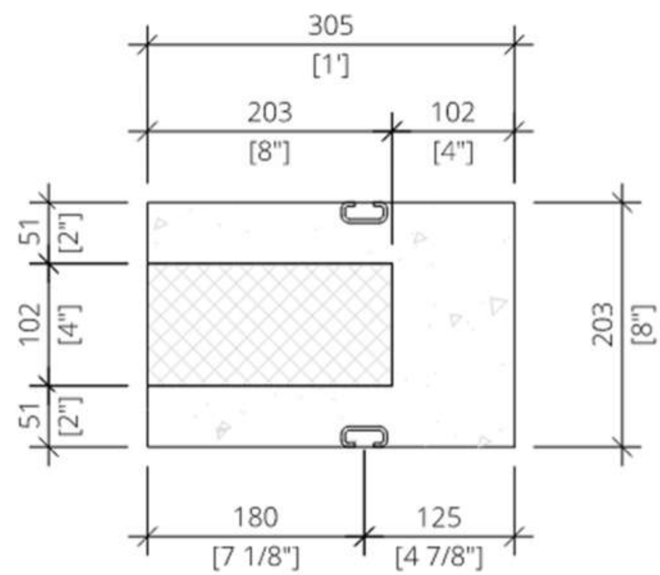


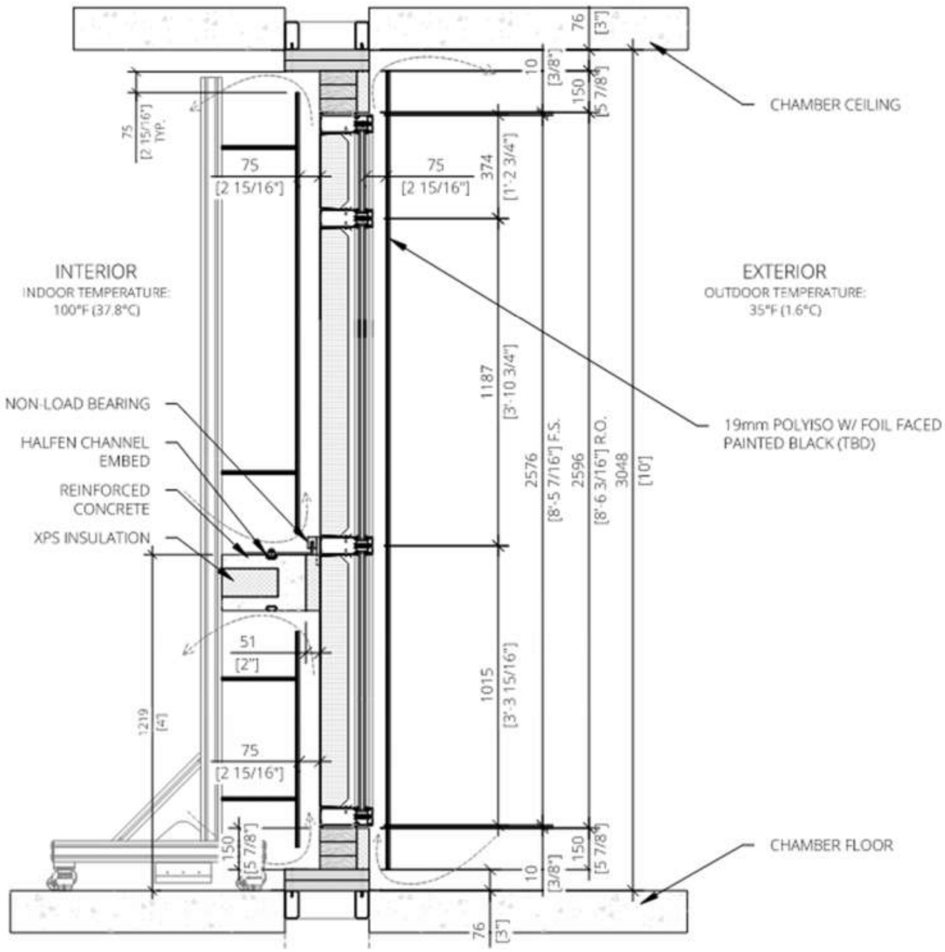
Figure 25: Intermediate Floor Slab Construction

Laboratory Test Description

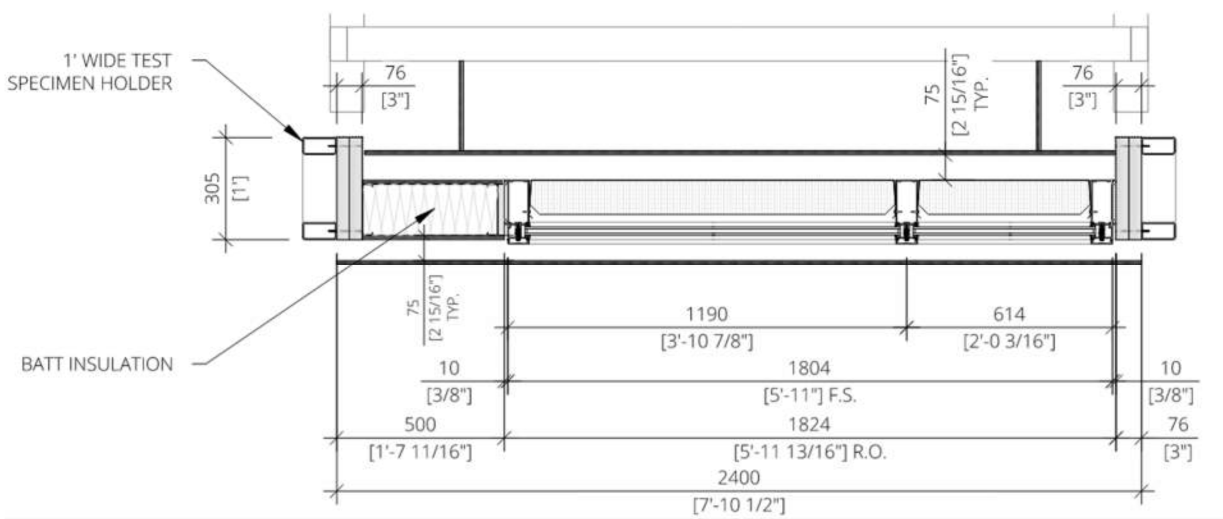
The laboratory tests will be carried out at the ORNL in Oak Ridge, Tennessee using hot box equipment capable of testing large articles at steady-state conditions as shown in Figure 26.

Temperatures at critical locations will be measured when the test articles are subjected to a temperature difference at steady-state conditions which will be used to validate thermal simulations. The test procedures will be similar to ASTM C1199 and ASTM C1363, with the exception that heat flow metering will not be required since only surface temperatures, air temperatures, and airflow around the test article will be measured. The articles will be tested at the following conditions:

- Indoor Temperature (Warm Side): 100°F (37.8°C).
- Outdoor Temperature (Cold Side): 35°F (1.7°C).
- Natural convection conditions on indoor/warm side.
- Winter wind conditions on outdoor/cold side.



Vertical Section



Horizontal Section

Figure 26: Detail of Proposed Chamber

Up to 200 temperature sensors, sensitive to 0.18°F (0.1°C) are to be installed at critical locations within the spandrel panel. The sensors will record measurements at frequent intervals (e.g., 5 to 15 minutes) to determine when a steady state is achieved. While Phase 2 of this work anticipates preliminary thermal simulations being used to inform the temperature sensor layout, Figure 27 illustrates an example layout based on the following principles:

- Measure center of panel, edge-of-panel, and frame temperatures of each unique panel.
- Measure interior temperatures at corners.
- Measure edge-of-panel temperatures at varying distances from the frame.
- Measure temperatures within the spandrel assembly.
- Locate the majority of sensors away from the baffle inlet/outlet.
- Pair interior and exterior sensors at the same elevation.

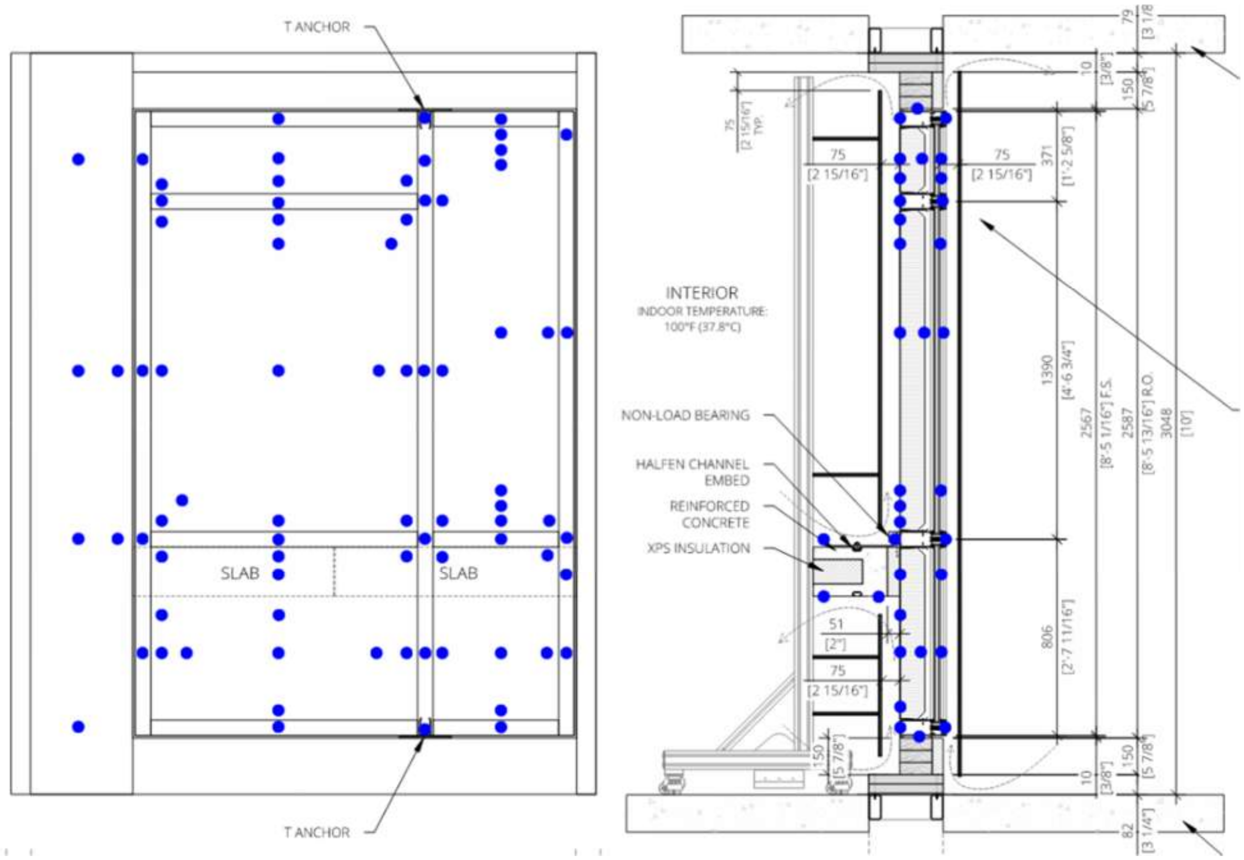


Figure 27: Temperature Sensor Layout (Sensors in Blue)

Additional sensors will be required to measure baffle temperatures and cold/warm side air temperatures to confirm chamber operation.

Airflow and air temperatures around the vision and spandrel areas will also be measured using low -velocity anemometers. These measurements will enable the calculation of localized film coefficients, which will be critical in validating measured and simulated surface temperatures of the test articles. Previous studies (*Ge 2006*) have shown significant differences between simulated and measured curtain wall temperatures when using default convection film coefficients, which can lead to underestimation of calculated U-factors by 20%.

The airflow sensor measurement locations and arrangement will be coordinated with ORNL, but air velocity and temperature measurements will be required as close as 0.04 in. (1 mm) from the surface of the vision glass and/or spandrel assembly and will cover the entire height of the test article, including at locations above and below the intermediate floor slab. The low-velocity omnidirectional anemometer should have a range of 0.03 to 3.28 ft/s (0.01 to 1 m/s).

Test Variations

To evaluate the impact of various components on spandrel thermal performance, variations to the spandrel panel construction will be made to the test articles for multiple rounds of testing. These variations will consist of discrete modifications of key components and will not impact the panel layout of all tested systems. Some of the variations considered are listed in Table 9. These individual variations or 'variables' may be combined with other modifications to form a set of 'variants' which will be made to the test article in between rounds of testing. Detailed description of the variables and variants can be found in the Laboratory Testing Guideline in Appendix H.

Table 9: List of Variables for Laboratory Testing

Component	Variable Description
Exterior Accessory	• Aluminum pressure plate for captured system. • Fiberglass pressure plate for captured system. • Deep/large cap over pressure plate.
Intermittent Thermal Bridges	• Various fastener spacing for captured system. • Horizontal or vertical solar shades. • Metal and non-metal glass chair/shim materials supporting glazing.
Spandrel Cladding	• Single-, double-, and triple-glazed. • Metal panel (sheet, ACM, insulated metal panel). • Stone/terra cotta. • Vacuum insulated glazing/vacuum insulated panel (VIG/ VIP).
Intermediate Panel	• With and without shadow box.
Backpan Configuration	• Taped foil facer. • Returned to glazing pocket (large, small). • Flat panel. • Aluminum, galvanized steel.
Backpan Insulation	• Mineral fiber. • Closed cell spray-applied polyurethane. • Foil-faced mineral fiber insulation. • Various thicknesses (1 in. [25.4 mm] to 6 in. [152.4 mm]).
Interior Wall Insulation	• Uninsulated. • Closed cell spray-applied polyurethane. • Batt insulation in stud cavity or continuous insulation behind back pan. • Foil-faced batt insulation wrapped around mullions.
Slab Anchorage	• Deflection anchor. • Non-thermally broken aluminum deflection header. • Thermally broken aluminum deflection header.
Adjacent Wall	• Interior insulated steel-frame wall. • Exterior insulated steel-frame wall with spandrel assembly not aligned to midpoint of insulation. • Exterior insulated steel-frame wall with spandrel assembly aligned to midpoint of insulation.

Schedule

Laboratory testing of the test articles and thermal simulation validation will be completed in 2023 and 2024. The exact timeline of the laboratory tests will depend on coordination with ORNL and the procurement and construction schedules of the suppliers and approved installers.

It is estimated that laboratory testing of each system will take approximately 18 working days (~30 calendar days) which includes installation and test article takedown as shown in Table 10.

Table 10: Approximate Laboratory Test Schedule for One System

Day	Description
1 and 2	Installation of Test Article
3 and 4	Instrumenting Test Article
4 through 8	Baseline Testing and Review of Results by Engineering Team
9	Modifying Article for Variant No. 1
10 and 11	Variant No. 1 Testing
12	Modifying Article for Variant No. 2
13 and 14	Variant No. 2 Testing
15	Modifying Article for Variant No. 3
16 and 17	Variant No. 3 Testing
18	Takedown Test Article

This schedule will be repeated for all six systems with some modifications to the number of variants tested. The Engineering Team also assumes testing of System No. 1 will require more time to allow for review of measurements and coordination with preliminary simulations. Following this preliminary schedule, the remaining laboratory tests should take around 90 to 108 working days.

Validation of the thermal simulations will commence after the first measurements from the laboratory are made available. It is anticipated that multiple scenarios will be evaluated as part of the validation process. Any minor changes made in the lab will be reflected in the thermal simulation models. The extent of simulations will depend on available budget. Further simulation work will be undertaken in Phase 3 of this study but it is important to capture enough data from laboratory testing to validate simulation models.

1.6 SUMMARY

The following is a brief outline of the scope and key findings in Phase 1 of the research.

Section 1.1 – Literature Review: A literature review of current studies and practices related to spandrel thermal performance.

- The Engineering Team used literature review findings to inform the development of the Test Program and to focus the research on areas where additional industry guidance is required.

Section 1.2 – Industry Survey: An industry survey to assess the prevalence of specific spandrel types and to assess the industry knowledge/expectation of spandrel thermal performance.

- The most common issues are aesthetics, condensation, and glass breakage.
- Thermal performance, code compliance, and lack of industry accepted analysis techniques are of concern.
- Methods for calculating thermal performance of spandrel assemblies vary widely.

Section 1.3 – Current State of Use: In-depth phone interviews with key industry members (e.g., glazing system designers) to identify barriers to future development of spandrels and to identify opportunities for innovation.

- Generally, knowledge of thermal modeling standards, processes, and resources specific to spandrel panels is considered very poor across the industry, even for major manufacturers.
- Most use 2D thermal simulation to assess the thermal performance of spandrel assemblies.
- Main impediments to innovation include current code language allowing less accurate 2D thermal simulation of spandrels and inconsistent enforcement of the performance documentation process.

Section 1.4 – CFD Modeling: CFD modeling to explore the effect of airflow within spandrel panels on thermal performance.

- Discrete vent openings in spandrel assemblies have marginal effect on the overall spandrel assembly U-factor. Spandrel ventilation will not be considered in the laboratory testing program and future simulations.
- Simulated spandrel cavity temperatures using 2D FEA and 3D CFD simulations differ by as much as 19°F (10.5°C), notably near vent openings.
- Interior convective film coefficients vary from floor to ceiling and are higher below the slab edge than above the slab edge. The common practice of using a single interior film coefficient does not account for such variations. In addition, the interior film coefficients vary with exterior air velocity, but is much less pronounced.

- Overall thermal performance (i.e., U-factors) varies minimally (0% to 6%) when calculated using 2D FEA thermal simulations versus 3D CFD simulations.
- The primary differences between the 2D FEA and 3D CFD simulations are the geometry simplifications, radiative film coefficients, and air volume modeling assumptions used in the 2D FEA thermal simulations.
- Additional studies should be performed to evaluate radiative film coefficients, solar radiation, and differing interior air film coefficients based on differing geometries and mechanical systems.

Section 1.5 – Test Program: Development of a laboratory testing program to validate computer simulation methods against measured empirical data to develop a set of simulation guidelines to evaluate the thermal performance of spandrels.

- The Engineering Team seeks to test both curtain wall and window wall systems with various configurations and spandrel construction components through multiple rounds of hot box testing at steady-state conditions.
- A total of six test articles and eighteen variations will be tested.
- To evaluate the impact of various factors on spandrel thermal performance, variations to the spandrel panel construction will be made to the test articles for multiple rounds of testing.

The Engineering Team has developed a detailed plan for Phase 2 in collaboration with the Research Team, Test Laboratory and Industry Champion that includes testing and modeling of the six test articles each with three variations for a total of eighteen variants. Supplementing the measurements with 2D and 3D thermal simulations will enable the development of procedures that can be universally applied, developed into standards, and adopted by codes.

Specifically, Phase 2 will include the tasks noted below:

- Test Program Specification: Prepare a "Test Program Specification Package", including drawings/details of the test articles/variants, and fabrication and testing schedule requirements.
- Pre-Construction Coordination: Coordinate with manufacturers and select final systems/materials to be tested, including coordination with the testing facility, ORNL.
- Submittals: Review manufacturer's shop drawings, product data, etc., to confirm final details of test articles prior to fabrication.
- Construction: Observe construction and instrumentation of the test articles, documenting observations.
- Testing: Collect laboratory test results and compare with 2D and 3D simulations. Prepare a summary package including relevant documentation and measurements so that independent researchers or professionals may conduct additional investigations or calibrate future 2D and 3D simulation techniques/software.

- Simulation: Construct 2D and 3D thermal simulations of select details, compare simulated and measured test results of select details.
- Report: Prepare a report of the Test Program results, the simulation calibration and validation process, and include findings for discrepancies between 2D and 3D software programs, and recommendations for modifications to calculation methodologies.
- Whole-Life Carbon Study: Construct whole-building life-cycle assessment of archetypal buildings in multiple locations and compare two test articles to determine the impacts on global warming potential. Construct whole-building energy models of the same archetypal buildings in the same locations to determine impacts on operational carbon emissions. Compare the carbon "investment" of higher performing spandrel assemblies including trade-off between high and low embodied carbon systems on operational carbon.

APPENDIX A – BIBLIOGRAPHY OF LITERATURE REVIEW

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APPENDIX B – SURVEY QUESTIONNAIRE

Thermal Performance of Spandrel Assemblies - Industry Survey

Thank you in advance for participating in this survey. The intent of these questions is to better understand the industry's perspective on the current and future role of spandrel panel systems for buildings in North America.

The survey will take approximately 15-20 minutes to complete.

This survey is part of a larger research program funded by a research grant awarded by the Charles Pankow Foundation. For more information on the research program, visit: www.pankowfoundation.org

Key Terms
Glazed Wall System: curtain wall or window wall system including glazing, frame, and spandrel components.
Effective U-value: thermal heat transmittance through glazed wall panel including center and edge of spandrel cladding and framing system.
Spandrel: opaque section of a glazed wall system (e.g., single-pane glass, insulated glazing unit, metal panel, stone, etc.)

* Required

1

Which of the following best describes your role? *

- ○ Designer (e.g., architect, engineer, consultant, specifier, construction manager, owner, etc.)
- ○ Contractor (e.g., installer, supplier, manufacturer, etc.)
- ○ Industry Organization (e.g., ASTM, NFRC, FGIA, NGA, etc.)

2

As a percentage of your projects, approximately, how often do you specify a glazed wall system (e.g., curtain wall, window wall)? *

- ◯ **Less than** 50% of work
- ◯ About 50% of work
- ◯ **More than** 50% of work
- ◯ on every job
- ◯ I do not work with glazed wall systems

3

In which of the following regions do you typically specify glazed wall systems? *(select all that apply)* *

- [ ] Climate Zone 1 - Very Hot
- [ ] Climate Zone 2 - Hot
- [ ] Climate Zone 3 - Warm
- [ ] Climate Zone 4 - Mixed
- [ ] Climate Zone 5 - Cool
- [ ] Climate Zone 6 - Cold
- [ ] Climate Zone 7 - Very Cold
- [ ] Climate Zone 8 - Subarctic
- [ ] All of the above

4

When designing a glazed wall system, what type of insulated glazing unit (IGUs) do you specify for the vision areas and approximately how often? *

	never	less than 25% of projects	25% - 50% of projects	50% - 75% of projects	greater than 75% of projects	I don't know	N/A
double-glazed with 1 low-e (surface #2 or #3)	◯	◯	◯	◯	◯	◯	◯
double-glazed with 2 low-e (#2 or #3 and #4)	◯	◯	◯	◯	◯	◯	◯
triple-glazed with 1 low-e (surface #2, #3, #4, or #5)	◯	◯	◯	◯	◯	◯	◯
triple-glazed with 2 low-e (#2 or #3, and #4 or #5)	◯	◯	◯	◯	◯	◯	◯
triple-glazed with 3 low-e (#2 or #3, and #4 or #5, and #6)	◯	◯	◯	◯	◯	◯	◯
non-air gas fills (e.g., Argon, Krypton)	◯	◯	◯	◯	◯	◯	◯
Metal box spacers (e.g., aluminum)	◯	◯	◯	◯	◯	◯	◯
Warm-edge spacers (e.g., metal composite, foam)	◯	◯	◯	◯	◯	◯	◯

5

How often do you specify the following type of glazed wall system? (Does not need to total 100%) *

	never	less than 25% of projects	25% - 50% of projects	50% - 75% of projects	greater than 75% of projects	I don't know	N/A
unitized curtain wall	○	○	○	○	○	○	○
stick-built curtain wall	○	○	○	○	○	○	○
window wall	○	○	○	○	○	○	○
Veneer system	○	○	○	○	○	○	○

6

Which type of glazing frame capture do you typically specify (*select all that apply*) *

- ☐ Structural Silicone Glazing (SSG)
- ☐ Captured (e.g., exterior pressure bar with snap cover) thermally-improved (e.g., gasket separator with discrete fasteners)
- ☐ Captured (e.g., exterior pressure bar with snap cover) thermally-broken (e.g., continuous polyamide or polyurethane thermal break)
- ☐ I don't know
- ☐ N/A

7

On average, how tall are the buildings you design? *

○ less than 5 storeys

○ 5 to 12 storeys

○ greater than 12 storeys

○ I don't know

○ N/A

8

What is a **common** percentage of glazed wall system (incl. vision and spandrel) vs. other exterior wall assemblies on your projects? Other exterior wall assemblies could include framed (e.g., wood, steel) cavity/rainscreen exterior wall assemblies or barrier exterior wall assemblies (e.g., precast concrete, mass masonry) *

- ◯ less than 20% glazed wall system
- ◯ 20% to 40% glazed wall system
- ◯ 40% to 60% glazed wall system
- ◯ 60% to 80% glazed wall system
- ◯ 80% to 100% glazed wall system
- ◯ I don't know
- ◯ N/A

9

What percentage of this glazed wall area is spandrel (i.e., remaining percentage is vision area)? *

- less than 20% spandrel
- 20% to 40% spandrel
- 40% to 60% spandrel
- 60% to 80% spandrel
- 80 to 100% spandrel
- I don't know
- N/A

10

What R-value ($ft^2 \cdot °F \cdot hr/BTU$) are you typically specifying for spandrels **today**? *

- [ ] less than R-3
- [ ] R-3 to R-5
- [ ] R-5 to R-7
- [ ] R-7 to R-10
- [ ] R-10 to R-15
- [ ] R-15 to R-20
- [ ] greater than R-20
- [ ] I don't know
- [ ] N/A

11

What R-value ($ft^2 \cdot °F \cdot hr/BTU$) do you anticipate specifying / will be required by energy codes for spandrels **by 2030**? *

- [ ] less than R-3
- [ ] R-3 to R-5
- [ ] R-5 to R-7
- [ ] R-7 to R-10
- [ ] R-10 to R-15
- [ ] R-15 to R-20
- [ ] R-20 to R-25
- [ ] R-25 to R-30
- [ ] greater than R-30
- [ ] I don't know
- [ ] N/A

12

Given that many energy codes (e.g., IECC, ASHRAE 90.1) do not include prescriptive U-factors for spandrels specifically, how do you typically take into account thermal performance of spandrels on your project? *

- ◯ I and/or my consultant/engineers assume the spandrel will meet the prescriptive thermal requirements (e.g., U-factor) of an "exterior wall above grade, metal-framed".
- ◯ I and/or my consultant/engineers assume the spandrel will meet the prescriptive thermal requirements (e.g., U-factor) of "fenestration".
- ◯ I and/or my consultant/engineers calculate spandrel thermal performance based on 1-D analysis (e.g., hand calculation)
- ◯ I and/or my consultant/engineers calculate spandrel thermal performance based on project-specific spandrel sizes and in general conformance with NFRC-100 requirements (e.g., area-weighted average of components, but I modify NFRC-defined 2-1/2" wide edge zone to something greater, such as 6" utilizing 2-D finite element modelling software (e.g., THERM by LBNL).
- ◯ I and/or my consultant/engineer calculate spandrel thermal performance based on project-specific spandrel sizes utilizing 3-D finite element model software (e.g, Heat 3, ANSYS)
- ◯ I and/or my consultant/engineer rely on published manufacturer's data for area-weight average spandrel U-factors
- ◯ I don't know
- ◯ N/A

13

How likely are you to specify spandrel panels on your next project? *

0	1	2	3	4	5	6	7	8	9	10

Not at all likely — Extremely likely

14

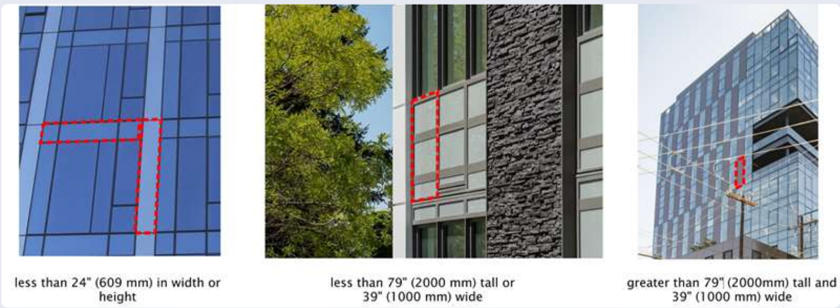
How likely are you to specify a larger relative spandrel area on your next project?
*

0	1	2	3	4	5	6	7	8	9	10

Not at all likely   Extremely likely

15

What is the average dimension of the spandrels you typically have on your projects? *



- [ ] less than 24" (609 mm) in width or height
- [ ] less than 79" (2000 mm) tall or 39" (1000 mm) wide
- [ ] greater than 79' (2000mm) tall and 39" (1000 mm) wide
- [ ] All of the above
- [ ] I don't know
- [ ] N/A

16

What are your reasons for choosing spandrels compared to another opaque exterior wall assembly (e.g., steel-framed wall)? *(select all that apply)* *

- [ ] speed/constructibilty
- [ ] aesthetics (e.g., visual continuity of spandrel to vision glass)
- [ ] thermal performance
- [ ] All of the above
- [ ] N/A
- [ ] Other

17

Do you specify vented, drained or fully sealed spandrel panels? *(select all that apply)* *

- [ ] vented (openings at top & bottom)
- [ ] drained (opening at bottom)
- [ ] fully sealed
- [ ] I don't know
- [ ] N/A

18

Which spandrel panel **claddings** do you typically specify? *(select all that apply)* *

- [ ] single-glazed with opaque coating (e.g., flood-coat of ceramic frit, opacifying frit)
- [ ] single-glazed shadow box (i.e., transparent glass with metal panel behind)
- [ ] IGU with opaque coating
- [ ] IGU shadow box (i.e., transparent glass with metal panel behind)
- [ ] metal panel (e.g., aluminum plate, aluminum composite material ACM, insulated metal panel)
- [ ] other opaque cladding (e.g., stone, terracotta, GFRC)
- [ ] I don't know
- [ ] N/A

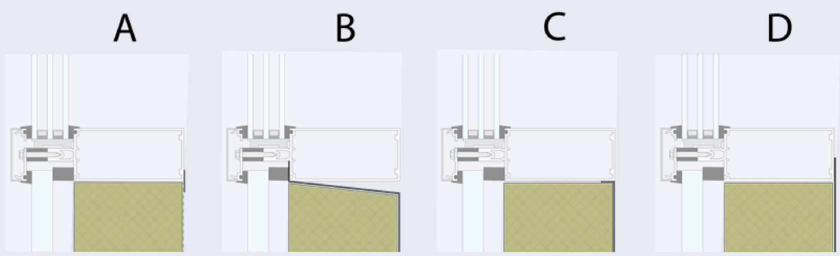
19

What **insulation** do you typically specify in the spandrel back pan? *(select all that apply)* *

- [ ] semi-rigid mineral wool
- [ ] fiberglass or mineral wool batt
- [ ] rigid foam board (e.g., XPS, EPS)
- [ ] spray-applied foam
- [ ] Insulated metal panels
- [ ] vacuum-insulated-panels (VIPs)
- [ ] Aerogel
- [ ] I don't know
- [ ] N/A
- [ ] Other

20

Which style of spandrel back pan is most common on your projects? *(select all that apply)* *



- [ ] A (no back pan - taped foil-faced insulation)
- [ ] B (metal back pan nested in shoulder)
- [ ] C (metal back pan sealed to mullion - with return)
- [ ] D (metal back pan sealed to mullion - overlapping)
- [ ] I don't know
- [ ] N/A

21

Are you aware of any thermal performance requirements for spandrel assemblies which are different from transparent glazing? For example, different R-value targets or simulation/testing methods? *(If yes, please include it in the 'Other' option)* *

- [ ] Yes
- [ ] No
- [ ] I don't know
- [ ] N/A
- [ ] Other

22

Based on currently available technologies, what do you think is the highest R-value a spandrel panel can achieve on its own (i.e., without insulation in interior cavity wall)? *

- less than R-3
- R-3 to R-5
- R-5 to R-7
- R-7 to R-10
- R-10 to R-15
- R-15 to R-20
- R-20 to R-25
- R-25 to R-30
- greater than R-30
- I don't know
- N/A
- Other

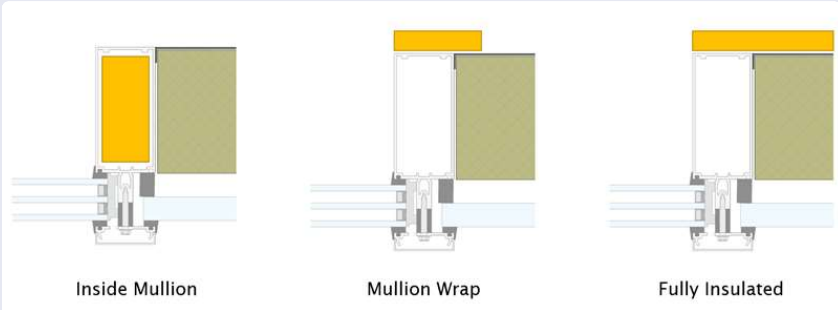
23

Do you typically specify insulation behind your spandrel panel? *

- ◯ Yes
- ◯ No
- ◯ I don't know
- ◯ N/A

24

How often, if ever, do you specify insulation outside of the backpan? Insulation could include an insulated framed back-up wall or direct applied insulation. *



	never	sometimes	always	I don't know
insulation within mullions	◯	◯	◯	◯
mullion wrap	◯	◯	◯	◯
full interior insulation	◯	◯	◯	◯

25

If available, would you use 3-D thermal simulation results over 2-D? *

- Yes
- No
- I don't know
- N/A

26

How accurate do you expect thermal simulation results (e.g., 2-D or 3-D finite element analysis) of spandrel to be when compared to physical testing? *

- less than 5% error
- less than 10% error
- less than 15% error
- less than 20% error
- I don't know
- N/A

27

What percentage of your projects do you have fins, sunshades or other exterior attachments with your glazed wall system? (*select all that apply*) *

	never	less than 25% of projects	25% - 50% of projects	50% - 75% of projects	greater than 75% of projects	I don't know	N/A
Fins	◯	◯	◯	◯	◯	◯	◯
Shades	◯	◯	◯	◯	◯	◯	◯
Other	◯	◯	◯	◯	◯	◯	◯

28

Which of the following issues, if any, have you experienced with spandrel panels? *(select all that apply)* *

- [ ] condensation (within spandrel unit)
- [ ] condensation (on interior surfaces)
- [ ] glass breakage
- [ ] water leakage
- [ ] air leakage
- [ ] aesthetic issues (e.g., dirt, streaking, condensation, hand-prints visible in shadow boxes)
- [ ] Fire performance issues
- [ ] N/A
- [ ] Other

29

Have you ever decided to use/not use spandrels and/or spandrel types (e.g., glass, opaque) based on glazed wall systems used on your projects? *

- ◯ No, the glazed wall system doesn't affect my spandrel choices
- ◯ Yes, if I have a fiend-installed system (e.g., stick-built curtain wall), I tend to select opaque spandrels over transparent spandrels (e.g., shadow boxes), whereas if I have shadow boxes, I tend to specify a factory/fabricated system (e.g., unitized curtain wall or window wall).
- ◯ I don't know
- ◯ N/A

30

What are concerns, if any, would prevent you from using spandrel panels on your next project? *(select all that apply)* *

- [ ] spandrel panel failures (e.g., condensation, glass breakage, water ingress, etc.)
- [ ] thermal performance
- [ ] cost
- [ ] availability
- [ ] embodied carbon
- [ ] combustibility
- [ ] N/A
- [ ] Other

31

What are some of the greatest challenges or concerns (technical or otherwise) you are facing with spandrels on your projects today? Challenges may include code issues, design difficulties, etc. *

32

Do you see any barriers preventing innovation of spandrels to achieve higher performance? (*select all that apply*) *

- [ ] Lack of industry accepted analysis techniques
- [ ] Cost of development
- [ ] Lack of testing
- [ ] Insufficient market demand for higher performing products
- [ ] Cost of current materials/solutions
- [ ] Industry Education
- [ ] Lack of enforcement of labeling requirements
- [ ] N/A
- [ ] Other

33

What factors would most likely lead you to want to see advances in spandrel panel design? (*select all that apply*) *

- [ ] Prescriptive Building or Energy Code requirements for higher R-values
- [ ] Sustainability goals
- [ ] Market Position
- [ ] Improved durability
- [ ] Lower liability
- [ ] Improved fabrication techniques/quality control
- [ ] N/A
- [ ] Other

34

Do you ask for documentation to support the manufacturer's reported spandrel U-value? (*select all that apply*) *

- [ ] yes - NFRC Label or Label Certificate
- [ ] Yes - simulation report
- [ ] Yes - manufacturer's datasheet or catalogue
- [ ] no documentation required (code default or tabulated U-value)
- [ ] I don't know
- [ ] N/A

35

If you would be interested/willing to discussing your answers to this survey and/or spandrels in greater detail with our research team further, please provide your name, company and phone number in 'Other' option. *

- [ ] Other

36

What questions, if any, do you have regarding spandrel performance? *

37

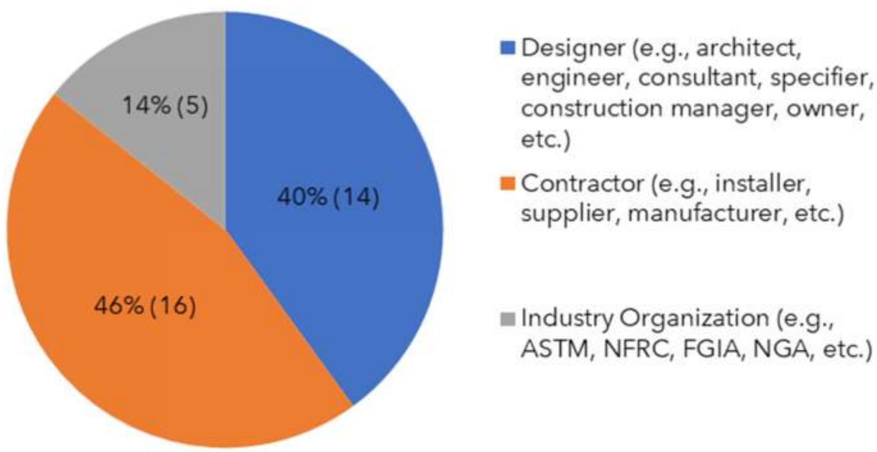
Is there anything else you'd like to share? *

APPENDIX C – EXTENDED SURVEY RESULTS

Question numbers are included herein in parentheses and reference questions listed in Appendix B. For example, Q1 is Question 1 in Appendix B.

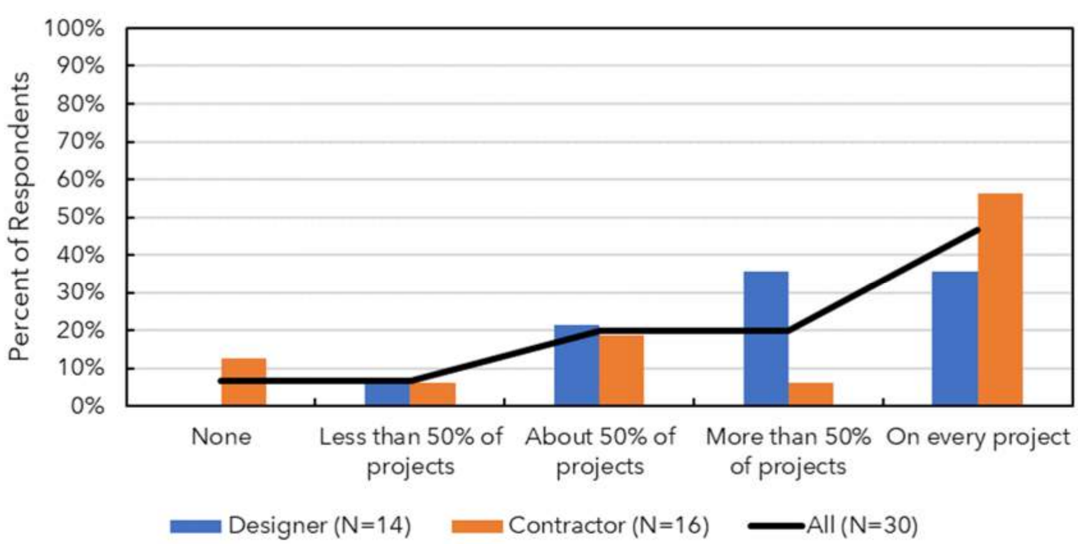
Surveyed Industry Professionals

- Thirty-five industry professionals were surveyed in various roles, including fourteen Designers, sixteen Contractors, and five representatives from Industry Organizations. (Q1)

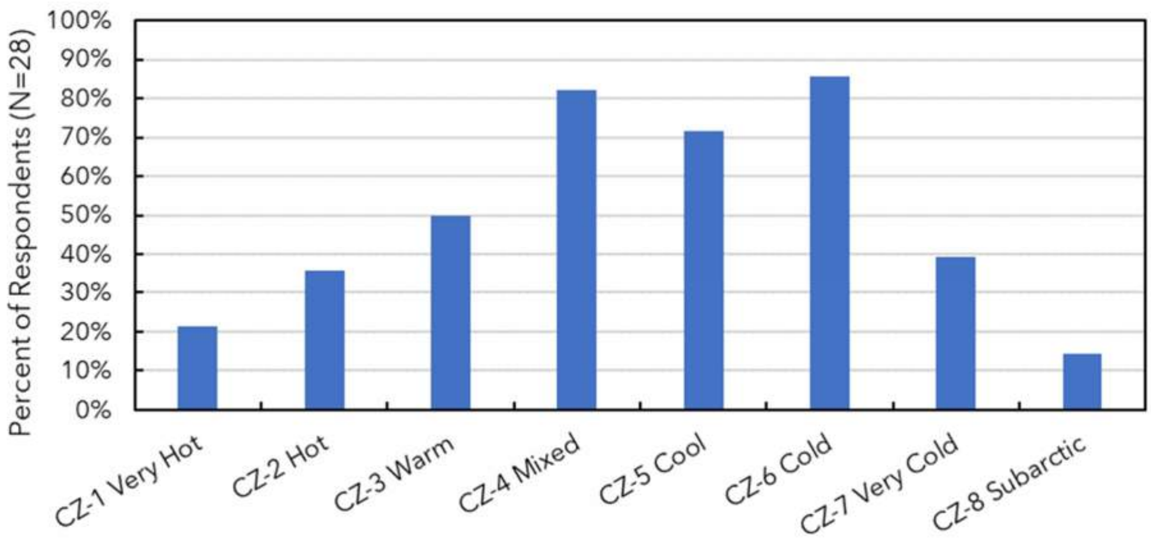


Prevalence of Glazed Wall Systems

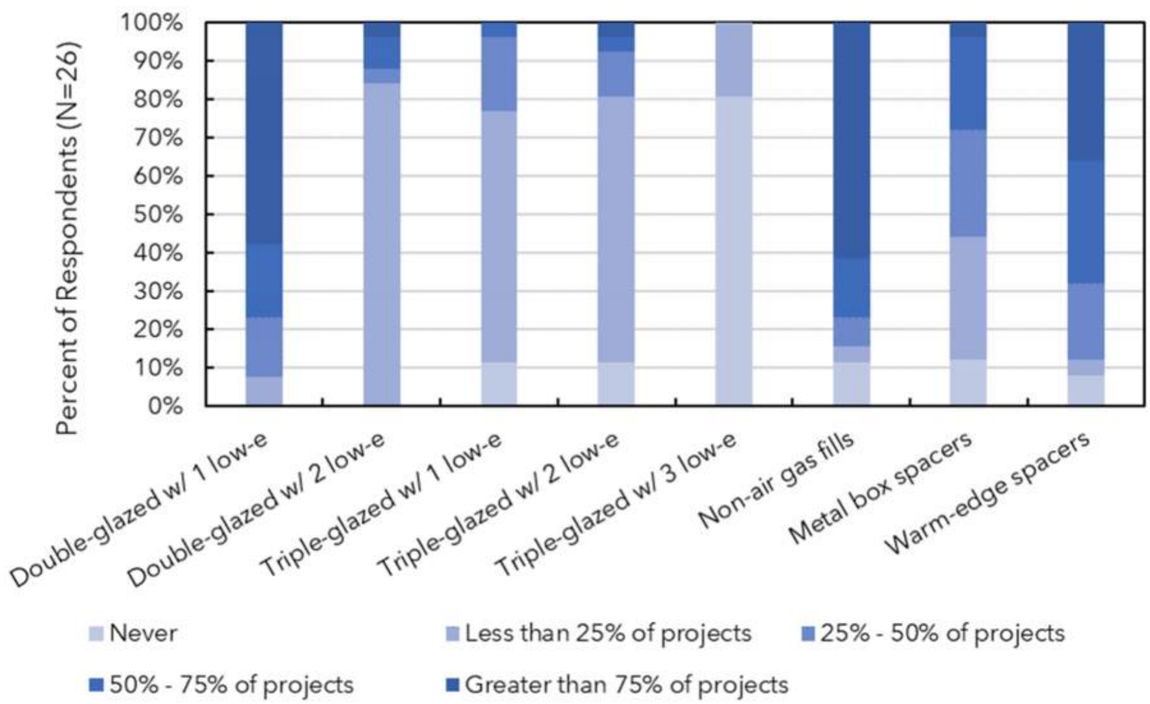
- About 90% of Designers and Contractors specify/install a glazed wall system in half or more of their projects, reflecting the prevalence of glazing systems in modern construction. (Q2+3)

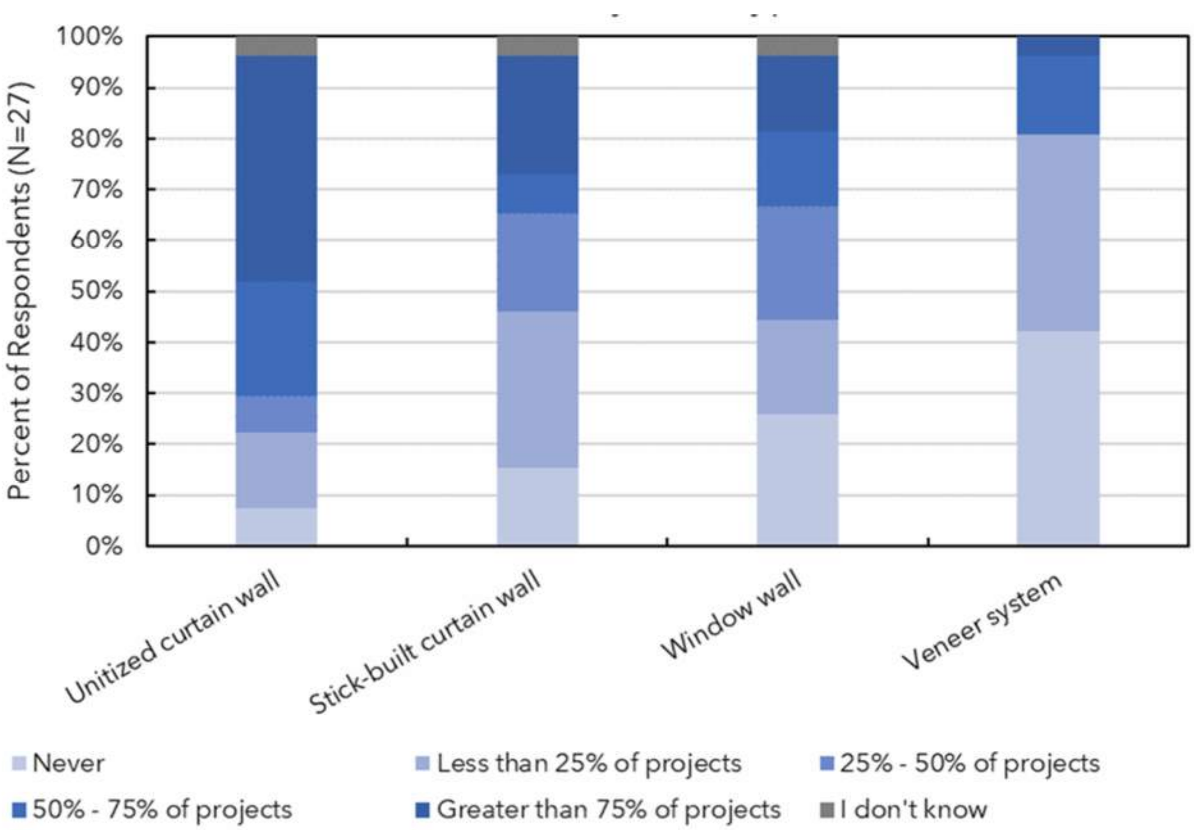


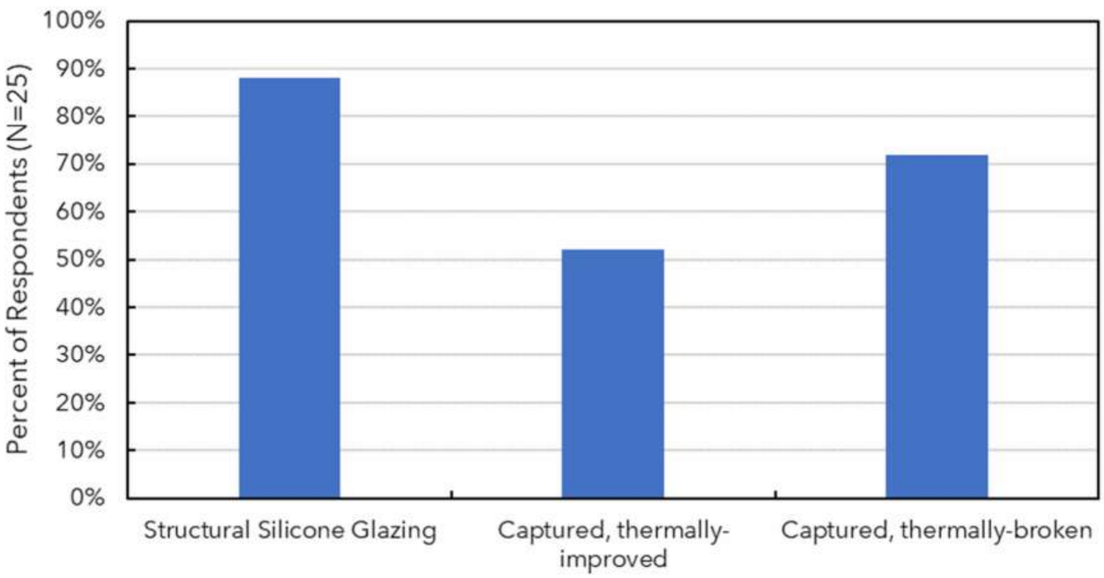
- Glazed wall systems are used in all eight ASHRAE Climate Zones (CZs), with most respondents having projects located in CZ-4 (mixed) and CZ-6 (cold) regions. However, this distribution may be reflective of the locations of the respondents, and not only of where glazed wall systems are most commonly used.



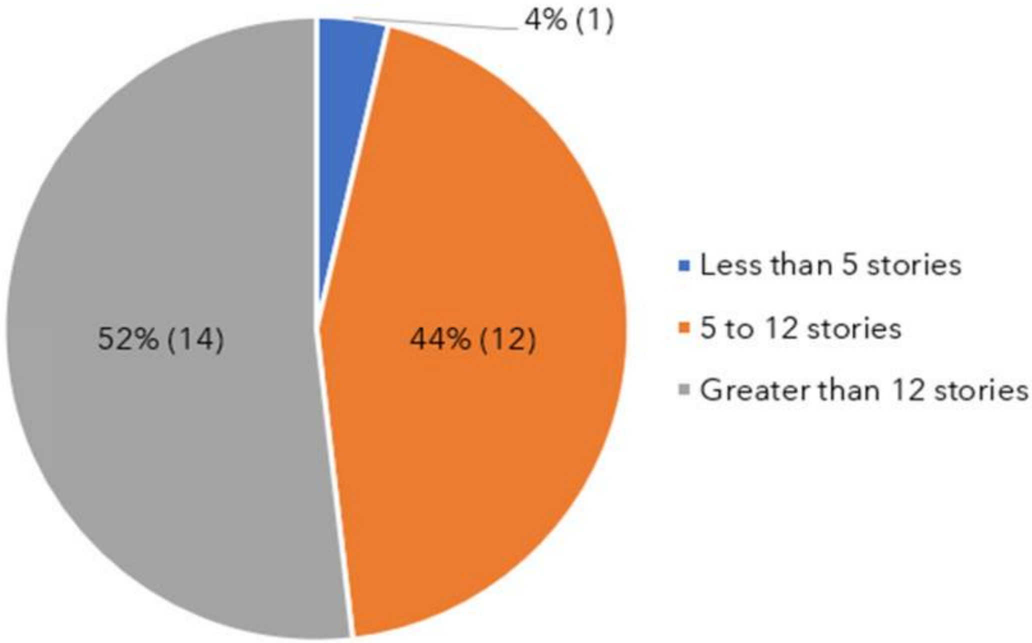
- The most common glazing type for the adjacent vision areas is double-glazed IGUs with low-e coating on one surface, non-air gas (e.g., argon) fill, and warm-edge spacers. (Q6+7) Unitized curtain wall is the most common type of glazed wall construction among the respondents. About half of the Contractors never work with window wall or veneer systems; whereas most of the Designers work with window walls on 25% to 50% of their projects and veneer systems on less than 25% of their projects. (Q8+9) The most typical glazing frame capture is structural silicone glazing, followed by thermally broken frames and thermally improved frames. (Q10+11)



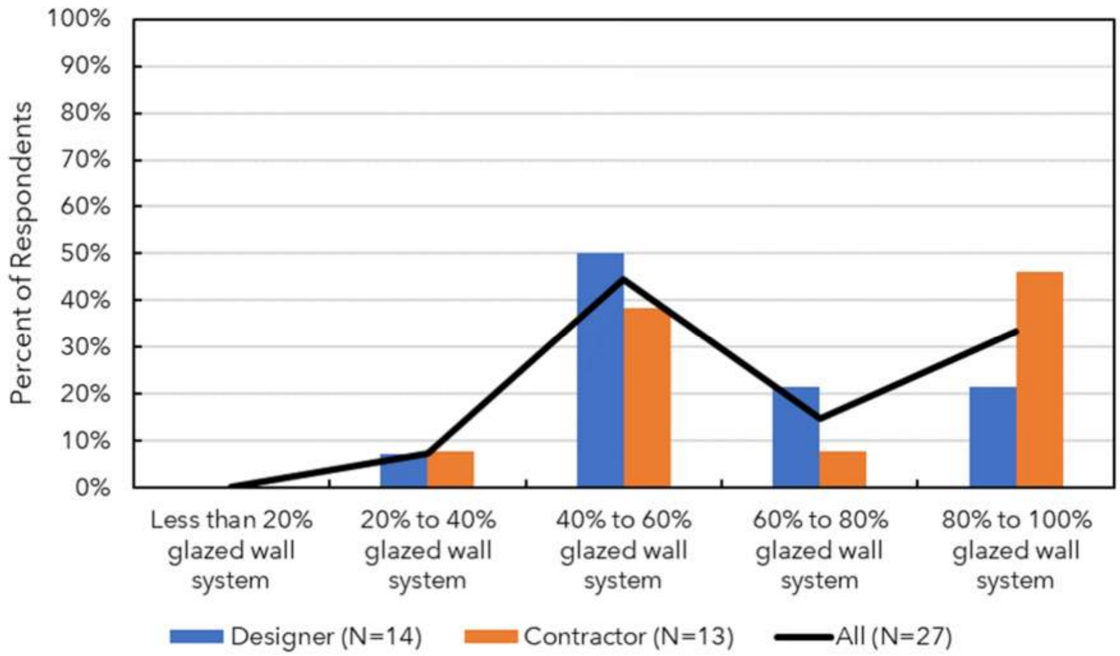

100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Percent of Respondents (N=27)
Unitized curtain wall
Stick-built curtain wall
Window wall
Veneer system
Never
Less than 25% of projects
25% - 50% of projects
50% - 75% of projects
Greater than 75% of projects
I don't know

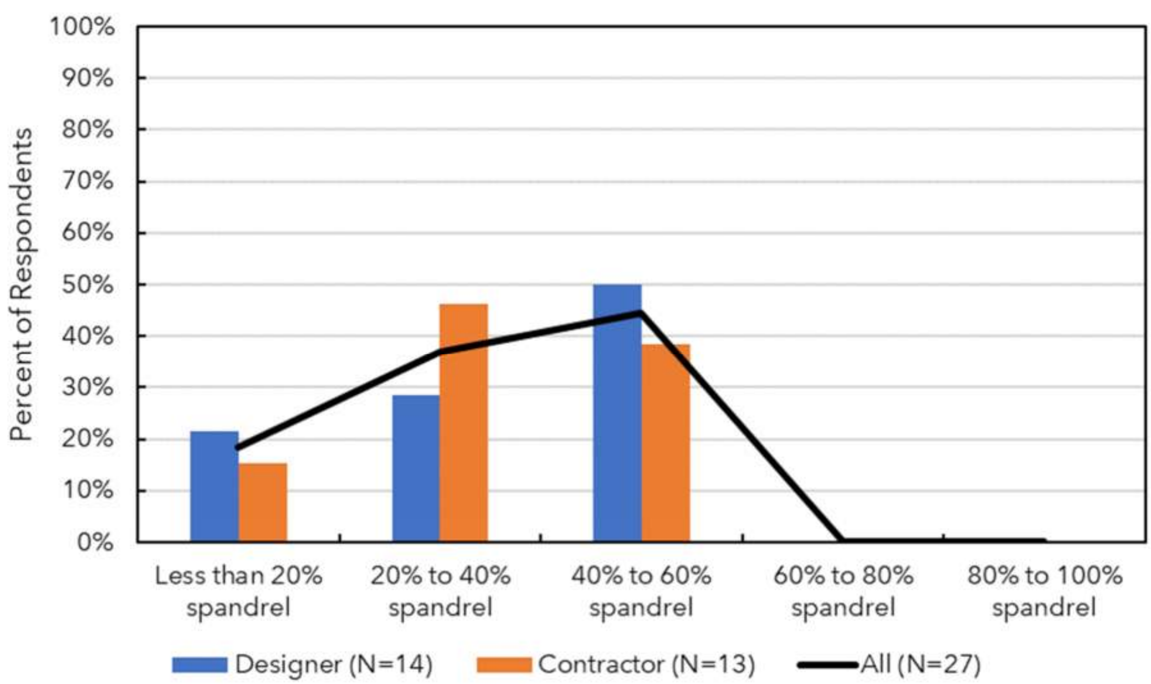

100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Percent of Respondents (N=25)
Structural Silicone Glazing
Captured, thermally-improved
Captured, thermally-broken

- The most common average height of the respondents' projects which utilize glazed wall systems is greater than twelve stories, followed by five to twelve stories. Only one respondent works with glazed systems on buildings that are less than five stories on average. This shows that glazed systems are almost exclusively used on mid- to high-rise buildings. However, it should be noted that the results may be influenced by the type of projects that the respondents work on, for example, single-family homes may not have Designers' involvement. (Q12+13)



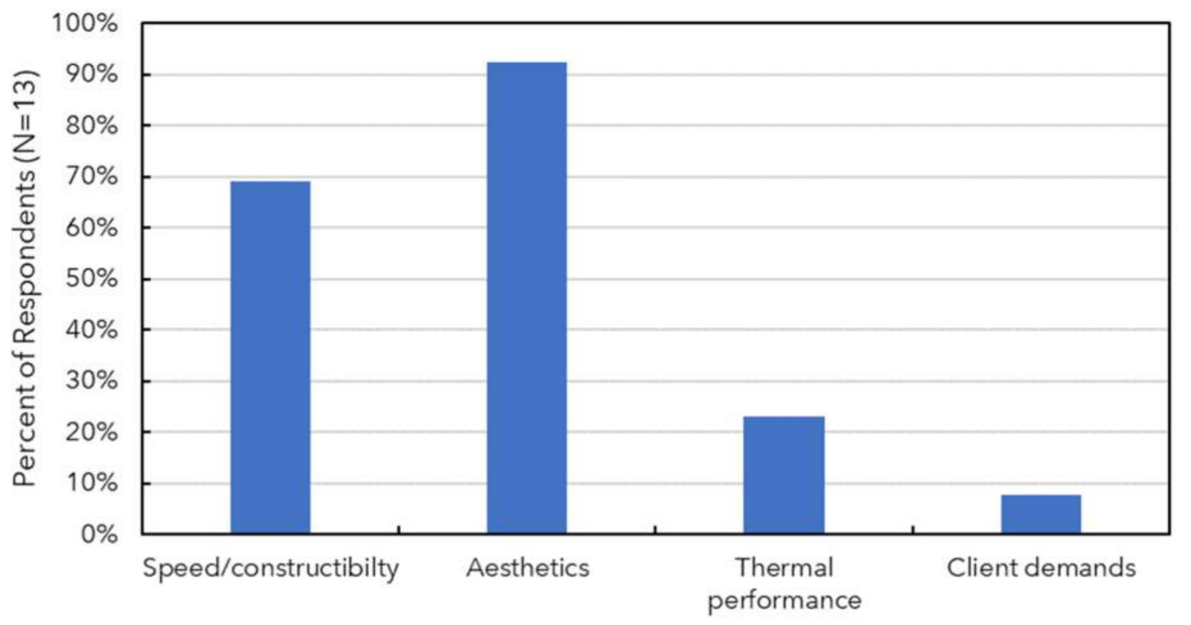
- The percentage of glazing area at exterior walls is typically between 40% to 60% for the Designers, versus between 80% to 100% for Contractors. In general, glazing systems account for more than half of the exterior wall area in most projects. Of the glazed areas, spandrel assemblies account for 40% to 60% for most projects. (Q14+15) Of the glazed areas, spandrel assemblies account for 40% to 60% for most projects. (Q16+17)

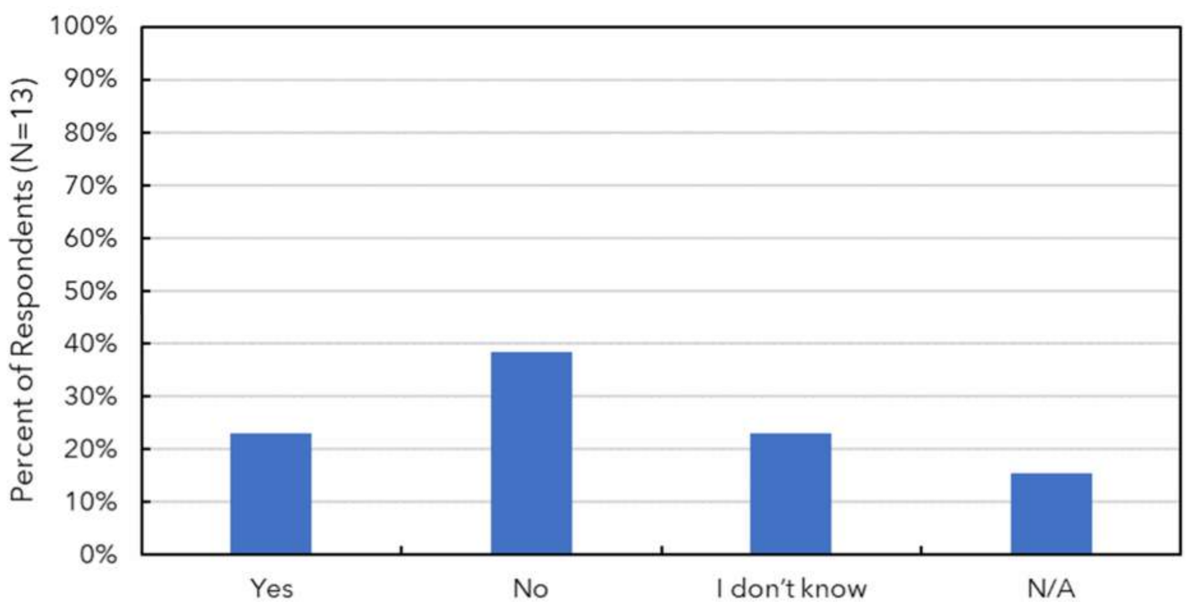


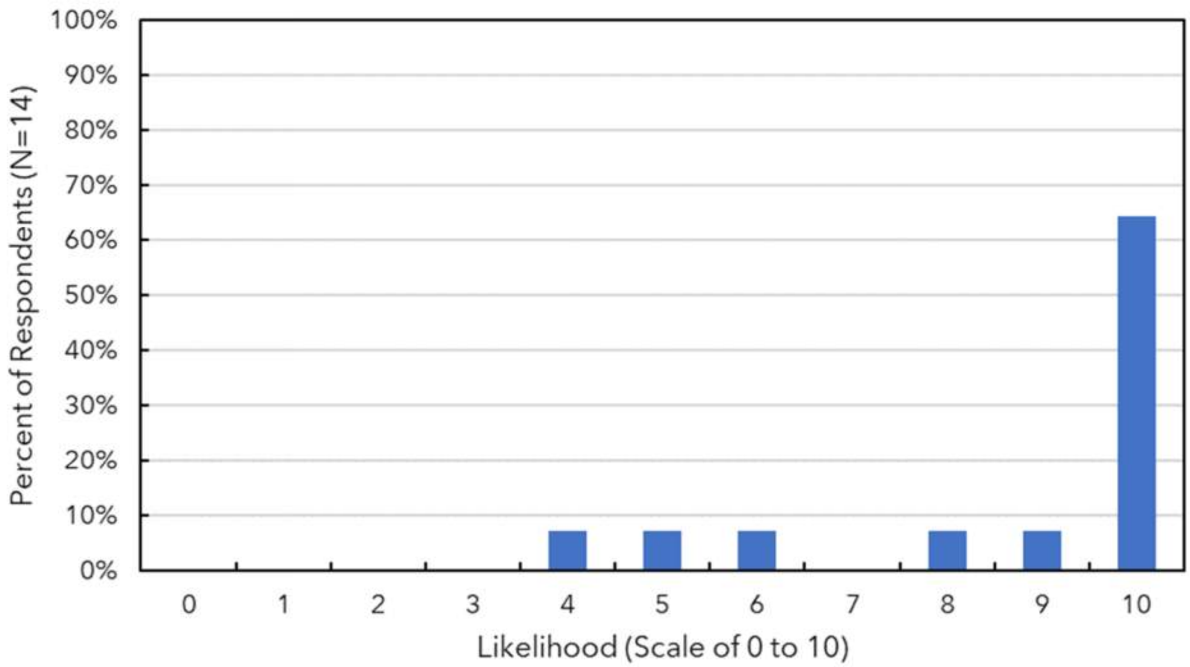


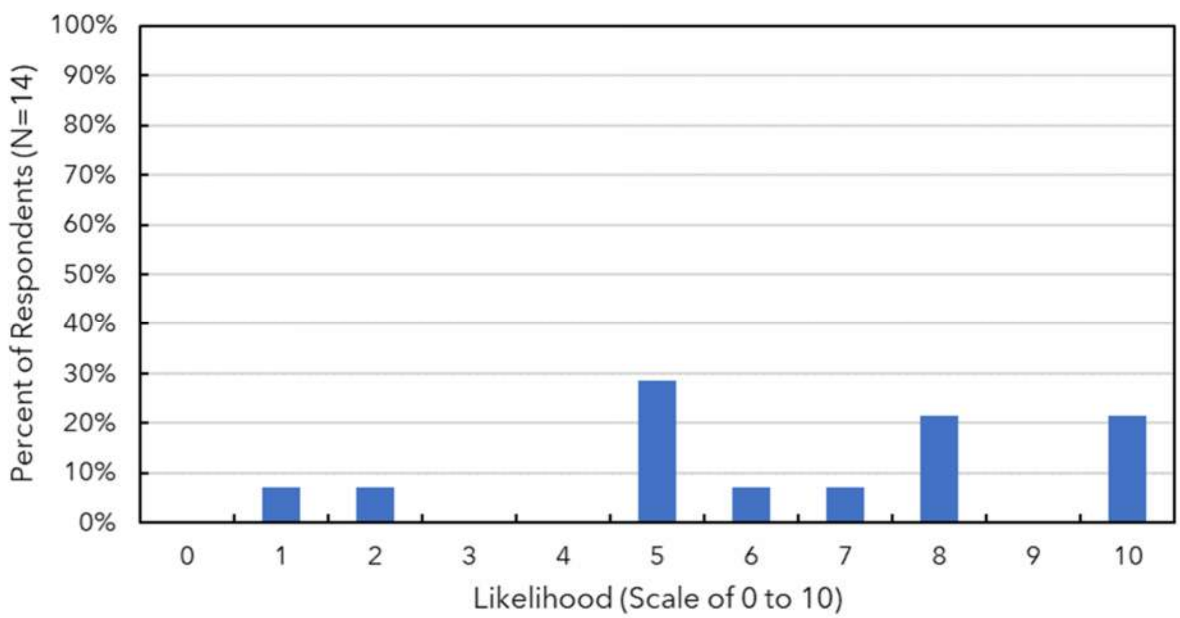
Prevalence of Spandrel Panels and Common Characteristics

- Almost all of the Designers (twelve out of thirteen) said that they chose spandrels for aesthetic reasons, followed by their speed/constructability. (Q28) Most of the Designers indicated that they will very likely specify spandrel panels on their next projects, (Q58) but there is less agreement on the expected relative proportion of spandrel areas in these future projects. (Q24) More than one third of Designers indicated that their decision on spandrel use is independent of the glazed wall systems used on their projects. (Q25)

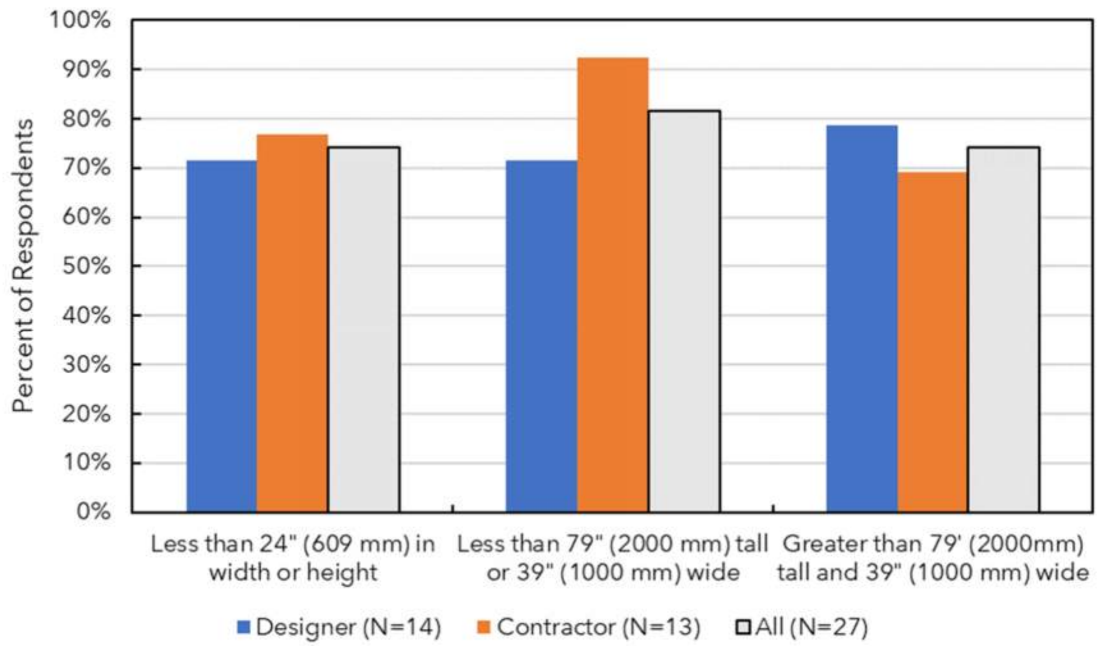




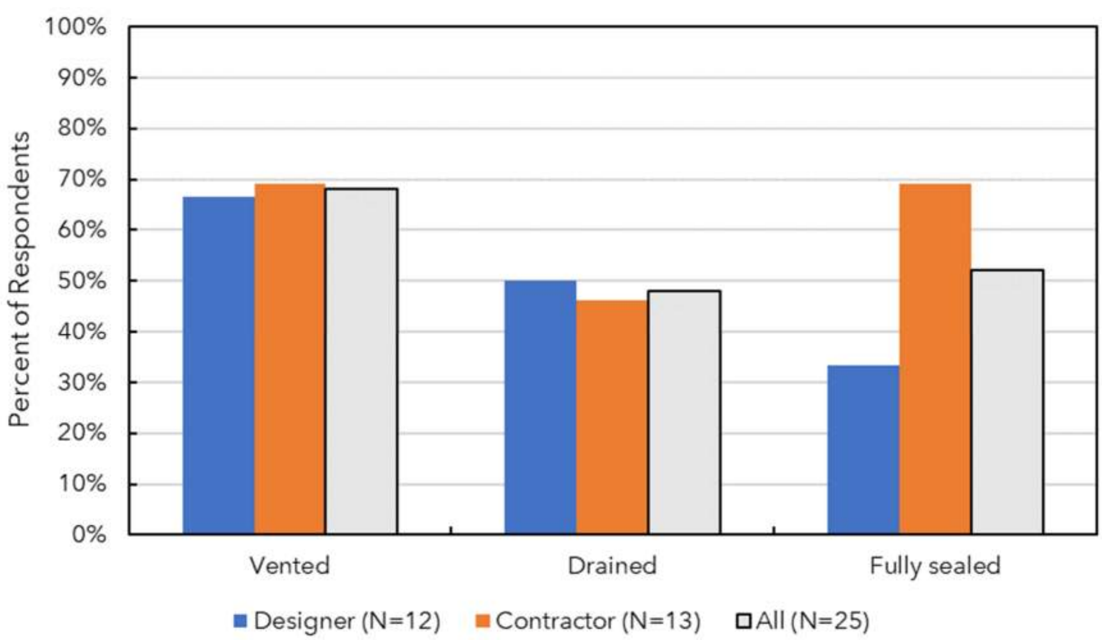

100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Percent of Respondents (N=14)
0
1
2
3
4
5
6
7
8
9
10
Likelihood (Scale of 0 to 10)


100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Percent of Respondents (N=14)
0
1
2
3
4
5
6
7
8
9
10
Likelihood (Scale of 0 to 10)

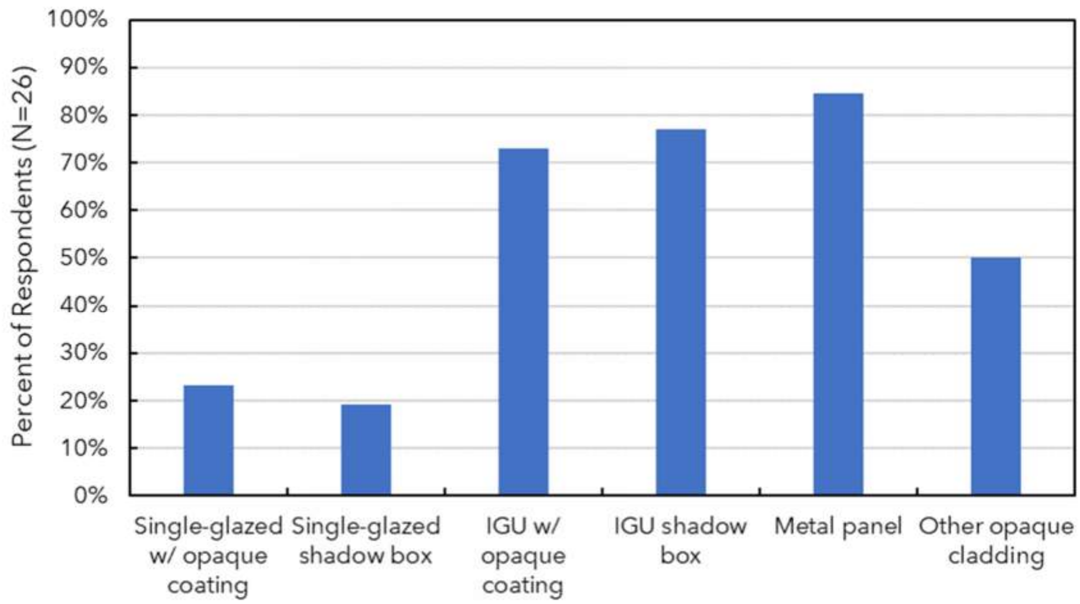
- Currently, the most common average spandrel dimensions are between 24 in. to 79 in. (609 mm to 2,000 mm) tall, and between 24 in. and 39 in. (609 mm and 1,000 mm) wide, although most respondents work with spandrels of all sizes on their projects. (Q26+27)

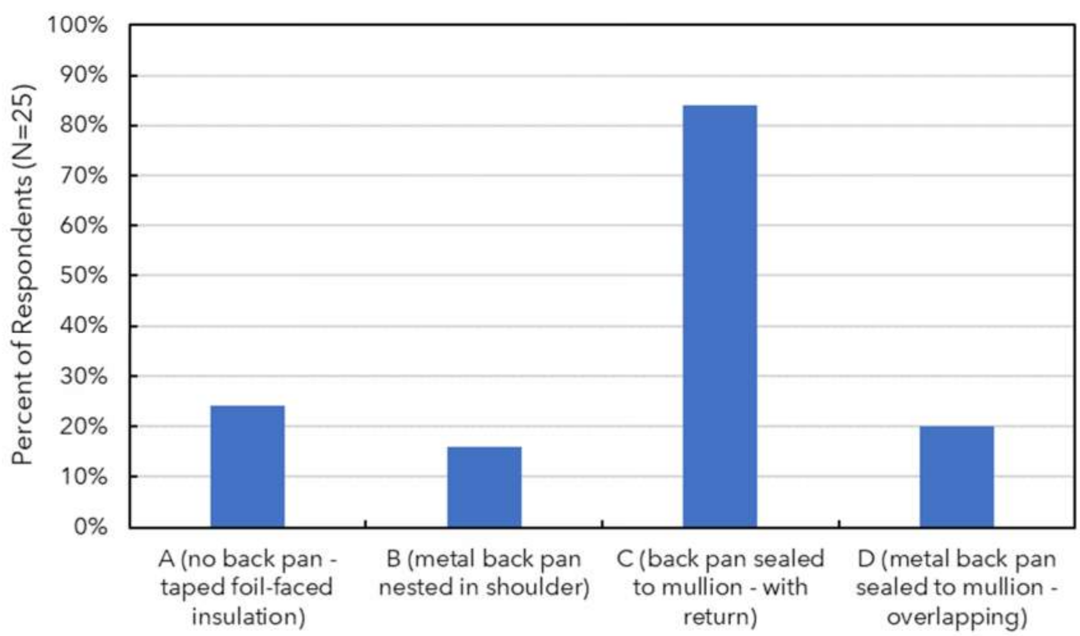


- Vented spandrels are more often specified by designers then than fully sealed panels. In contrast, vented and fully sealed spandrel panels are equally specified among Contractors. (Q29+30)

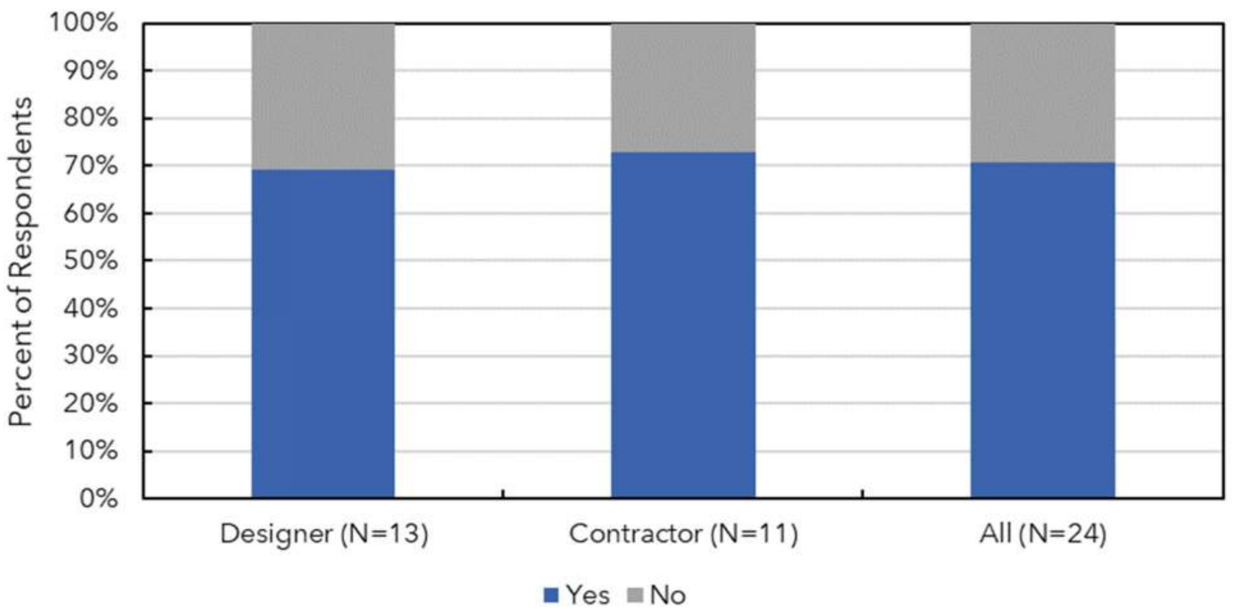


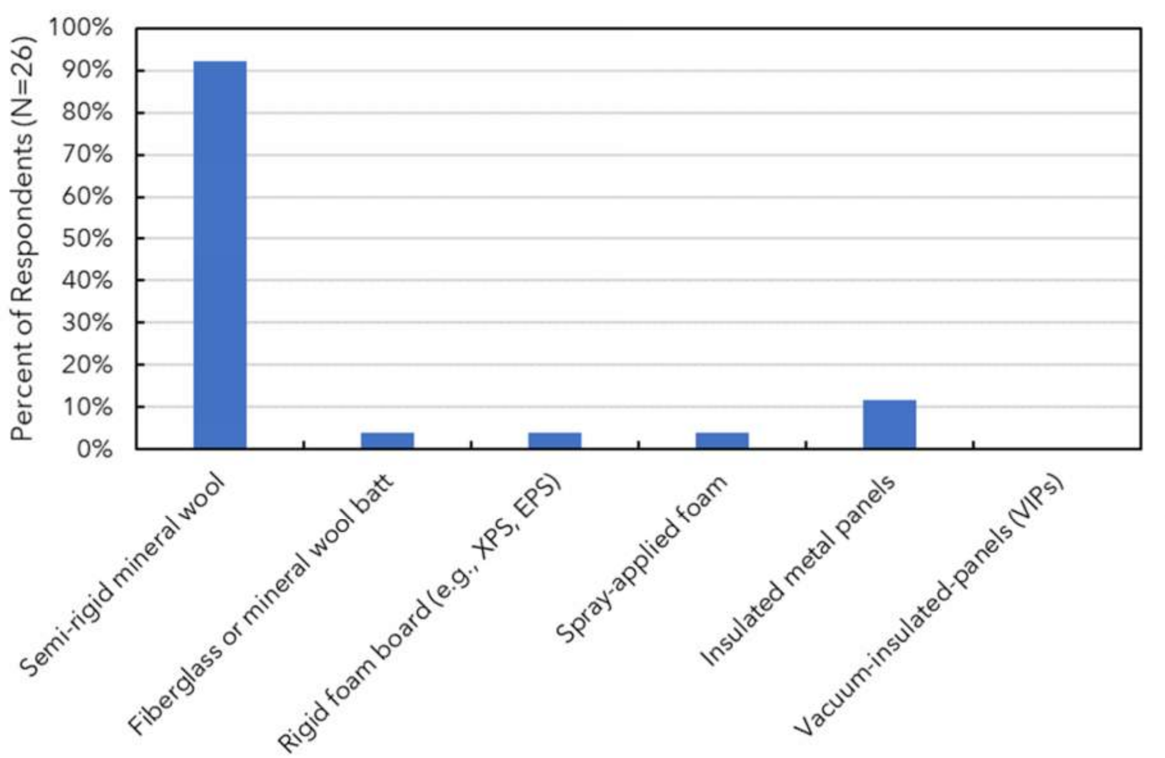
- Metal panel is the most typical spandrel panel cladding, followed by IGU shadow box, IGU with opaque coating, and other opaque cladding types. Single-glazed cladding types are less common. (Q31+32) Backpan sealed to mullion with return is the most common configuration of the spandrel backpan. This may have been skewed by limited respondents in cooling-dominated climates, which typically use foil-faced insulation in lieu of a metal backpan. (Q35+36)



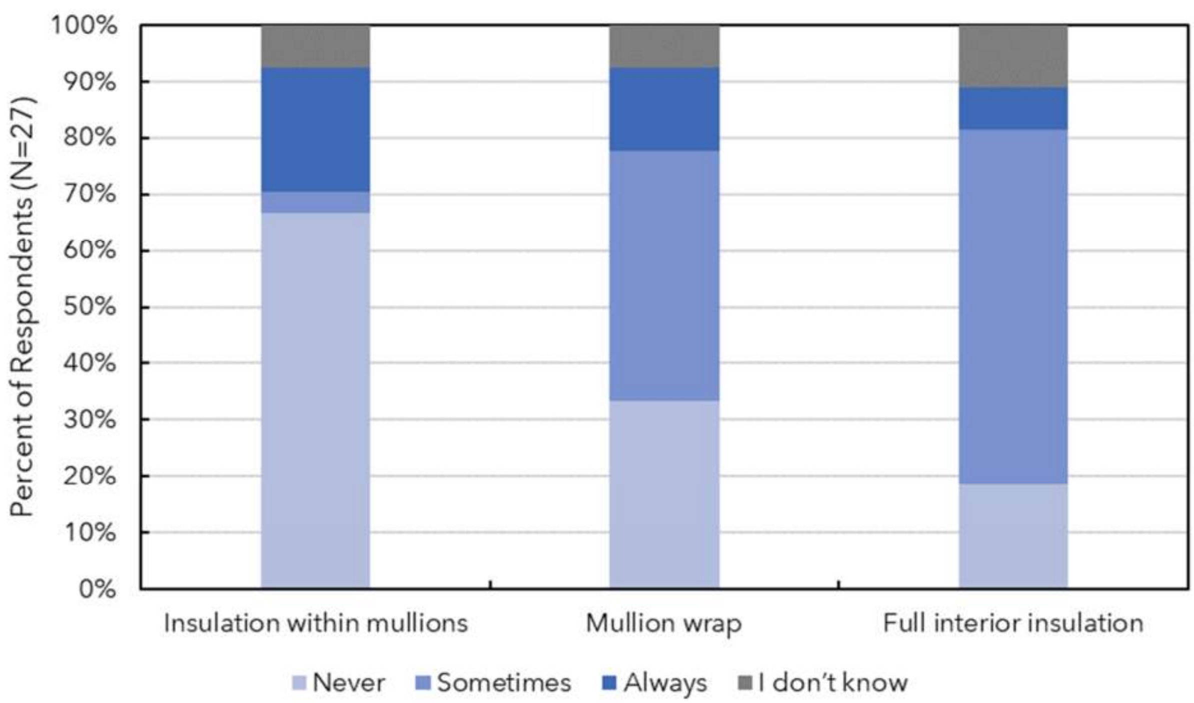


- Of the respondents, 71% of designers and contractors include insulation within spandrel panels. (Q43+44) Backpan insulation is almost exclusively semi-rigid mineral wool, which is used by twenty-four of twenty-six respondents, excluding blank responses. (Q33+34) Outside of the backpan, interior insulation is sometimes or always included by 70% of respondents, and mullion wrap is sometimes or always included by 59% of respondents. Insulation within the mullion is more polarizing, as it is where it's never included by 67% of respondents and always included by 22% of respondents. (Q45+46) Fins are the most common shading element compared to shades, or others. (Q53+54)

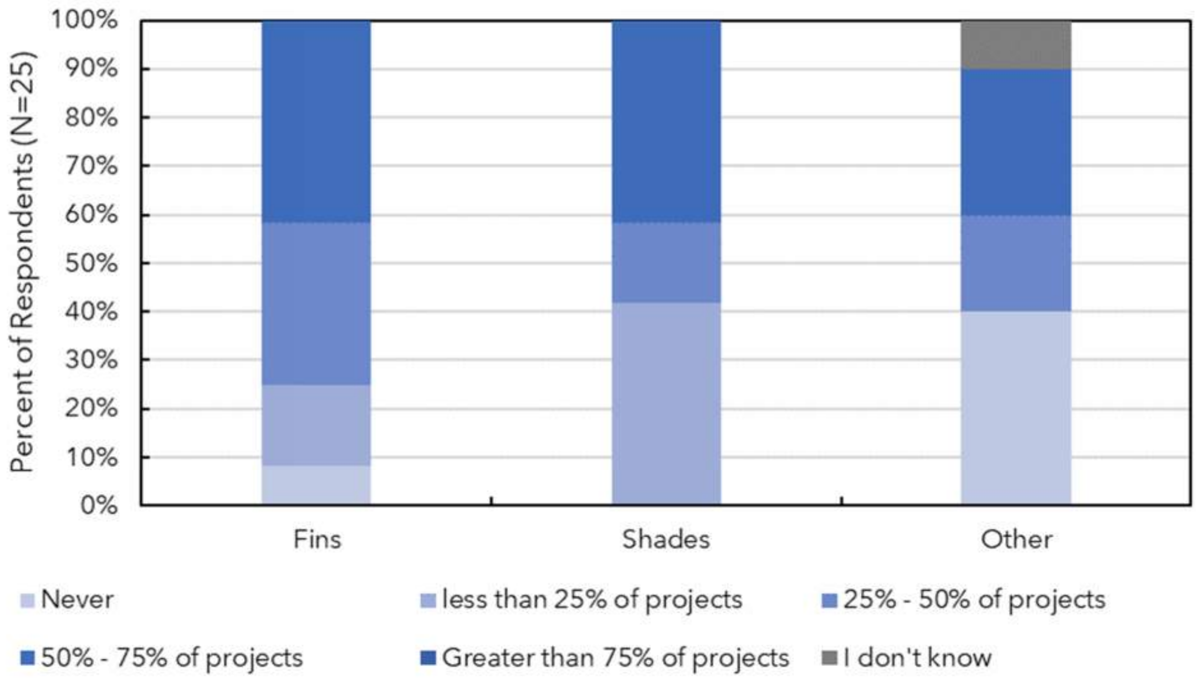




Percent of Respondents (N=26)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Semi-rigid mineral wool
Fiberglass or mineral wool batt
Rigid foam board (e.g., XPS, EPS)
Spray-applied foam
Insulated metal panels
Vacuum-insulated-panels (VIPs)

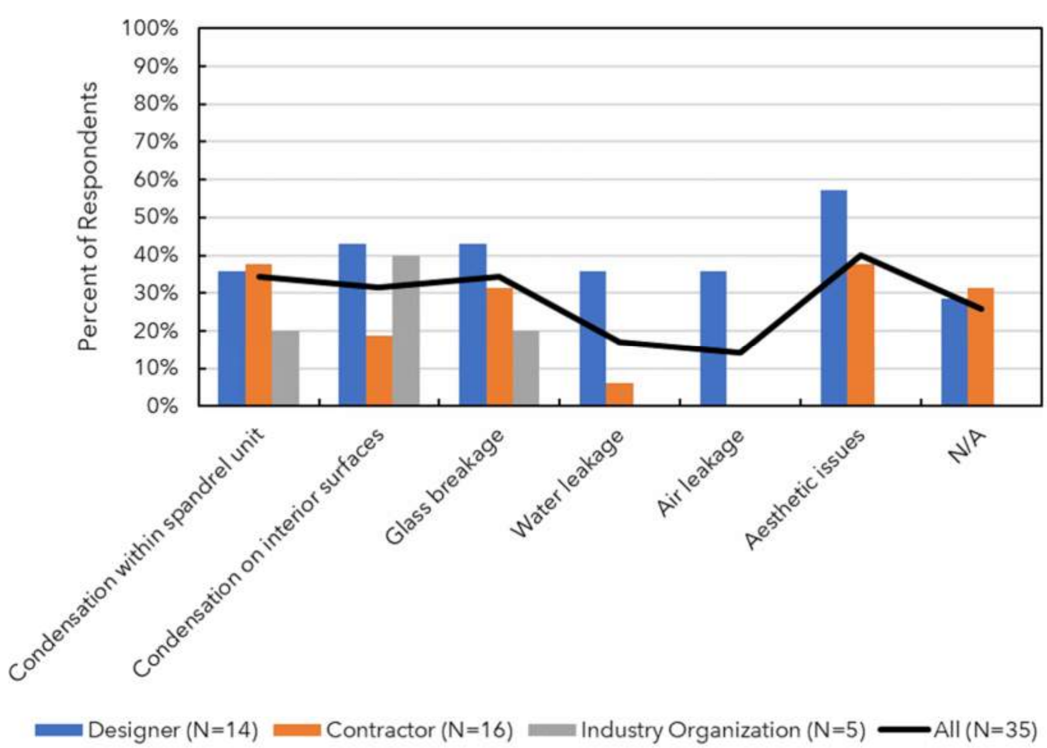


Percent of Respondents (N=27)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Insulation within mullions
Mullion wrap
Full interior insulation
Never
Sometimes
Always
I don't know

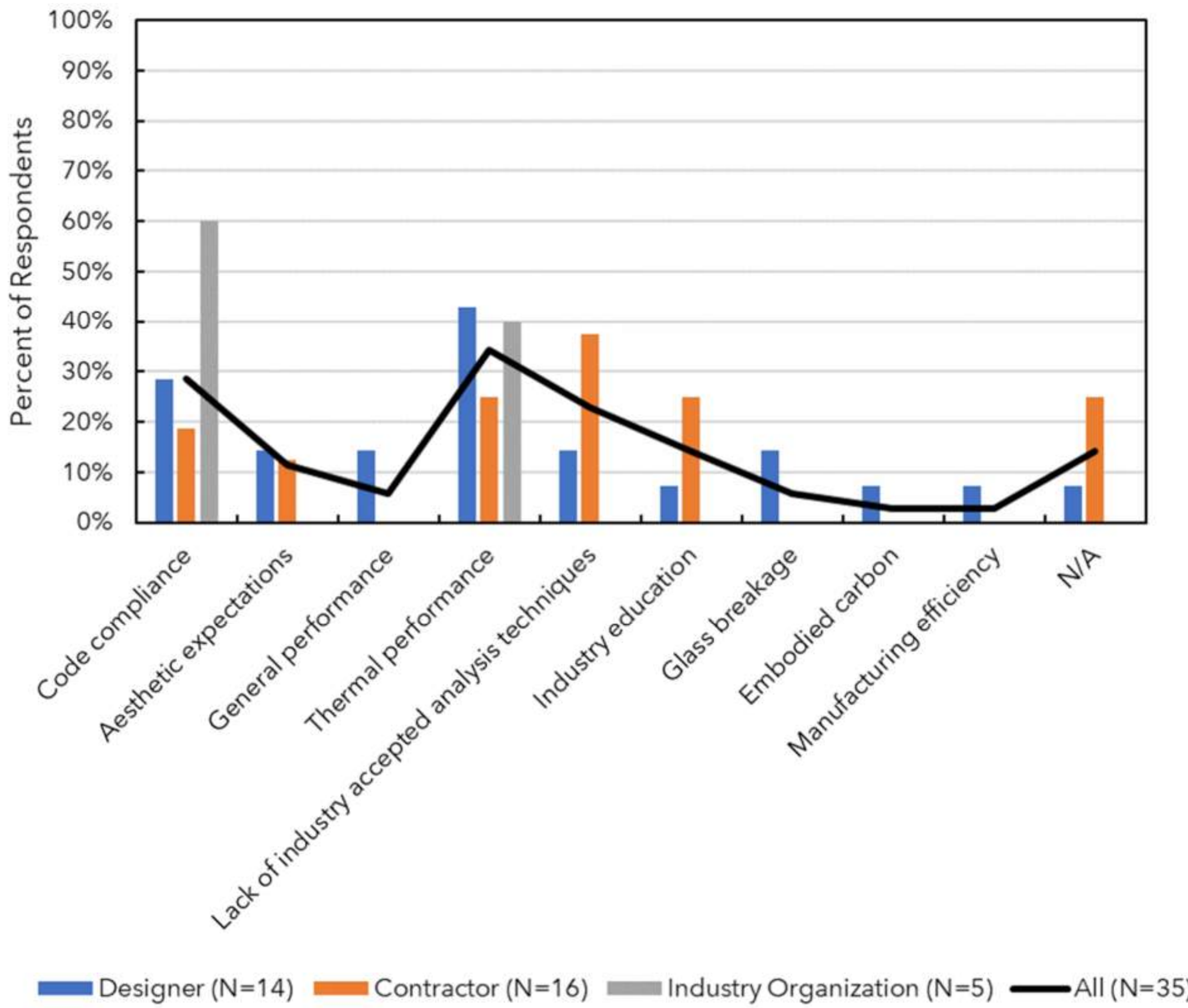


Spandrel Panel Concerns and Innovation

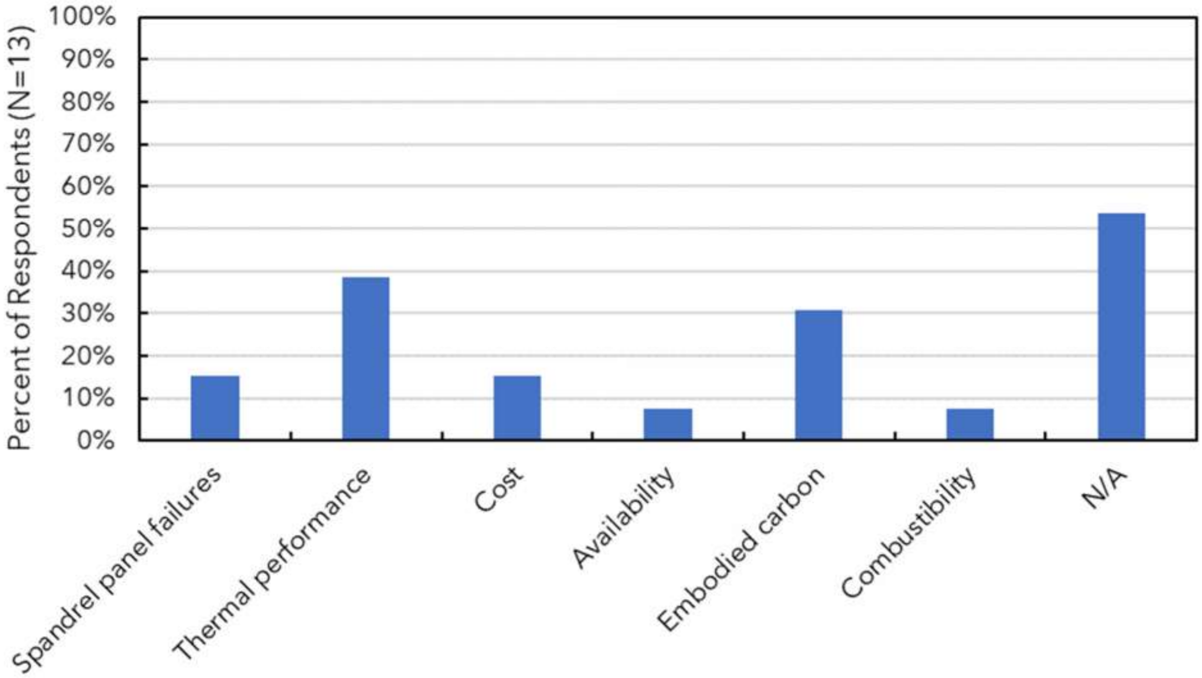
- The most common spandrel issues experienced by the respondents are, in order, aesthetic issues, condensation, and glass breakage. Of Designers, 36% cited that they have experienced water and air leakages with spandrel panels; however, these leakages were not common among Contractors. Of all respondents, 26% did not cite any issues. (Q55+56+57)



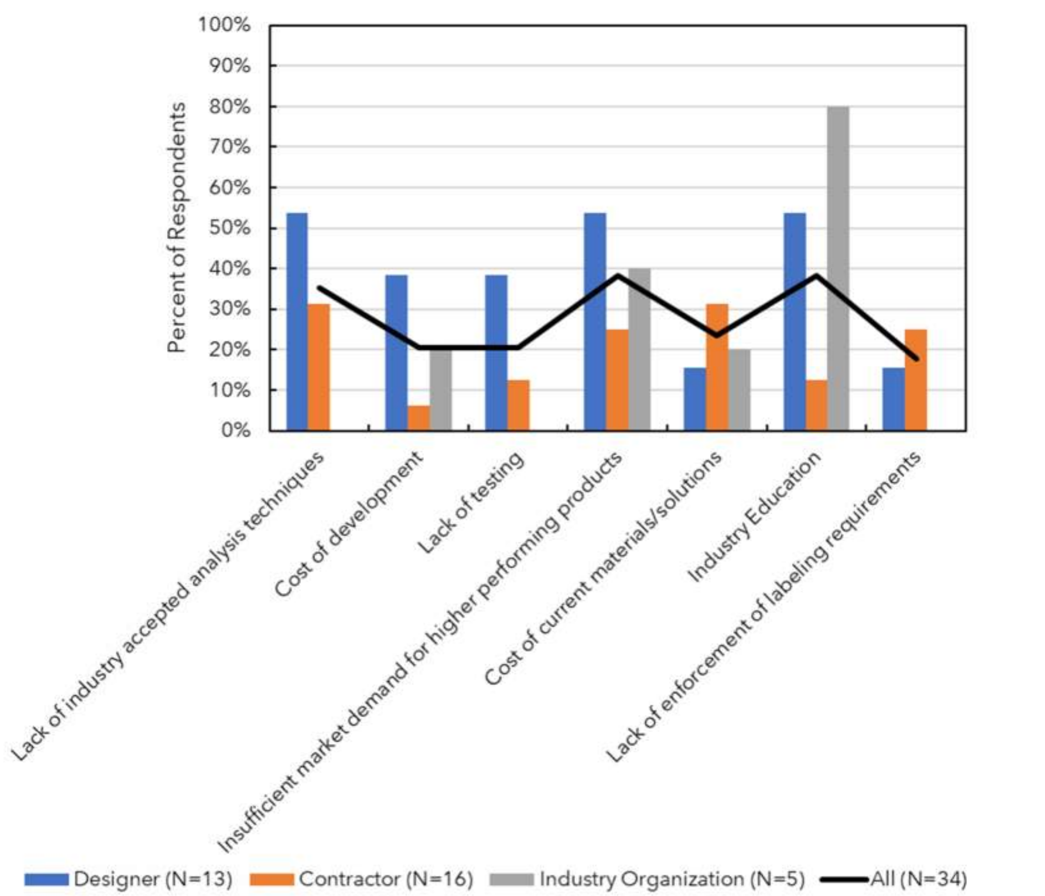
- Thermal performance, code compliance, and lack of industry accepted analysis techniques are considered the greatest challenge or concern faced by the respondents on current projects that involve spandrel panels. (Q60+61+62)

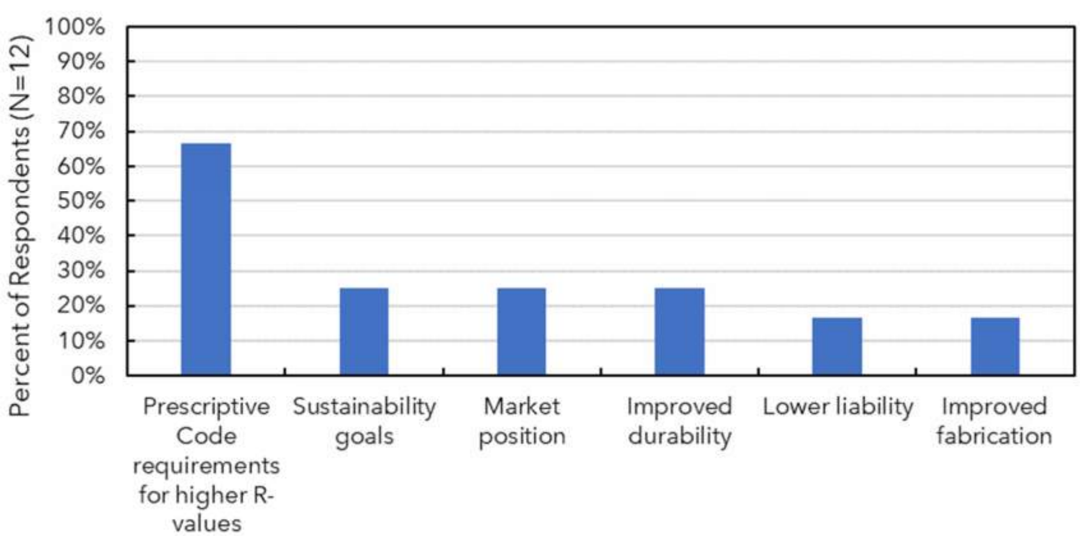


- Common concerns that prevent Designers' use of spandrels on future projects include spandrel thermal performance and embodied carbon, though more than half of the Designers did not cite any concerns. (Q59)



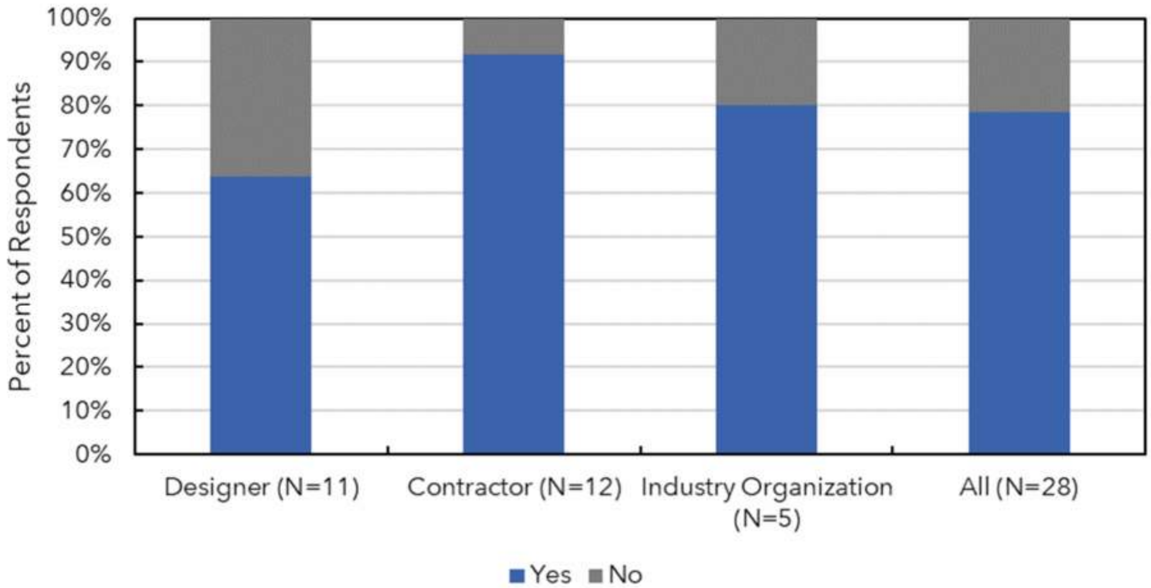
- Insufficient market demand for higher performing products, industry education, and lack of industry-accepted analysis techniques are the top three barriers to spandrel innovation cited by the respondents. The cost of current materials/solutions is another significant barrier cited by Contractors. (Q63+64+65) Of Designers, 75% agree that more stringent code requirements are the biggest motivator to advancing spandrel design. (Q66)



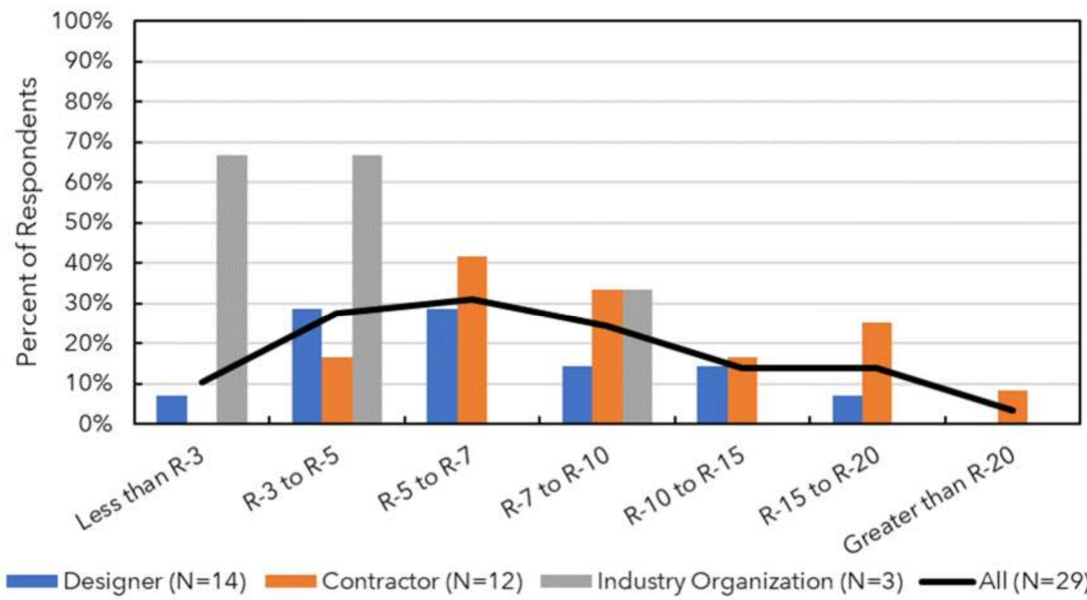


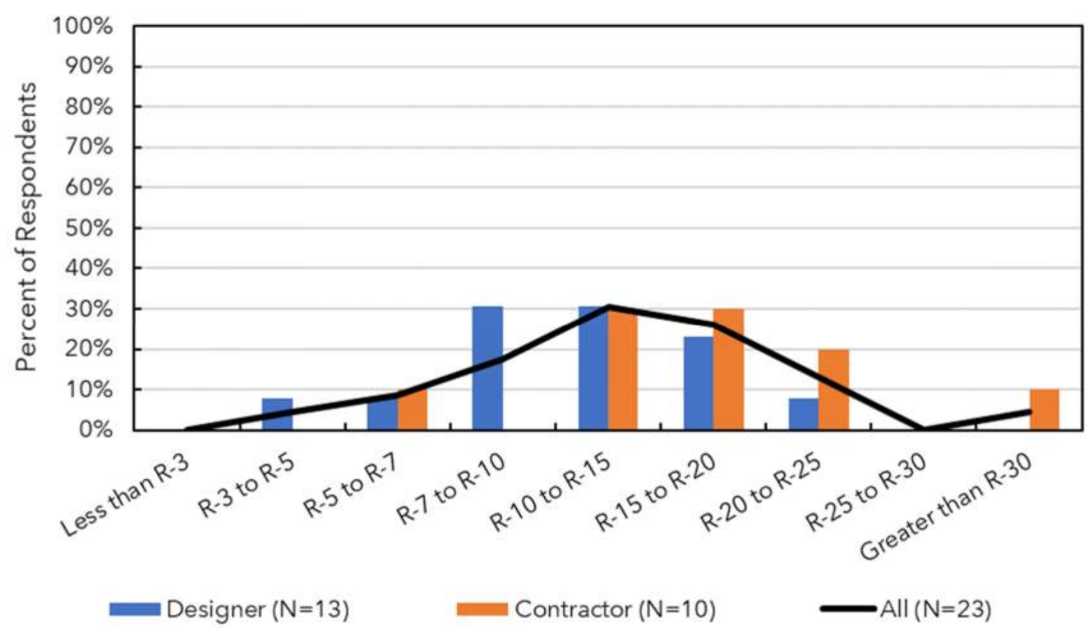
Spandrel Thermal Performance

- Of the respondents, 64% of the Designers and 92% of the Contractors/Manufacturers indicated that they are aware of the difference in thermal performance required of spandrel panels compared to transparent glazing. (Q37+38+39)

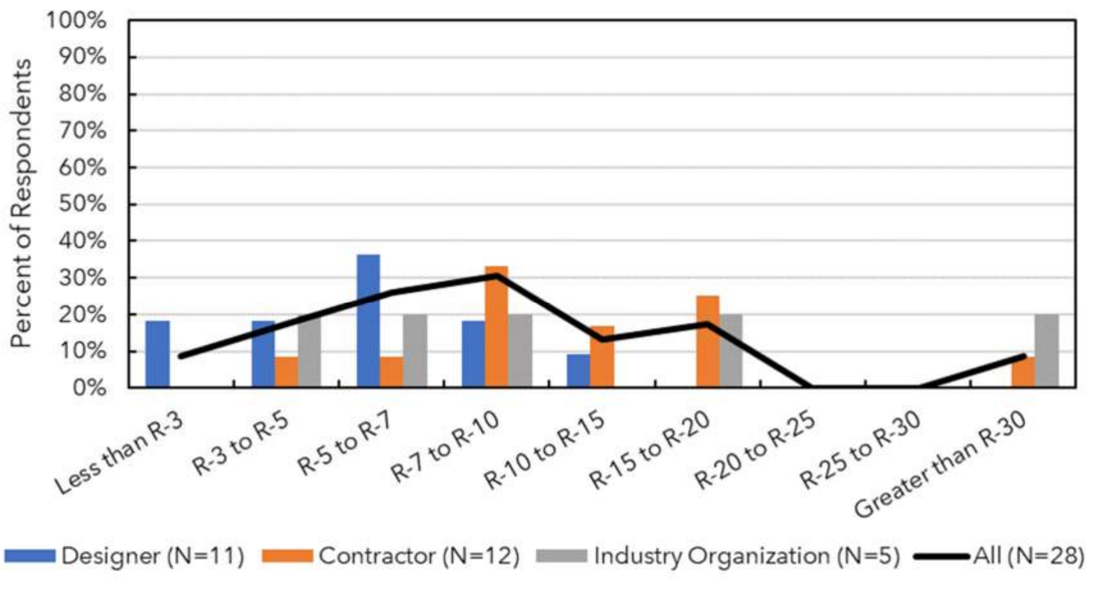


- The average thermal performance of spandrel products in today's market seen by most representatives from Industry Organizations is less than R-5 ft²-°F-hr/BTU (RSI-0.88 m2-K/W), while more than half of the Designers specify R-3 (RSI-0.53) to R-7 (RSI-1.23) for spandrel assemblies in their projects. In comparison, 75% of the Contractors indicated that they typically work with R-5 (RSI-0.88) to R-10 (RSI-1.76) spandrels, with some Contractors working with even better assemblies. (Q18+19+20) This difference in expectation is also true for the anticipated code-required spandrel R-value in 2030, with most Designers expecting R-7 (RSI-1.23) to R-15 (RSI-2.64) to be required and most Contractors expecting R-10 (RSI-1.76) to R-20 (RSI-3.52) to be required. (Q21+22)

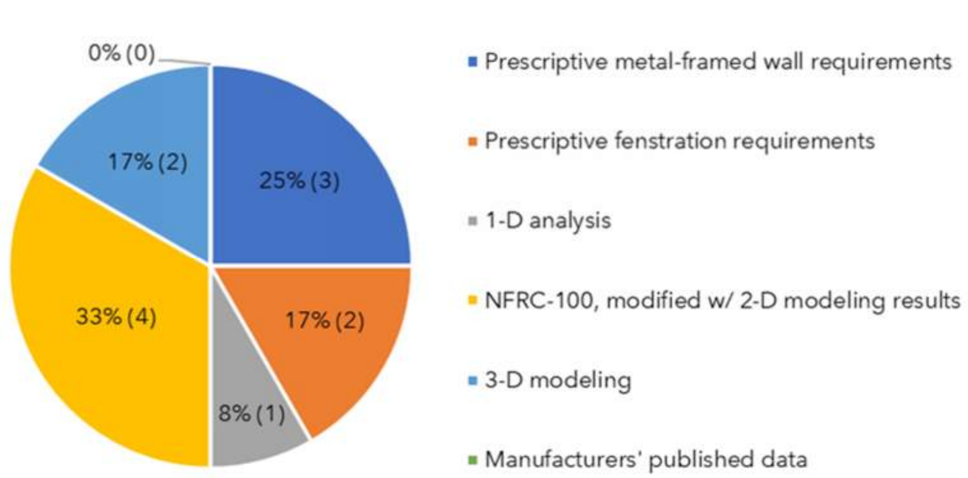




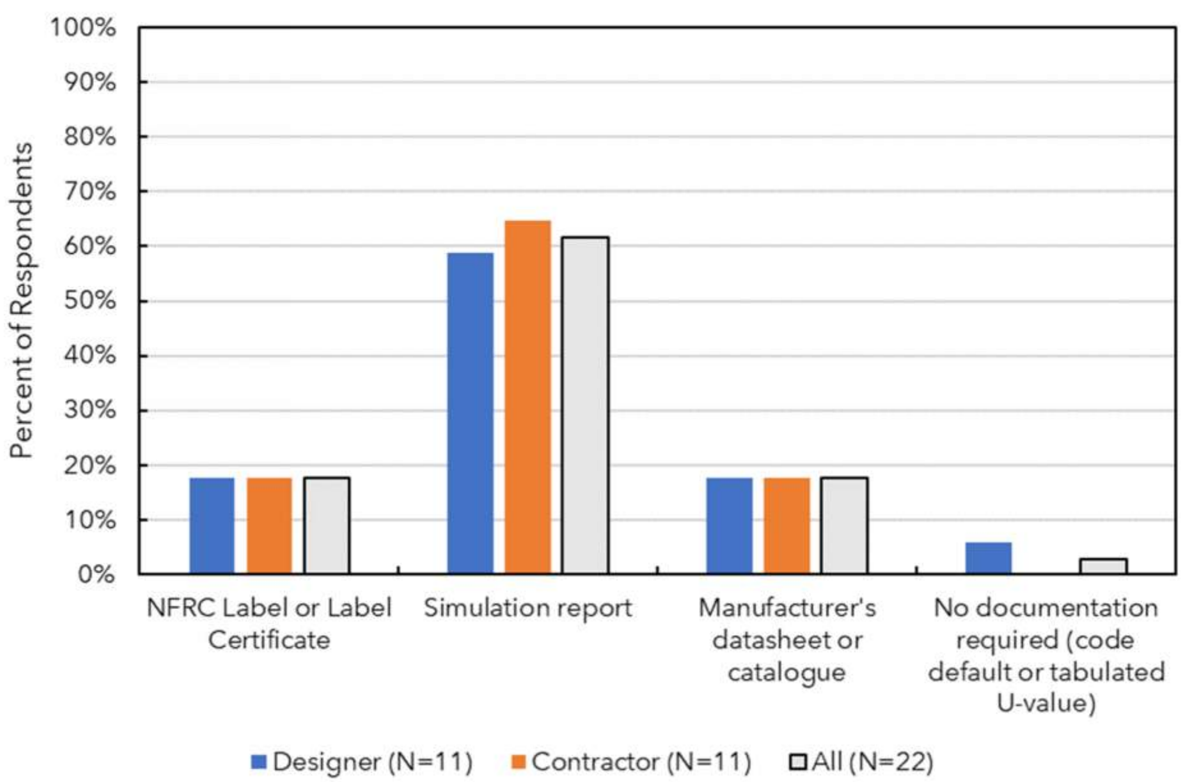
- Based on current technologies, most Designers think that the highest achievable spandrel R-value is between R-5 (RSI-0.88) to R-7 (RSI-1.23), while most Contractors think that R-7 (RSI1.23) to R-10 (RSI-1.76) or higher, is achievable. (Q40+41+42)

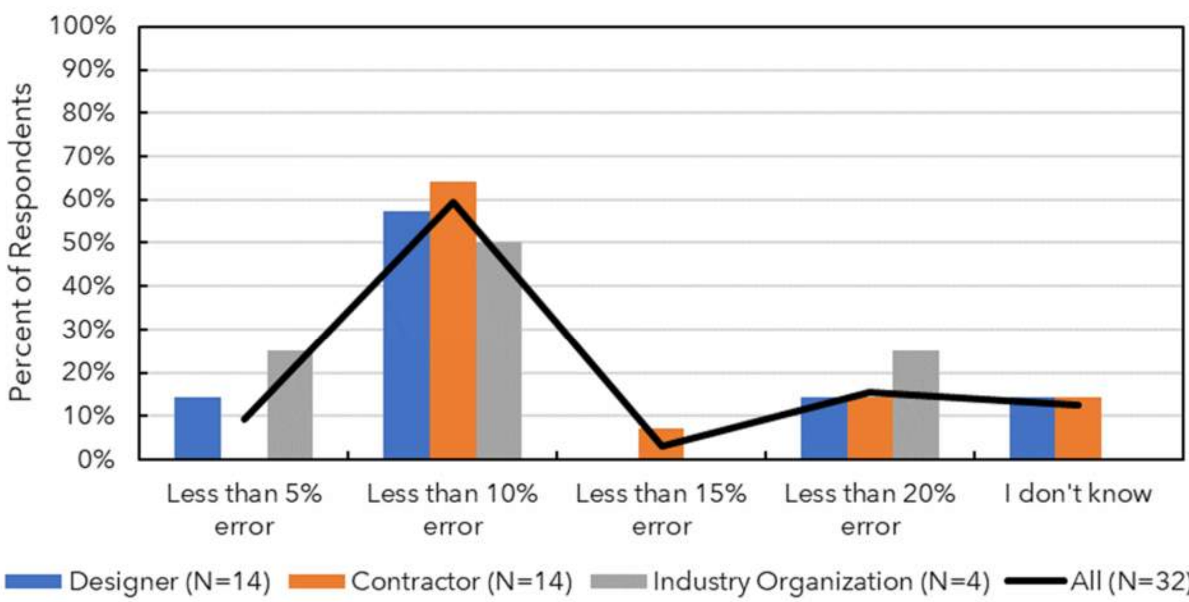


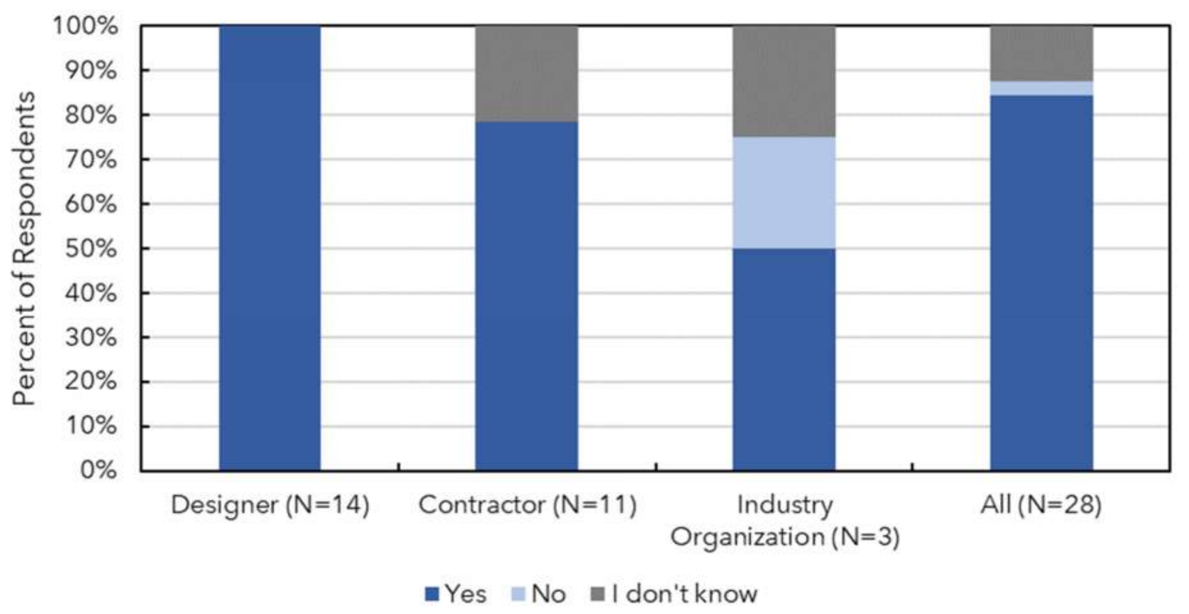
- Given that many energy codes and standards (e.g., IECC, ASHRAE 90.1) do not include prescriptive U-factors specifically for spandrels, one-third of Designers follow the procedures outlined by ANSI/NFRC 100 with modified edge zone values using 2D finite element modeling results. The next most common methods to account for spandrel thermal performance are to follow prescriptive requirements for metal-framed wall or fenestration systems, and some Designers utilize 1D or 3D analyses. None of the respondents indicated that they use manufacturers' published data – it is unclear whether this is due to limited published data, or if this is a choice by the Designers. (Q23)



- About 60% of respondents indicate that they rely on simulation reports to support the manufacturer's reported spandrel U-factor. (Q67+68) Most respondents expect thermal simulation results to have less than 10% error, with Contractors generally expecting less accuracy than Designers and representatives from Industry Organizations. (Q50+51+52) If available, 96% of all respondents indicated that they would use 3D over 2D simulation results. (Q47+48+49)






100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Percent of Respondents
Designer (N=14)
Contractor (N=11)
Industry Organization (N=3)
All (N=28)
Yes
No
I don't know

APPENDIX D – CONVECTIVE FILM COEFFICIENTS

Table D1 – Default Boundary Condition Film Coefficients in Various Industry Standards

Ref.	Boundary Condition	Convection (Only) Btu/h-ft²-°F (W/m²K)	Combined Btu/h-ft²-°F (W/m²K)	Notes
ANSI/ NFRC 100	Exterior (all surfaces)	4.578 (26.00)	*Calculated in THERM/WINDOW iteratively*	Convection based on a 12.3 mph [5.5 m/s] wind speed. Assumes forced convection calculated (SI). Blackbody radiation model (ISO15099).
	Interior Aluminum Frame	0.579 (3.29)		Convection based on natural convection and standardized values based on an assumed frame temperature.
	Interior Thermally Improved Frame	0.549 (3.12)		
	Interior Thermally Broken Frame	0.528 (3.00)		
	Interior Wood/Vinyl Frame	0.430 (2.44)		
	Interior Glazing System	Calculated in WINDOW		Per ISO 15099.
	Interior Insulated Opaque Spandrel Panel	Based on the frame type		Assumes the interior boundary condition that is equivalent to the glazed wall system's intermediate frame type.
ISO 10077-2	Exterior		4.403 (25.00)	Based on ISO 6946.
	Interior		1.356 (7.70)	
	Interior, reduced Applied at corners		0.880 (5.00)	
ISO 15099	Exterior	3.522 (20.00)	*Calculated iteratively by validated software*	Default convective heat transfer coefficients provided. Radiation determined using blackbody (exterior) or automatic enclosure (interior) models.
	Interior	0.634 (3.60)		
EN 673	Exterior		4.051 (23.00)	Standardized value for reporting glazing U-factors.

Ref.	Boundary Condition	Convection (Only) Btu/h-ft^2-°F (W/m^{2}K)	Combined Btu/h-ft^2-°F (W/m^{2}K)	Notes
	Interior	0.634 (3.60)	1.356 (7.70)	Default combined coefficient with a simplified correction for surfaces with lower emissivity.
CSA Z5010	Exterior	*Optional calc. for exterior convection based on exterior wind speed*	6.073 (34.00)	* Exterior protected films (e.g., rainscreen cladding) assumed to be equivalent to the interior film coefficient based on direction of heat flow when cladding is not directly simulated. The reduced heat transfer coefficient for condensation analysis is based on ISO 13788.
	Exterior, protected		*	
	Interior, horizontal heat flow (ε = 0.9)		1.456 (8.29)	
	Interior, upward heat flow (ε = 0.9)		1.631 (9.26)	
	Interior, downward heat flow (ε = 0.9)		1.080 (6.13)	
	Interior, condensation (all surfaces)		0.704 (4.00)	
AAMA 515	Exterior	$h_c = 4 + 4V_s$ *V_s = windspeed in m/s based on the ASHRAE 99.6% mean coincident wind speed (MCWS)*	*Calculated in THERM/WINDOW iteratively* *(User defined BC)*	Voluntary procedure to account for project specific conditions. Default parameters remain ANSI/NFRC 100. Range in exterior convective film coefficients ranging from 2.23 (12.9) to 7.00 (39.8) based on wind speeds ranging from 5 to 20 mph (2.2 to 8.9 m/s)
	Interior	*Match ANSI/NFRC*		

APPENDIX E – CFD SIMULATION PARAMETERS

Software:

- Dassault Systems' SOLIDWORKS 2021
- Siemens Simcenter StarCCM+ 2021.1

Solid Elements:

- The IGU spacer bar and screw splines are modeled as simplified solid one-box lumped parameter model, with effective conductivities calculated using THERM.
- Solids are modeled using conjugate heat transfer methods.

Air Volumes:

- Figure E-1 shows the three air volumes: air cavity within the spandrel, air volume outboard of the spandrel, and air volumes inboard of the spandrel, above and below the floor slab.
- All three air volumes are modeled explicitly using a polyhedral mesh:
  - For the ventilated case, the air volume within the spandrel cavity is connected to air volumes within the horizontal mullion pressure plate and beauty cap assembly through vent holes in the gaskets, pressure plate and beauty cap. For the sealed case, the holes were changed to solid objects to disconnect the spandrel air volume from the exterior air volume.
  - Approximately 13.5 million total cells.
  - Prism layer elements are located along the perimeter of the exterior air, interior air, and panel cavity.
  - The interior air volumes above and below the slab edge are not connected.
- The hollows of framing members and IGU cavity (green-colored zones in Figure E-1) are regions of stagnant air that do not interact with outside air volumes, and so are modeled as solids with effective conductivity calculated from THERM. This simplification avoids significant computational efforts on negligible air movements.
- Buoyancy effects are modeled explicitly.

Boundary Conditions:

- Figure E-1 shows the extents of the model boundary conditions.
- The temperature of the air volumes on the exterior side is 0°F and 70°F on the interior side, which matches temperatures often seen on a building.
- There is no temperature exchange across the adiabatic boundaries (green boundaries in Figure E-1).
- At inlets, we simulated a small fan, similar to that used in an experimental test set up, with slow moving laminar air flow that generates a curtain of air flowing across the curtain wall to the outlets. The entire system is at atmospheric pressure.
- The velocities at the inlets are determined by dividing the volumetric flow rate at each inlet by the area at these locations.
- CFM values (50 cfm and 100 cfm) were chosen based on ORNL's lab test values, correlating to minimum wind speeds on building facades.

Numerical Error Tolerance: ~0.01% based on energy convergence criterion.

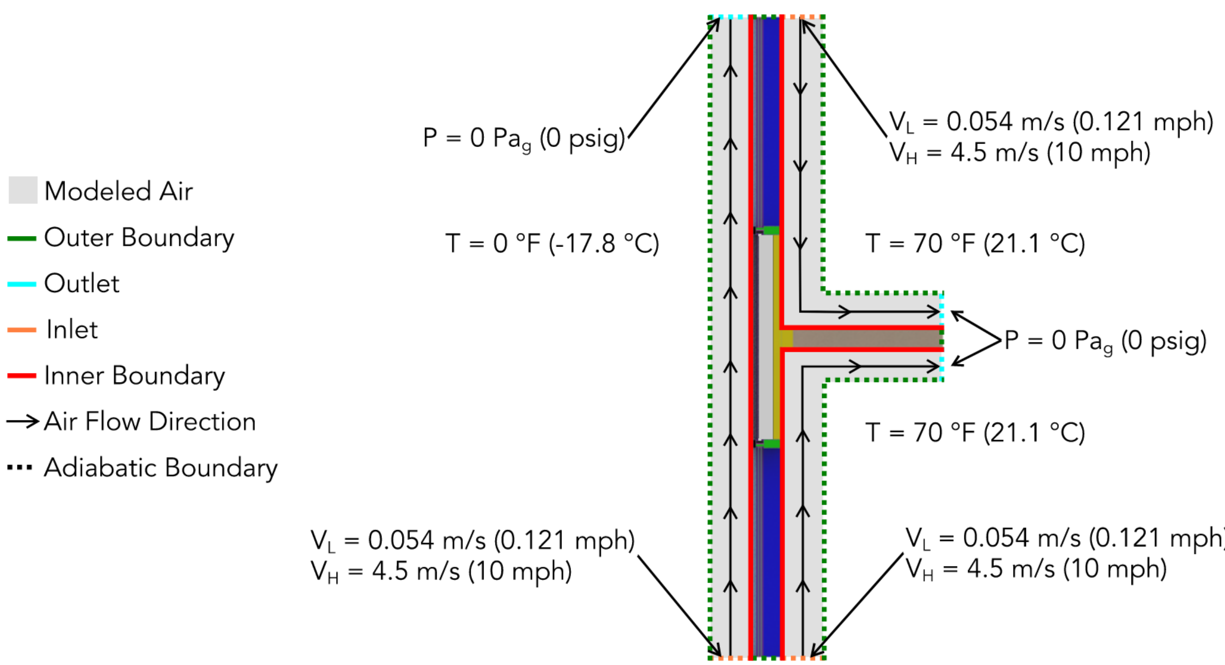


Figure E-1 – Boundary Conditions of CFD Model

APPENDIX F – FEA SIMULATION PARAMETERS

Software:

LBNL THERM 7.8 / WINDOW 7.8

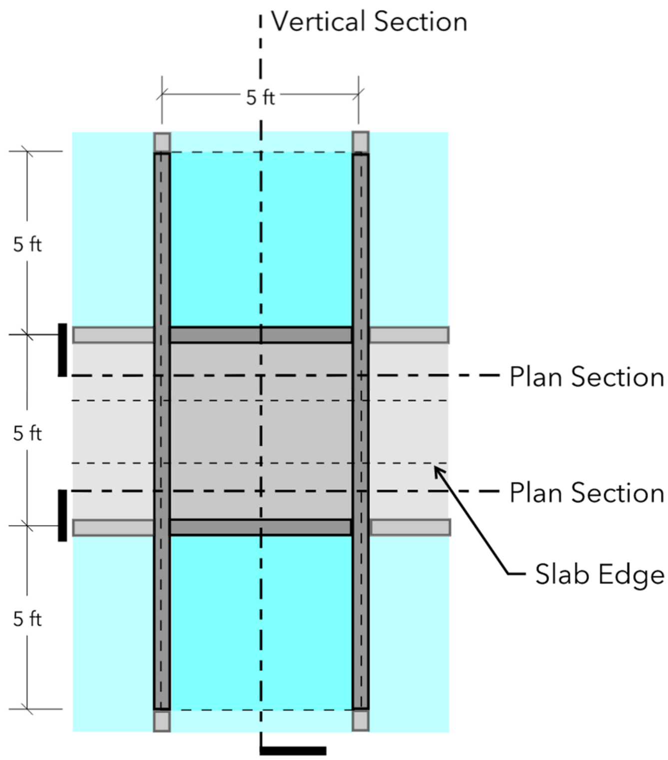


Figure F-1 – FEA Simulation Sections

Simulation Assumptions:

- Two-dimensional steady-state approximation of the three-dimensional geometry.
- All component dimensions are identical to the CFD model dimensions.
- A total of three simulations were constructed to calculate spandrel U-factors. The simulations are categorized into the following sections (refer to Figure F-1):
    - Vertical Section: The spandrel panel with glazing above and below at the midplane of the system. The vertical section geometry is identical to a vertical section of the 3D CFD simulation; the section does not include any vent openings.
    - Plan Section – Spandrel: The spandrel jamb above and below the slab edge. The simulation results are averaged between these two plan sections.

Solid Elements:

- Material properties such as conductivities and emissivities are sourced from THERM and WINDOW, except for the mineral wool, which was sourced from ROCKWOOL.
- The glazing units are modeled in WINDOW and imported into THERM.
- The glazing unit spacer bar and curtain wall screw spline are modeled explicitly.
- Effective conductivity of pressure plate fasteners through the mullion thermal break, firesafing, and anchorage at the slab edge is calculated in accordance with Section 8.8 of the THERM 7/WINDOW 7 NFRC Simulation Manual.

Air Volumes:

- WINDOW and THERM do not explicitly model air flow. Air volumes in FEA are simulated in accordance with THERM's simulation procedure as, "Frame Cavity ANSI/NFRC 100."
- Frame cavity thermal properties are automatically calculated by THERM using the ISO 15099 procedure.

Boundary Conditions:

- U-factor Surface Tags are assigned on the exterior surfaces of the spandrel simulation boundary to provide a consistent basis of comparison between simulations with and without a slab edge.
- Edge distances used for calculating spandrel U-factors are 6 in. as recommended by the FenBC reference procedure.
- The exterior and interior temperatures at all boundary conditions are 0°F (-17.8°C) and 70°F (21.1°C), respectively. The temperatures are identical to the CFD simulation and are rounded from ANSI/NFRC 100 boundary condition temperatures (-0.4°F [-18°C] and 69.8°F [21°C], respectively).
- The FEA simulation includes the following two methods for assigning film coefficients to calculate U-factors:
    - <u>CFD</u>: Uses film coefficients calculated directly from CFD. Figure F-2 shows the boundary conditions used with the CFD-calculated film coefficients. CFD-calculated film coefficients for non-adiabatic surfaces are obtained from the CFD model at a plane offset 3 in. (7.62 cm) from all horizontal and vertical surfaces.

- FenBC / ANSI / NFRC: Uses film coefficients determined by following the FenBC reference procedure. Figure F-3 shows the boundary conditions used following the FenBC reference procedure. The horizontal slab edge film coefficients are obtained from ASHRAE Handbook – Fundamentals. All exterior surfaces use an "ANSI/NFRC 100-2010 Exterior" boundary condition. Glazing unit interior surfaces use a "U-factor Inside Film" boundary condition. All other non-adiabatic interior surfaces use an "Interior Thermally Broken Frame (convection only)" boundary condition.

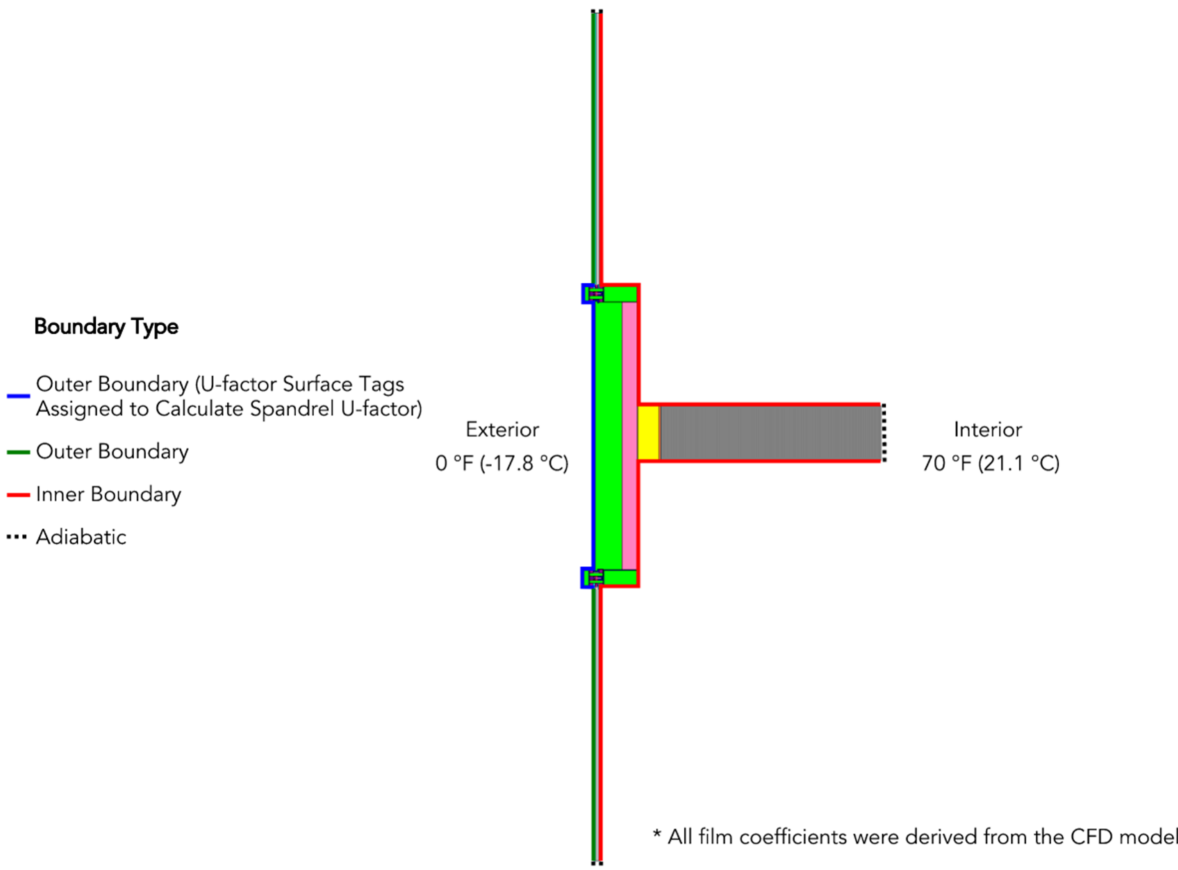


Figure F-2 – Boundary Conditions – CFD Film Coefficients

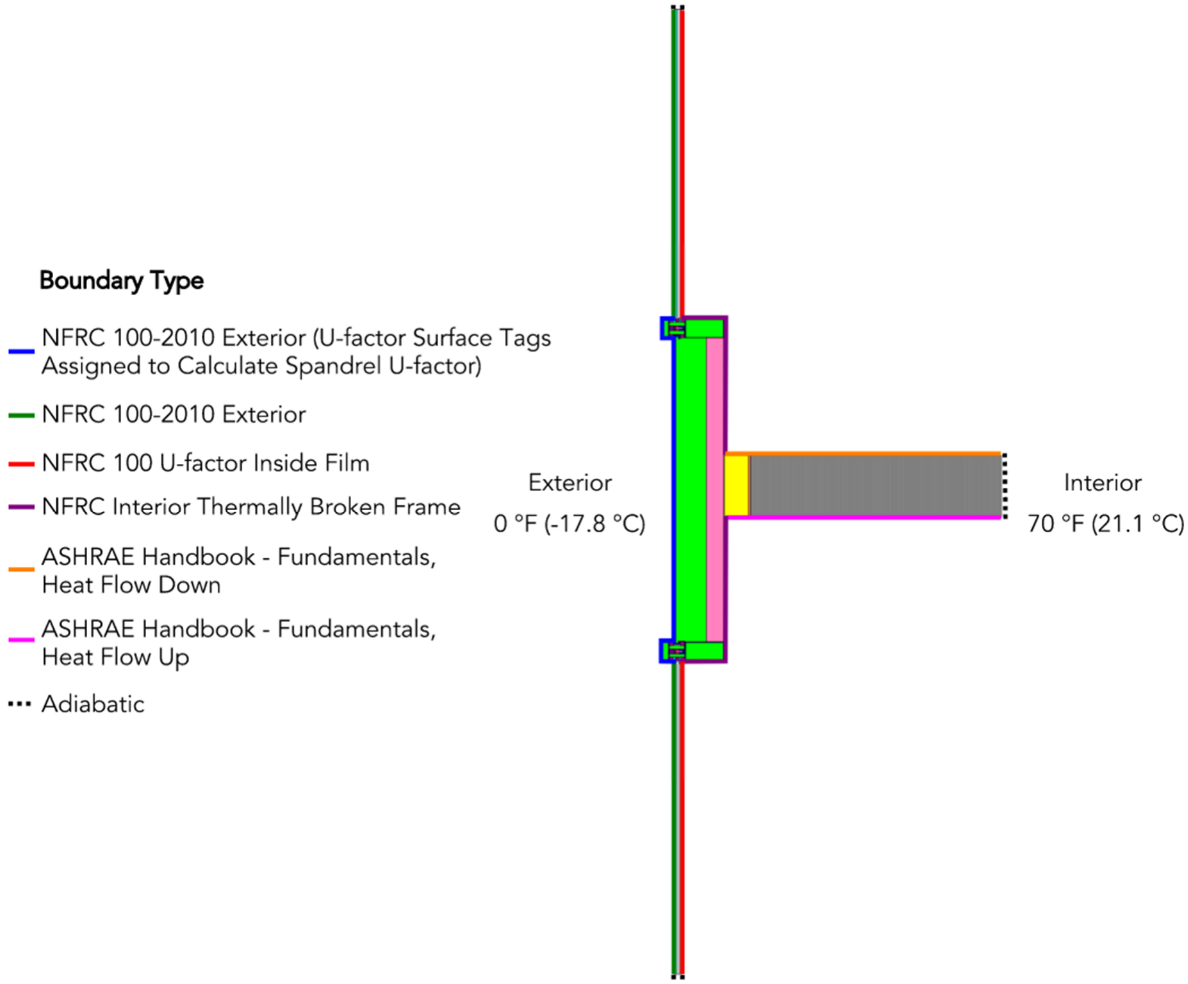


Figure F-3 – Boundary Conditions - FenBC Film Coefficients

Numerical Error Tolerance: 1% per Section 6.6.2 in LBNL THERM Simulation Manual.

APPENDIX G – AIRFLOW VARIABLES

The following list includes additional information on variables that impact airflow in spandrels. We provide explanations on how the variables may vary in the built environment.

- Panel Height: Panel height impacts the aspect ratio of the air cavity and the height of convection loops that form within the cavity space. This increases the temperature exchange with the surface the loop contacts and increases the temperature gradient along the elongated air current. Spandrel panel heights typically vary on buildings; they may only cover a slab edge, be several feet tall to conceal equipment above a ceiling, or they may be full floor height to cover structural columns.
- Air Cavity between Panel and Insulation: The air cavity depth between the panel and insulation will impact the convection loops within the spandrel cavity. A deeper air cavity allows for a larger volume of air and more potential for air movement within the cavity space. A very narrow cavity will "choke off" airflow.
- Exterior Air Velocity: The exterior air movement can be quite turbulent and varies based on wind speed, direction, and exposure conditions. In an experimental setup to measure thermal performance, the exterior air flow is more controlled with multiple fans set up to simulate the movement of air on the outside of the entire system. The air curtain that develops is slower, more laminar in profile, and is only representative of real-world conditions when there is minimal wind. Faster moving air is more turbulent and can potentially bypass the small vent holes in a spandrel entirely.
- Backpan Profile: Varying geometry of backpan profiles impacts the perimeter thermal heat flux and increases thermal bridging. For stick-built curtain walls, the backpan typically returns into the curtain wall glazing pocket, which is the worst case for thermal bridging.
- Framing Type: Frame types impact the perimeter thermal isolation and heat flux at the perimeter of the air volume. While there are many frame types available, a stick-built system has the most direct airflow path between the spandrel air cavity and the exterior. With other systems and frame types, the air flow paths can be more convoluted and would restrict airflow.
- Glazing Support Type: Both pressure plate and silicone glazed systems have relatively direct air flow paths between the spandrel air cavity and exterior, but the pressure plate system generally has lower thermal performance.
- Spandrel Panel Insulation Type: Mineral wool was selected as it is the most common insulation type used in curtain wall systems.

- **Exterior Panel Type:** An uninsulated metal panel was selected to increase heat exchange with the cold exterior air volume to encourage more convection loops to form within the spandrel air cavity and thereby potentially increasing air exchange with the exterior.
- **Surface Roughness:** A rougher surface could encourage more heat exchange within the spandrel cavity, but could add friction and slow down air flow and thereby reduce heat exchange. We modeled smooth surfaces within the spandrel cavity as a conservative approach.
- **Cavity Ventilation:** Cavity ventilation is the only variable that differs between the 3D CFD models. The models varied between having no vent openings and four 0.5 in. (1.27 cm) vent openings (two at the top and two at the bottom) located 15.4 in. (39. cm) perpendicular to the vertical boundary of the model.

Appendix H - Test Program Laboratory Testing Guideline

Background

The Thermal Performance of Spandrel Assemblies in Glazed Wall Systems Research project for the Charles Pankow Foundation includes laboratory testing as part of the investigation program. This document provides an overview of the laboratory tests as well as a set of guidelines developed by the Engineering Team to help design the experimental test protocol and instrumentation requirements.

The objective of laboratory testing is to validate computer simulation models against measured data and help develop a set of simulation guidelines and techniques. As such, the laboratory tests will cover multiple systems and configurations to push the limits of current simulation methods. This document presents a list of proposed spandrel assemblies to test, planned layouts, a set of proposed test procedures and test equipment, as well as proposed variations. Oak Ridge National Laboratory (ORNL) are the laboratory testing partners for this study. Specific details of the laboratory test program will be further developed with ORNL input.

Spandrel System Types

Spandrel panels of multiple curtain wall and window wall systems have been proposed for laboratory testing. These test articles encompass system types that are typically found on buildings in North America in current practice, as well as progressive systems that the Engineering Team anticipate will become more common in the future. The proposed system types are listed in Table H1. Specific manufactured products for each system type will be chosen in Phase 2 during the material procurement stage for laboratory testing.

Table H1 –Proposed Curtain Wall and Window Wall System Types

Description/Attributes	Description/Attributes
Stick-Built Curtain Wall • Thermally-broken aluminum captured system. • Commonly used in industry. • Can accommodate various types of spandrel cladding (e.g., glazing, metal panel, etc.). • Can accommodate various types of spandrel construction (e.g., sealed, ventilated, shadow box). • Anchor point at intermediate floor slab. • Individual components installed on site.	Window Wall (Canadian) • Thermally-broken aluminum captured system. • Very common in Canadian market. • Can accommodate various types of spandrel cladding (e.g., glazing, metal panel, etc.). • Can accommodate various types of spandrel construction (e.g., sealed, ventilated, shadow box) • Seismic deflection header detail • Significant integration with intermediate floor slab, more than US window wall systems, more space for insulation outboard of slab, but still high heat loss.
Unitized Curtain Wall • Thermally-broken aluminum system structural glazed (SSG) system. • Commonly used in industry. • Can accommodate various types of spandrel cladding (e.g., glazing, metal panel, etc.). • Can accommodate various types of spandrel construction (e.g., sealed, ventilated, shadow box). • Anchor point at intermediate floor slab. • Prefabricated panels shipped to and assembled on site.	Veneer System • Captured system with wood or steel mullions (SSG) • Alternative to traditional aluminum systems with potentially less heat loss • Can accommodate various types of spandrel cladding (e.g., glazing, metal panel, etc.). • Can accommodate various types of spandrel construction (e.g., sealed, ventilated, shadow box). • Individual components installed on site.
Window Wall (US) • Thermally-broken aluminum captured system. • Can accommodate various types of spandrel cladding (e.g., glazing, metal panel, etc.). • Can accommodate various types of spandrel construction (e.g., sealed, ventilated, shadow box). • Supported on slab edge; mullion above and below slab. • Greater integration with intermediate floor slab, less space available for insulation leading to greater heat loss.	Next Generation High Performance System • Industry state of the art high performance systems. • Thermally broken aluminum systems with insulation (R-40+).

Test Article Layout

The test article is divided into five panels that includes four opaque spandrel panels types, one vision panel, and an adjacent insulated steel-frame wall assembly as shown in Figure H1.

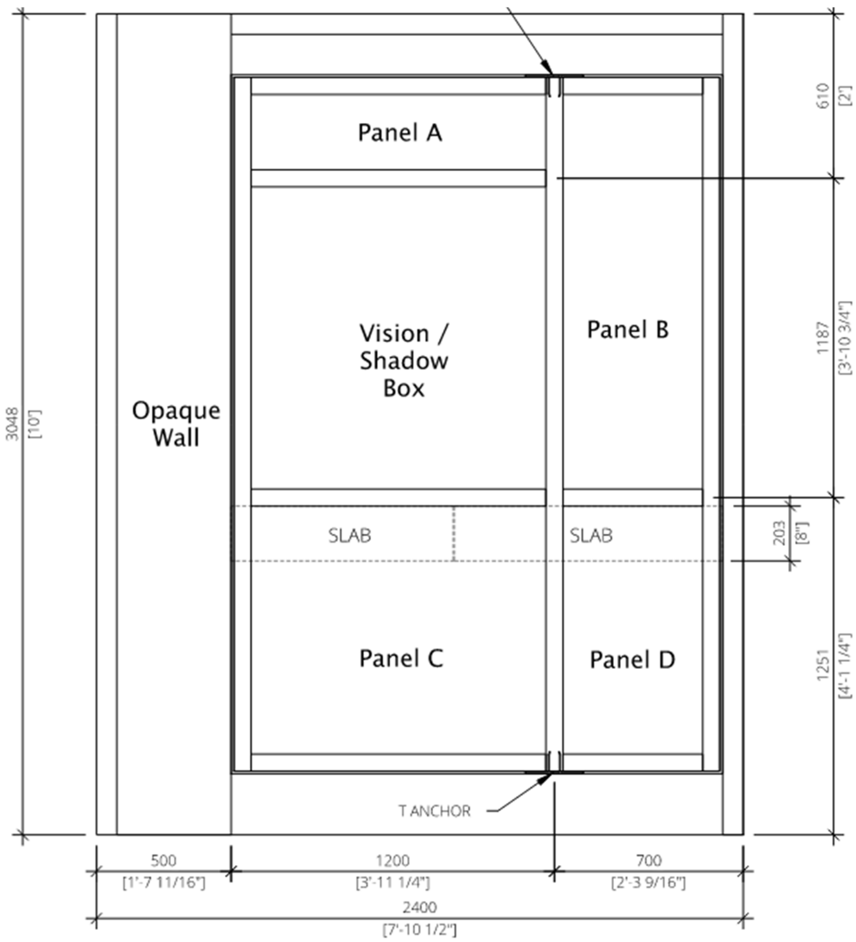


Figure H1 – Test Article Layout

The article also includes a truncated concrete intermediate floor slab at Panels C and D. The intermediate floor slab will help determine the impact of slab anchorages for curtain wall systems and deflection header frames for window wall systems on thermal performance.

The intermediate slab construction is shown in Figure H2 and will be 8 in. (203 mm) thick, 12 in. (305 mm) in depth, and span across entire 95 in. (2,400 mm) width of the test article. The slab will be composed of concrete with rigid insulation core and weigh less than approximately 600 lbs (272 kg). The intermediate slab will be supported on the interior side by steel support frame to help secure the slab into the test article. The interior steel support frame will be designed with input from ORNL.

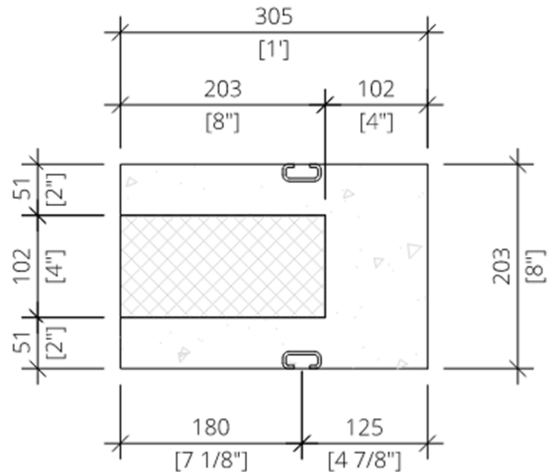


Figure H2 – Intermediate Slab Construction

The insulated steel-frame opaque wall consists of:

- 1/2 in. (12 mm) interior gypsum drywall.
- 6 in. x 1-5/8 in. (152 mm x 42 mm) 18 ga galvanized steel studs at 20 in. (500 mm) o.c.
- Fiberglass batt insulation in stud cavity (R-19).
- 1/2 in. (12 mm) exterior gypsum sheathing.
- 2 to 4 in. (51 to 102 mm) mineral fiber insulation (R-8.4 or R-16.8) attached with stick pins to the steel stud back up wall.

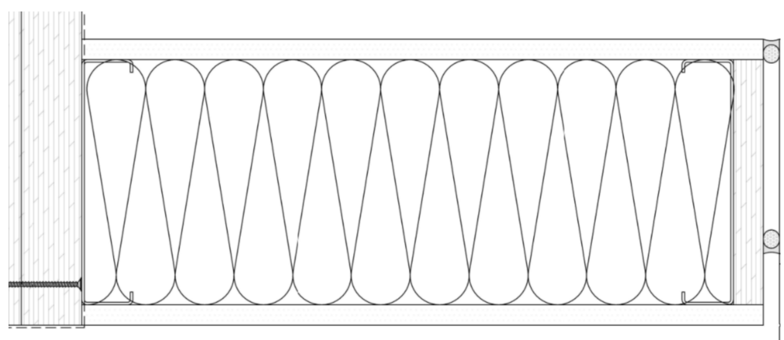
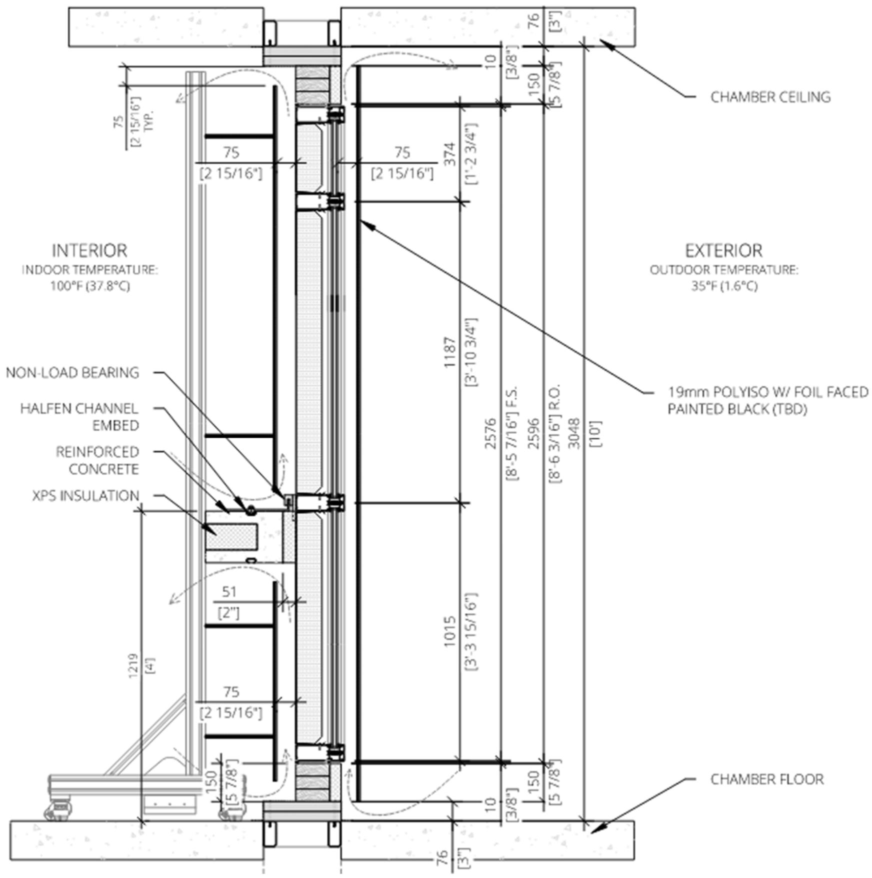


Figure H3 –Steel-Frame Wall Configuration (without Exterior Insulation)

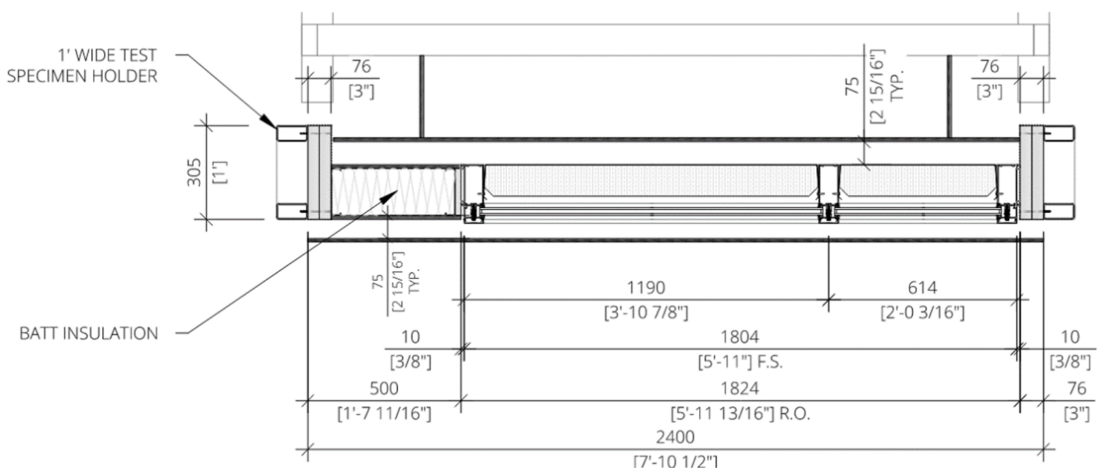
Detail descriptions about the article layout and variations in spandrel construction are provided in the Test Variations section.

Laboratory Test Description

The laboratory tests will be carried out at the Oak Ridge National Laboratory (ORNL) in Oak Ridge, Tennessee using hot box equipment capable of testing large articles at steady-state conditions as shown in Figure H4.



Vertical Section



Horizontal Section

Figure H4 –Vertical and Horizontal Sections Detail of Proposed Chamber

The test articles will be mounted on a movable frame that will be placed in between the indoor and outdoor rooms of the hot box as shown in Figure H5. The test frame is lined with aluminum sheets on the interior and insulated at the exterior. Wood framing and insulation will be added to the test frame to provide some thermal isolation to the test article.

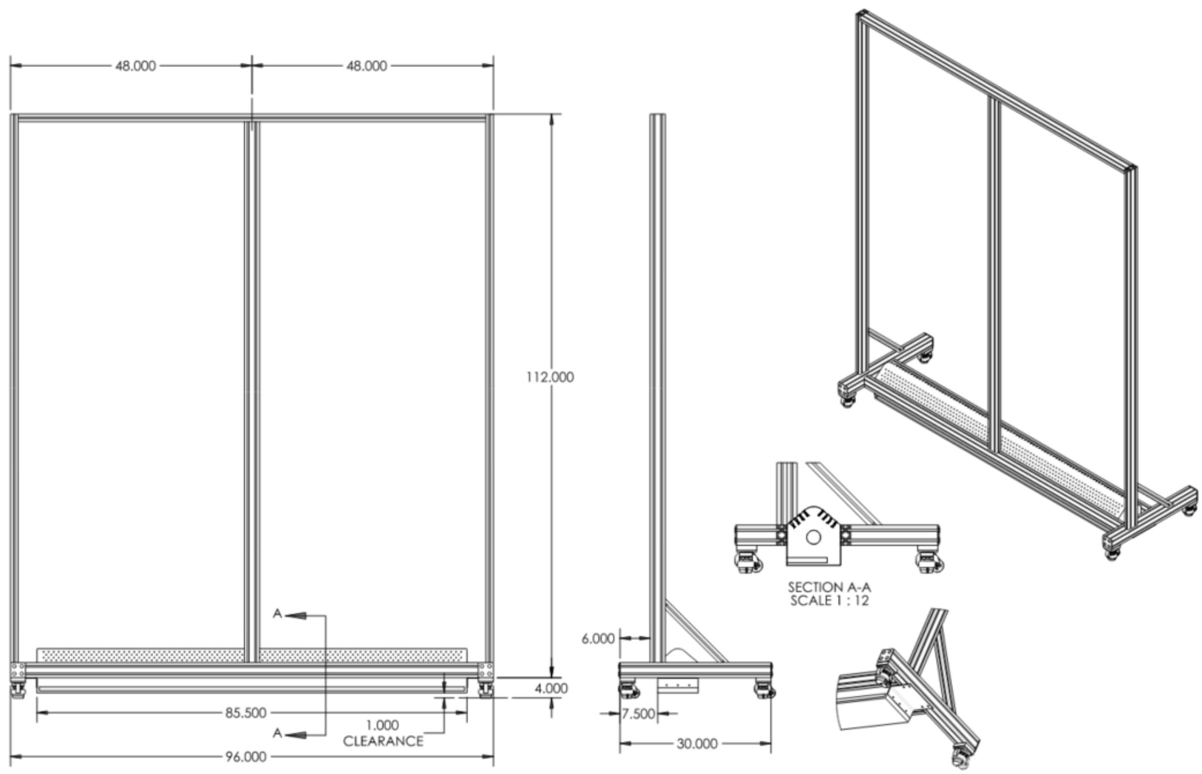


Figure H5 – Movable Test Frame Layout

Laboratory Test Procedures

The laboratory tests will measure temperatures at critical locations when the test articles are subjected to a temperature difference at steady-state conditions. The test procedures will be similar to ASTM C1199 and ASTM C1363 with the exception that:

- Heat flow metering will not be required.
- Measurements will be made for: surface temperatures, air temperatures, and airflow around the test article.

The articles will be tested at the following conditions:

- Indoor Temperature (Warm Side): 100°F (37.8°C)
- Outdoor Temperature (Cold Side): 35°F (1.7°C)
- Natural convection conditions on indoor/warm side.
- Winter wind conditions on outdoor/cold side.

Up to 200 surface temperature sensors, sensitive to 0.18°F (0.1°C), are to be installed at critical locations within the spandrel panel. The sensors will record measurements at frequent intervals (e.g., 5 to 15 minutes) to determine when a steady-state is achieved. Figure H6 shows an example temperature sensor layout based on the following principles:

- Measure center of panel, edge-of-panel, and frame temperatures of each unique panel.
- Measure interior temperature at corners.
- Measure edge-of-panel temperatures at varying distances from the frame.
- Measure temperatures within the spandrel assembly.
- Locate the majority of sensors away from baffle inlet/outlet.
- Pair interior and exterior sensors at the same elevation.

The final locations of the temperature sensors will be confirmed based on preliminary thermal simulations in Phase 2 and coordinated with ORNL. Additional sensors will be required to measure baffle temperature and cold/warm side air temperatures to confirm chamber operation.

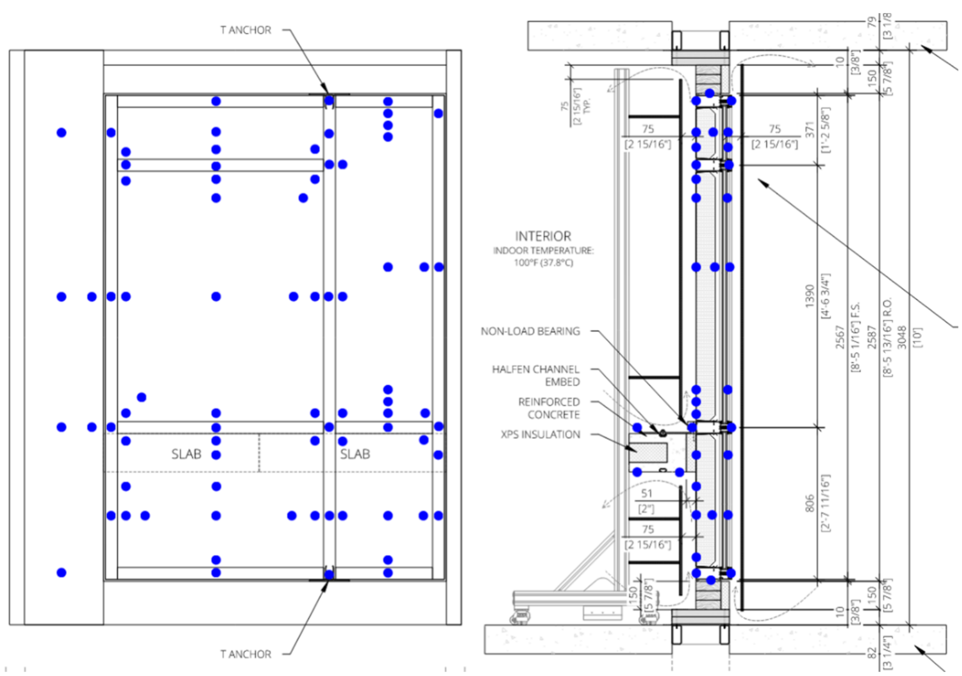


Figure H6 – Temperature Sensor Layout (Sensors in Blue)

In addition to temperature measurements on the surface of the test article, additional sensors will be required to measure:

- Low-Velocity Anemometers: To measure air flow on the cold and warm side of the test article. The measurement locations and arrangement of the anemometers will be coordinated with ORNL, but air velocity and temperature measurements will be required as close as 0.04 in. (1 mm) from the surface of the vision glass and/or spandrel assembly and will cover the entire height of the test article including at locations above and below the intermediate floor slab. The low-velocity omnidirectional anemometers should have a range of 0.03~3.28 ft/s (0.01~1 m/s)

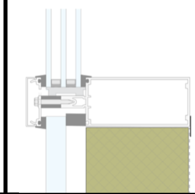
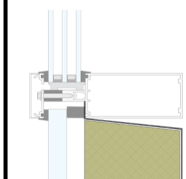
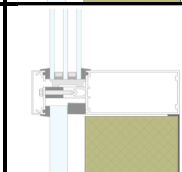
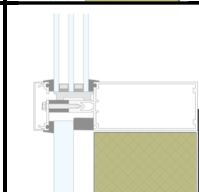
- Intermediate Floor Temperature Sensors: To measure surface temperature of the intermediate floor near the test article. Temperature sensor location to be determined with ORNL.
- Ambient Air Temperature Sensors: To measure ambient cold and warm side temperatures. Temperature sensor location to be determined with ORNL.

Test Variations

All tested curtain wall and window wall systems will share the same panel layout as shown in Figure H1, however, the components within the spandrel panel assemblies will vary between tests for all systems. Each system will undergo multiple rounds of testing with variations to the spandrel and framed wall sections. In Appendix H, individual changes to the spandrel panels are referred to as ‘variables’, which are listed in Table H2, and set of these variables implemented on each panel are referred to as ‘variants’ which are listed in the Variant Matrix at the end of Appendix H. Variations from the ‘variables’ are considered to be minor and the ‘variants’ for the panels will not alter the layout of the test article.

Table H2: List of Variables for Laboratory Testing

Component	Variables	Description
Exterior Accessory	None	No modifications to as built system.
	Aluminum Pressure Plate	Replace pressure plate in existing system with an aluminum pressure plate compatible with tested captured framing systems.
	Fiberglass Pressure Plate	Replace pressure plate in existing system with a fiberglass pressure plate compatible with tested captured framing systems.
	Deep Cap	Deep exterior snap cap.
Intermittent Thermal Bridges	Fastener Spacing #1	Default spacing of fasteners through pressure plate in captured framing systems at 12 in. (305 mm).
	Fastener Spacing #2	Modified spacing of fasteners through pressure plate in captured framing systems at 6 in. (152 mm).
	Vertical Solar Shade	Add vertical solar shade connector to framing system. Connector must be compatible with tested system from same manufacturer.
	Glass Chair #1	Metal glass chair/shim supporting glazed spandrel cladding Type 1.
	Glass Chair #2	Metal glass chair/shim supporting glazed spandrel cladding Type 2.
	Non-Metal Glass Chair	Non-metal glass chair/shim supporting glazed spandrel cladding.
Spandrel Cladding	Single-Glazed	Single tinted glass pane.
	Double-Glazed	Double glazed IGU with aluminum spacer.
	Triple-Glazed	Triple glazed IGU with aluminum spacers.
	Metal Panel (Sheet)	Painted galvanized steel sheet panel.
	Metal Panel (ACM)	Painted aluminum composite metal panel with polyethylene core *(details to be determined based on procurement).*
	Insulated Metal Panel	Panels with galvanized steel skins and insulating foam core *(details to be determined based on procurement).*
	Stone	Stone type to be determined.
	Terra Cotta	Terra cotta panel to be determined.
	VIG	Vacuum insulated glazing cladding.
	VIP	Vacuum insulated panel cladding.
Intermediate Panel	None	No panels between glazed spandrel cladding and spandrel insulation.
	Yes	Metal panel in between glazed spandrel cladding and spandrel insulation to create shadow box condition.
Spandrel Venting	Sealed	No openings along perimeter of spandrel panel into spandrel cavity.
Backpan Material	Galvanized Steel Painted	18 ga painted galvanized steel sheet.
	Galvanized Steel Unpainted	18 ga galvanized steel sheet.
	Aluminum Sheet, Painted	18 ga painted aluminum sheet.
	Aluminum Composite	Aluminum composite panel.
	Aluminum Tape	Aluminum tape.
Backpan Insulation Material	Mineral Fiber	R-4.2/inch mineral fiber.
	CCSP + Spray Thermal Insulation	Closed cell spray applied polyurethane foam insulation with thermal insulation.
	Foiled Faced Mineral Fiber Insulation	Foil-faced mineral fiber insulation.
Backpan Insulation Thickness	1 in.	1 in. (25 mm) insulation
	2 in.	2 in. (51 mm) insulation
	3 in.	3 in. (76 mm) insulation
	4 in.	4 in. (102 mm) insulation

Component	Variables	Description
	6 in.	6 in. (152 mm) insulation
Backpan Configuration	Taped	 Spandrel insulation is taped to interior side of frame.
	Returned to Glazing Pocket	 Metal panel backpan with full depth returns covering spandrel insulation.
	Small Return	 Metal panel backpan with partial depth returns covering spandrel insulation.
	Flat Panel	 Flat metal panel.
Interior Wall Insulation	None	No insulation on the interior side of the back pan (between back pan and interior steel-frame wall).
	CCSPF Insulated Steel-Frame Wall	2 in. (51mm) continuous closed cell polyurethane foam insulation between back pan and steel frame wall.
	Batt Insulated Steel-Frame Wall	Continuous batt insulation between back pan and steel frame wall.
	Foil-faced Batt Insulation (Full Depth)	Continuous foil-faced fiberglass or mineral fiber batt insulation covering framing and back pan.
	Foil-faced Batt Insulation (wrap)	Foil-faced fiberglass or mineral fiber batt insulation wrapping around mullions.
Deflection Header	None	Not applicable for certain systems.
	Deflection Anchor	Anchor to intermediate slab to accommodate movement.
	Without Thermal Break	Aluminum deflection header frame without thermal break
	With Thermal Break	Aluminum deflection header frame with thermal break
Adjacent Wall	None	Not applicable
	Interior Insulated	Interior insulation between stud cavity (e.g., R-19 fiberglass batt insulation)
	Exterior Insulated, Unaligned	Exterior insulation outboard of sheathing with framing system not aligned with mid-point of insulation
	Exterior Insulated, Aligned	Exterior insulation outboard of sheathing with framing system aligned with mid-point of insulation

Schedule

Laboratory testing of the articles will be completed in 2023 and 2024. The exact timelines of the tests will depend on coordination with ORNL as well as with procurement and construction schedules of suppliers and approved installers. It is estimated testing of each system will take approximately 18 working days (~30 calendar days) which includes installation and article takedown as shown in Table H3.

Table H3 –Approximate Laboratory Test Schedule for One System

Day	Description
1 and 2	Installation of Test Article
3 and 4	Instrumenting Test Article
4 through 8	Baseline Testing and review of results by Engineering Team
9	Modifying Article for Variant No. 1
10 and 11	Variant No. 1 Testing
12	Modifying Article for Variant No. 2
13 and 14	Variant No. 2 Testing
15	Modifying Article for Variant No. 3
16 and 17	Variant No. 3 Testing
18	Takedown Test Article

This schedule will be repeated for all six systems with some modifications to the number of variants tested. Note, the Engineering Team assumes System No. 1 will have a longer schedule to allow for additional time for review measurements and coordination with preliminary models. The Engineering Team would like to have a brief period in between testing Systems No.1 and No. 2 to allow for the review of measurements and discussion. Following this preliminary schedule, the tests should take around 90 to 108 working days.

Variant Matrix

		Frame Type	Glazing Method	Exterior Accessory	Intermittent Thermal Bridges	Spandrel Cladding	Intermediate Panel	Spandrel Venting	Backpan Material	Backpan Insulation	Backpan Insulation Thickness	Backpan	Interior Insulation	Deflection Header	Adjacent Exterior Wall
Stick-Built Curtain Wall	Panel A v1 (Base)	Thermally Broken Aluminum	Captured	Aluminum Pressure Plate	Fastener Spacing #1	Single-glazed	Yes (e.g. Shadow Box)	Sealed	Galv. Steel, unpainted	Mineral Wool	4"	Returned to Glazing Pocket	None	None	Ext. Insulated, Unaligned
	Panel B v1	Thermally Broken Aluminum	Captured	Aluminum Pressure Plate	Fastener Spacing #1	Single-glazed	Yes (e.g. Shadow Box)	Sealed	Galv. Steel, unpainted	Mineral Wool	4"	Returned to Glazing Pocket	None	None	
	Panel C v1	Thermally Broken Aluminum	Captured	Aluminum Pressure Plate	Fastener Spacing #1	Metal Panel (ACM)	None	Sealed	Galv. Steel, unpainted	Mineral Wool	4"	Returned to Glazing Pocket	None	None	Ext. Insulated, Unaligned
	Panel D v1	Thermally Broken Aluminum	Captured	Aluminum Pressure Plate	Fastener Spacing #1	Metal Panel (ACM)	None	Sealed	Galv. Steel, unpainted	Mineral Wool	4"	Returned to Glazing Pocket	None	None	
	E (Vision)	Thermally Broken Aluminum	Captured	Aluminum Pressure Plate	Fastener Spacing #1	Double-glazed	None							None	Ext. Insulated, Unaligned
	Panel A v2	Thermally Broken Aluminum	Captured	Fiberglass Pressure Plate	Fastener Spacing #1	Triple-glazed	Yes (e.g. Shadow Box)	Sealed	AL Sheet, painted	Mineral Wool	4"	Flat Panel	None	None	Ext. Insulated, Unaligned
	Panel B v2	Thermally Broken Aluminum	Captured	Fiberglass Pressure Plate	Fastener Spacing #1	Double-glazed	Yes (e.g. Shadow Box)	Sealed	Galv. Steel, unpainted	Mineral Wool	4"	Returned to Glazing Pocket	Foil-faced batt (FG or MW), wrap	None	
	Panel C v2	Thermally Broken Aluminum	Captured	Aluminum Pressure Plate	Fastener Spacing #2	Metal Panel (ACM)	None	Sealed	AL Sheet, painted	Mineral Wool	4"	Flat Panel	None	None	Ext. Insulated, Unaligned
	Panel D v2	Thermally Broken Aluminum	Captured	Aluminum Pressure Plate	Fastener Spacing #2	Metal Panel (ACM)	None	Sealed	Galv. Steel, unpainted	Mineral Wool	4"	Returned to Glazing Pocket	Foil-faced batt (FG or MW), wrap	None	
	E (Vision)	Thermally Broken Aluminum	Captured	Aluminum Pressure Plate	Fastener Spacing #2	Double-glazed	None								Ext. Insulated, Unaligned
	Panel A v3	Thermally Broken Aluminum	Captured	Aluminum Pressure Plate	Fastener Spacing #1	Triple-glazed	Yes (e.g. Shadow Box)	Sealed	AL Sheet, painted	Mineral Wool	4"	Flat Panel	None	None	Ext. Insulated, Unaligned
	Panel B v3	Thermally Broken Aluminum	Captured	Aluminum Pressure Plate	Fastener Spacing #1	Double-glazed	Yes (e.g. Shadow Box)	Sealed	Galv. Steel, unpainted	Mineral Wool	4"	Returned to Glazing Pocket	Foil-faced batt (FG or MW), full depth	None	
	Panel C v3	Thermally Broken Aluminum	Captured	Aluminum Pressure Plate	Fastener Spacing #1	VIG	None	Sealed	AL Sheet, painted	Mineral Wool	4"	Flat Panel	None	None	Ext. Insulated, Unaligned
	Panel D v3	Thermally Broken Aluminum	Captured	Aluminum Pressure Plate	Fastener Spacing #1	VIG	None	Sealed	Galv. Steel, unpainted	Mineral Wool	4"	Returned to Glazing Pocket	Foil-faced batt (FG or MW), full depth	None	
	E (Vision)	Thermally Broken Aluminum	Captured	Aluminum Pressure Plate	Fastener Spacing #1	Double-glazed	None								Ext. Insulated, Unaligned
	Panel A v4	Thermally Broken Aluminum	Captured	Fiberglass Pressure Plate	Fastener Spacing #1	Triple-glazed	Yes (e.g. Shadow Box)	Sealed	AL Sheet, painted	Mineral Wool	4"	Flat Panel	CCSPF Insulated Steel-frame Wall	None	Ext. Insulated, Aligned
	Panel B v4	Thermally Broken Aluminum	Captured	Aluminum Pressure Plate	Vertical Solar Shade	Double-glazed	Yes (e.g. Shadow Box)	Sealed	Galv. Steel, unpainted	Mineral Wool	4"	Returned to Glazing Pocket	CCSPF Insulated Steel-frame Wall	None	
	Panel C v4	Thermally Broken Aluminum	Captured	Deep Cap	Fastener Spacing #1	VIG	None	Sealed	AL Sheet, painted	Mineral Wool	4"	Flat Panel	CCSPF Insulated Steel-frame Wall	None	Ext. Insulated, Aligned
	Panel D v4	Thermally Broken Aluminum	Captured	Deep Cap	Vertical Solar Shade	VIG	None	Sealed	Galv. Steel, unpainted	Mineral Wool	4"	Returned to Glazing Pocket	CCSPF Insulated Steel-frame Wall	None	
	E (Vision)	Thermally Broken Aluminum	Captured	Aluminum Pressure Plate	Fastener Spacing #1	Double-glazed	None								Ext. Insulated, Aligned

		Frame Type	Glazing Method	Exterior Accessory	Intermittent Thermal Bridges	Spandrel Cladding	Intermediate Panel	Spandrel Venting	Backpan Material	Backpan Insulation	Backpan Insulation Thickness	Backpan	Interior Insulation	Deflection Header	Adjacent Exterior Wall
Unitized Curtain Wall	Panel A v1 (Base)	Thermally Broken Aluminum	SSG	None	Glass Chair #1	Triple-glazed	Yes (e.g. Shadow Box)	Sealed	Galv. Steel, unpainted	Mineral Wool	4"	Flat Panel	None	None	Ext. Insulated, Aligned
	Panel B v1	Thermally Broken Aluminum	SSG	None	Fastener Spacing #1	Metal Panel (ACM)	None	Sealed	Galv. Steel, unpainted	Mineral Wool	4"	Flat Panel	None	None	
	Panel C v1	Thermally Broken Aluminum	SSG	None	Glass Chair #1	Triple-glazed	None	Sealed	Galv. Steel, unpainted	Mineral Wool	4"	Flat Panel	None	None	Ext. Insulated, Aligned
	Panel D v1	Thermally Broken Aluminum	SSG	None	Fastener Spacing #1	Metal Panel (ACM)	None	Sealed	Galv. Steel, unpainted	Mineral Wool	4"	Flat Panel	None	None	
	E (Vision)	Thermally Broken Aluminum	SSG	None	Glass Chair #2	Triple-glazed	None								Ext. Insulated, Aligned
	Panel A v2	Thermally Broken Aluminum	SSG	None	Glass Chair #1	Triple-glazed	Yes (e.g. Shadow Box)	Sealed	Galv. Steel, painted	CCSPF + Spray Thermal Insulation	4"	Small Return	Foil-faced batt (FG or MW), wrap	None	Ext. Insulated, Aligned
	Panel B v2	Thermally Broken Aluminum	SSG	None	Fastener Spacing #1	Metal Panel (ACM)	None	Sealed	Galv. Steel, painted	CCSPF + Spray Thermal Insulation	4"	Small Return	Foil-faced batt (FG or MW), wrap	None	
	Panel C v2	Thermally Broken Aluminum	SSG	None	Glass Chair #1	Triple-glazed	None	Sealed	AL Tape	Foiled Face Min Wool	4"	Taped	Foil-faced batt (FG or MW), wrap	None	Ext. Insulated, Aligned
	Panel D v2	Thermally Broken Aluminum	SSG	None	Fastener Spacing #1	Metal Panel (ACM)	None	Sealed	AL Tape	Foiled Face Min Wool	4"	Taped	Foil-faced batt (FG or MW), wrap	None	
	E (Vision)	Thermally Broken Aluminum	SSG	None	Glass Chair #2	Triple-glazed	None								Ext. Insulated, Aligned

		Frame Type	Glazing Method	Exterior Accessory	Intermittent Thermal Bridges	Spandrel Cladding	Intermediate Panel	Spandrel Venting	Backpan Material	Backpan Insulation	Backpan Insulation Thickness	Backpan	Interior Insulation	Deflection Header	Adjacent Exterior Wall
Window Wall - US	Panel A v1 (Base)	Thermally Broken Aluminum	Captured	None	Fastener Spacing #1	Triple-glazed	None	Sealed	Galv. Steel, unpainted	Mineral Wool	4"	Small Return	None	None	Ext. Insulated, Aligned
	Panel B v1	Thermally Broken Aluminum	Captured	None	Fastener Spacing #1	Double-glazed	None	Sealed	Galv. Steel, unpainted	Mineral Wool	4"	Small Return	None	None	
	Panel C Upper v1	Thermally Broken Aluminum	Captured	None	Fastener Spacing #1	Double-glazed	None	Sealed	Galv. Steel, unpainted	Mineral Wool	1"	n/a	None	None	Ext. Insulated, Aligned
	Panel C Lower v1	Thermally Broken Aluminum	Captured	None	Fastener Spacing #1	Double-glazed	Yes (e.g. Shadow Box)	Sealed	Galv. Steel, painted	Mineral Wool	4"	Small Return	None	None	Ext. Insulated, Aligned
	Panel D Upper v1	Thermally Broken Aluminum	Captured	None	Fastener Spacing #1	Metal Panel (ACM)	None	Sealed	Galv. Steel, unpainted	Mineral Wool	1"	n/a	None	None	
	Panel D Lower v1	Thermally Broken Aluminum	Captured	None	Fastener Spacing #1	Metal Panel (ACM)	None	Sealed	Galv. Steel, painted	Mineral Wool	4"	Small Return	None	None	
	E (Vision)	Thermally Broken Aluminum	Captured	None	Fastener Spacing #1	Triple-glazed	None								Ext. Insulated, Aligned
	Panel A v2	Thermally Broken Aluminum	Captured	None	Fastener Spacing #1	Triple-glazed	None	Sealed	Galv. Steel, unpainted	Mineral Wool	4"	Small Return	Foil-faced batt (FG or MW), full depth	None	Ext. Insulated, Aligned
	Panel B v2	Thermally Broken Aluminum	Captured	None	Fastener Spacing #1	Double-glazed	None	Sealed	Galv. Steel, unpainted	Mineral Wool	4"	Small Return	Foil-faced batt (FG or MW), full depth	None	
	Panel C Upper v2	Thermally Broken Aluminum	Captured	None	Fastener Spacing #1	Double-glazed	None	Sealed	Galv. Steel, unpainted	Mineral Wool	2"	n/a	None	None	Ext. Insulated, Aligned
	Panel C Lower v2	Thermally Broken Aluminum	Captured	None	Fastener Spacing #1	Double-glazed	Yes (e.g. Shadow Box)	Sealed	Galv. Steel, painted	Mineral Wool	4"	Small Return	Foil-faced batt (FG or MW), full depth	None	Ext. Insulated, Aligned
	Panel D Upper v2	Thermally Broken Aluminum	Captured	None	Fastener Spacing #2	Metal Panel (ACM)	None	Sealed	Galv. Steel, unpainted	Mineral Wool	2"	n/a	None	None	
	Panel D Lower v2	Thermally Broken Aluminum	Captured	None	Fastener Spacing #2	Metal Panel (ACM)	None	Sealed	Galv. Steel, painted	Mineral Wool	4"	Small Return	Foil-faced batt (FG or MW), full depth	None	
	E (Vision)	Thermally Broken Aluminum	Captured	None	Fastener Spacing #1	Triple-glazed	None								Ext. Insulated, Aligned
	Panel A v3	Thermally Broken Aluminum	Captured	None	Fastener Spacing #1	Triple-glazed	None	Sealed	Galv. Steel, unpainted	Mineral Wool	4"	Small Return	Batt Insulated Steel-frame Wall	None	Ext. Insulated, Aligned
	Panel B v3	Thermally Broken Aluminum	Captured	None	Fastener Spacing #1	Double-glazed	None	Sealed	Galv. Steel, unpainted	Mineral Wool	4"	Small Return	Batt Insulated Steel-frame Wall	None	
	Panel C Upper v3	Thermally Broken Aluminum	Captured	None	Fastener Spacing #1	Double-glazed	None	Sealed	Galv. Steel, unpainted	Mineral Wool	2"	n/a	None	None	Ext. Insulated, Aligned
	Panel C Lower v3	Thermally Broken Aluminum	Captured	None	Fastener Spacing #1	Double-glazed	Yes (e.g. Shadow Box)	Sealed	Galv. Steel, painted	Mineral Wool	4"	Small Return	Batt Insulated Steel-frame Wall	None	Ext. Insulated, Aligned
	Panel D Upper v3	Thermally Broken Aluminum	Captured	None	Fastener Spacing #2	Metal Panel (ACM)	None	Sealed	Galv. Steel, unpainted	Mineral Wool	2"	n/a	None	None	
	Panel D Lower v3	Thermally Broken Aluminum	Captured	None	Fastener Spacing #2	Metal Panel (ACM)	None	Sealed	Galv. Steel, painted	Mineral Wool	4"	Small Return	Batt Insulated Steel-frame Wall	None	
	E (Vision)	Thermally Broken Aluminum	Captured	None	Fastener Spacing #1	Triple-glazed	None								Ext. Insulated, Aligned

		Frame Type	Glazing Method	Exterior Accessory	Intermittent Thermal Bridges	Spandrel Cladding	Intermediate Panel	Spandrel Venting	Backpan Material	Backpan Insulation	Backpan Insulation Thickness	Backpan	Interior Insulation	Deflection Header	Adjacent Exterior Wall
Window Wall - CAN	Panel A v1 (Base)	Thermally Broken Aluminum	Captured	None	None	Triple-glazed	Yes (e.g. Shadow Box)	Sealed	Galv. Steel, unpainted	Mineral Wool	4"	Small Return	None	None	Ext. Insulated, Unaligned
	Panel B v1	Thermally Broken Aluminum	Captured	None	None	Double-glazed	Yes (e.g. Shadow Box)	Sealed	Galv. Steel, unpainted	Mineral Wool	4"	Small Return	Insulated Frame	None	
	Panel C v1	Thermally Broken Aluminum	Captured	None	None	Metal Panel (ACM)	None	Sealed	Galv. Steel, unpainted	Mineral Wool	4"	Returned to Glazing Pocket	None	With Thermal Break, Unaligned	Ext. Insulated, Unaligned
	Panel D v1	Thermally Broken Aluminum	Captured	None	None	Metal Panel (ACM)	None	Sealed	Galv. Steel, unpainted	Mineral Wool	4"	Returned to Glazing Pocket	None	With Thermal Break, Unaligned	
	E (Vision)	Thermally Broken Aluminum	Captured	None	None	Triple-glazed	None							None	Ext. Insulated, Unaligned
	Panel A v2	Thermally Broken Aluminum	Captured	None	None	Triple-glazed	Yes (e.g. Shadow Box)	Sealed	AL Sheet, painted	Mineral Wool	6"	Flat Panel	None	None	Ext. Insulated, Aligned
	Panel B v2	Thermally Broken Aluminum	Captured	None	None	Double-glazed	Yes (e.g. Shadow Box)	Sealed	AL Sheet, painted	Mineral Wool	6"	Flat Panel	Insulated Frame	None	
	Panel C v2	Thermally Broken Aluminum	Captured	None	None	Metal Panel (ACM)	None	Sealed	Galv. Steel, unpainted	Mineral Wool	4"	Returned to Glazing Pocket	None	With Thermal Break, Aligned	Ext. Insulated, Aligned
	Panel D v2	Thermally Broken Aluminum	Captured	None	None	Metal Panel (ACM)	None	Sealed	Galv. Steel, unpainted	Mineral Wool	4"	Returned to Glazing Pocket	None	With Thermal Break, Aligned	
	E (Vision)	Thermally Broken Aluminum	Captured	None	None	Triple-glazed	None								Ext. Insulated, Aligned
	Panel A v3	Thermally Broken Aluminum	Captured	None	None	Triple-glazed	Yes (e.g. Shadow Box)	Sealed	AL Sheet, painted	Mineral Wool	6"	Flat Panel	Batt Insulated Steel-frame Wall	None	Ext. Insulated, Aligned
	Panel B v3	Thermally Broken Aluminum	Captured	None	None	Double-glazed	Yes (e.g. Shadow Box)	Sealed	AL Sheet, painted	Mineral Wool	6"	Flat Panel	Batt Insulated Steel-frame Wall	None	
	Panel C v3	Thermally Broken Aluminum	Captured	None	None	Metal Panel (ACM)	None	Sealed	Galv. Steel, unpainted	Mineral Wool	4"	Returned to Glazing Pocket	CCSPF Insulated Steel-frame Wall	With Thermal Break, Aligned	Ext. Insulated, Aligned
	Panel D v3	Thermally Broken Aluminum	Captured	None	None	Metal Panel (ACM)	None	Sealed	Galv. Steel, unpainted	Mineral Wool	4"	Returned to Glazing Pocket	CCSPF Insulated Steel-frame Wall	With Thermal Break, Aligned	
	E (Vision)	Thermally Broken Aluminum	Captured	None	None	Triple-glazed	None								Ext. Insulated, Aligned

		Frame Type	Glazing Method	Exterior Accessory	Intermittent Thermal Bridges	Spandrel Cladding	Intermediate Panel	Spandrel Venting	Backpan Material	Backpan Insulation	Backpan Insulation Thickness	Backpan	Interior Insulation	Deflection Header	Adjacent Exterior Wall
Next Gen - Veneer	Panel A v1 (Base)	Thermally Broken Aluminum	Captured	Aluminum Pressure Plate	Fastener Spacing #1	Triple-glazed	Yes (e.g. Shadow Box)	Sealed	AL Tape	Foiled Face Min Wool	4"	Taped	None	None	Ext. Insulated, Aligned
	Panel B v1	Wood	Captured	Aluminum Pressure Plate	Fastener Spacing #1	Double-glazed	None	Sealed	AL Tape	Foiled Face Min Wool	4"	Taped	None	None	
	Panel C v1	Steel	Captured	Aluminum Pressure Plate	Fastener Spacing #1	Triple-glazed	None	Sealed	AL Tape	Foiled Face Min Wool	4"	Taped	None	None	Ext. Insulated, Aligned
	Panel D v1	Steel	Captured	Aluminum Pressure Plate	Fastener Spacing #1	Double-glazed	None	Sealed	AL Tape	Foiled Face Min Wool	4"	Taped	None	None	
	E (Vision)	Wood	Captured	Aluminum Pressure Plate	Fastener Spacing #1	Triple-glazed	None								Ext. Insulated, Aligned
	Panel A v2	Thermally Broken Aluminum	Captured	Aluminum Pressure Plate	Non-metal Glass Chair	Triple-glazed	Yes (e.g. Shadow Box)	Sealed	Galv. Steel, unpainted	Mineral Wool	6"	Flat Panel	None	None	Ext. Insulated, Aligned
	Panel B v2	Wood	Captured	Aluminum Pressure Plate	Non-metal Glass Chair	VIP	None	Sealed	Galv. Steel, unpainted	Mineral Wool	6"	Flat Panel	None	None	
	Panel C v2	Steel	Captured	Aluminum Pressure Plate	Fastener Spacing #1	Triple-glazed	None	Sealed	Galv. Steel, unpainted	Mineral Wool	6"	Flat Panel	None	None	Ext. Insulated, Aligned
	Panel D v2	Steel	Captured	Aluminum Pressure Plate	Fastener Spacing #1	Double-glazed	None	Sealed	Galv. Steel, unpainted	Mineral Wool	6"	Flat Panel	None	None	
	E (Vision)	Wood	Captured	Aluminum Pressure Plate	Fastener Spacing #1	VIP	None								Ext. Insulated, Aligned
	Panel A v3	Thermally Broken Aluminum	Captured	Fiberglass Pressure Plate	Non-metal Glass Chair	Triple-glazed	Yes (e.g. Shadow Box)	Sealed	Galv. Steel, unpainted	Mineral Wool	6"	Flat Panel	Foil-faced batt (FG or MW), wrap	None	Ext. Insulated, Aligned
	Panel B v3	Wood	Captured	Aluminum Pressure Plate	Vertical Solar Shade	VIP	None	Sealed	Galv. Steel, unpainted	Mineral Wool	6"	Flat Panel	Foil-faced batt (FG or MW), wrap	None	
	Panel C v3	Steel	Captured	Deep Cap	Fastener Spacing #1	Triple-glazed	None	Sealed	Galv. Steel, unpainted	Mineral Wool	6"	Flat Panel	Foil-faced batt (FG or MW), full depth	None	Ext. Insulated, Aligned
	Panel D v3	Steel	Captured	Deep Cap	Vertical Solar Shade	Double-glazed	None	Sealed	Galv. Steel, unpainted	Mineral Wool	6"	Flat Panel	Foil-faced batt (FG or MW), full depth	None	
	E (Vision)	Wood	Captured	Aluminum Pressure Plate	Fastener Spacing #1	VIP	None								Ext. Insulated, Aligned

		Frame Type	Glazing Method	Exterior Accessory	Intermittent Thermal Bridges	Spandrel Cladding	Intermediate Panel	Spandrel Venting	Backpan Material	Backpan Insulation	Backpan Insulation Thickness	Backpan	Interior Insulation	Deflection Header	Adjacent Exterior Wall
Next Gen - Aluminum	Panel A v1 (Base)	Thermally Broken Aluminum	Captured	None	Fastener Spacing #1	Triple-glazed	Yes (e.g. Shadow Box)	Sealed	Galv. Steel, unpainted	Mineral Wool		Returned to Glazing Pocket	None	None	Ext. Insulated, Unaligned
	Panel B v1	Thermally Broken Aluminum	Captured	None	Fastener Spacing #1	Double-glazed	None	Sealed	Galv. Steel, unpainted	Mineral Wool		Returned to Glazing Pocket	None	None	
	Panel C v1	Thermally Broken Aluminum	Captured	None	Fastener Spacing #1	Triple-glazed	None	Sealed	Galv. Steel, unpainted	Mineral Wool		Returned to Glazing Pocket	None	None	Ext. Insulated, Unaligned
	Panel D v1	Thermally Broken Aluminum	Captured	None	Fastener Spacing #1	Double-glazed	None	Sealed	Galv. Steel, unpainted	Mineral Wool		Returned to Glazing Pocket	None	None	
	E (Vision)	Thermally Broken Aluminum	Captured	None	Fastener Spacing #1	Triple-glazed	None								Ext. Insulated, Unaligned
	Panel A v2	Thermally Broken Aluminum	Captured	None	Fastener Spacing #2	Terracotta	Yes (e.g. Shadow Box)	Sealed	Galv. Steel, unpainted	Mineral Wool		Returned to Glazing Pocket	None	None	Ext. Insulated, Aligned
	Panel B v2	Thermally Broken Aluminum	Captured	None	Fastener Spacing #2	Terracotta	None	Sealed	Galv. Steel, unpainted	Mineral Wool		Returned to Glazing Pocket	None	None	
	Panel C v2	Thermally Broken Aluminum	Captured	None	Fastener Spacing #2	Terracotta	None	Sealed	Galv. Steel, unpainted	Mineral Wool		Returned to Glazing Pocket	None	None	Ext. Insulated, Aligned
	Panel D v2	Thermally Broken Aluminum	Captured	None	Fastener Spacing #2	Terracotta	None	Sealed	Galv. Steel, unpainted	Mineral Wool		Returned to Glazing Pocket	None	None	
	E (Vision)	Thermally Broken Aluminum	Captured	None	Fastener Spacing #2	Triple-glazed	None								Ext. Insulated, Aligned
	Panel A v3	Thermally Broken Aluminum	Captured	None	Glass Chair #2	Terracotta	Yes (e.g. Shadow Box)	Sealed	Galv. Steel, unpainted	Mineral Wool		Returned to Glazing Pocket	Foil-faced batt (FG or MW), wrap	None	Ext. Insulated, Aligned
	Panel B v3	Thermally Broken Aluminum	Captured	None	Glass Chair #2	Terracotta	None	Sealed	Galv. Steel, unpainted	Mineral Wool		Returned to Glazing Pocket	Foil-faced batt (FG or MW), wrap	None	
	Panel C v3	Thermally Broken Aluminum	Captured	None	Glass Chair #2	Terracotta	None	Sealed	Galv. Steel, unpainted	Mineral Wool		Returned to Glazing Pocket	Foil-faced batt (FG or MW), full depth	None	Ext. Insulated, Aligned
	Panel D v3	Thermally Broken Aluminum	Captured	None	Glass Chair #2	Terracotta	None	Sealed	Galv. Steel, unpainted	Mineral Wool		Returned to Glazing Pocket	Foil-faced batt (FG or MW), full depth	None	
	E (Vision)	Thermally Broken Aluminum	Captured	None	Glass Chair #2	Triple-glazed	None								Ext. Insulated, Aligned