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Thermal Analysis of Cold-Formed Steel Wall Assemblies

American Iron and Steel Institute

research report

Thermal Analysis of Cold-Formed Steel Wall Assemblies

RESEARCH REPORT RP18-1

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American Iron and Steel Institute

DISCLAIMER

PREFACE

In February 2018, this report was first issued. In April 2018, this report was reissued because errors were found and corrected in the tabulated values for thickness, conductivity and R-value for gypsum sheathing (ID 4) in Table A-5: Material Properties Used in Project Assemblies.

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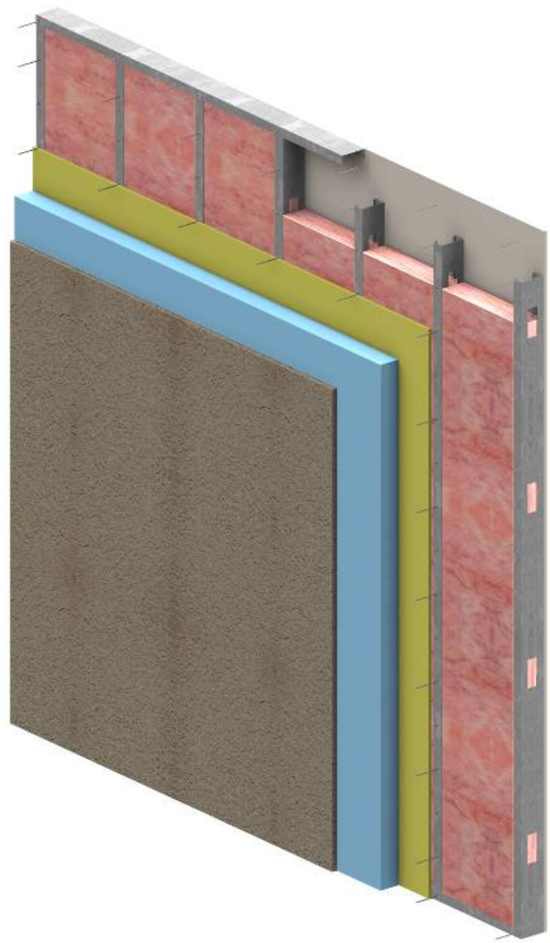
Thermal Analysis of Cold-Formed Steel Wall Assemblies for AISI



Presented to:

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EXECUTIVE SUMMARY

For building envelope assemblies, thermal bridging through conductive components can greatly reduce the overall thermal resistance of that assembly. Steel stud assemblies are particularly susceptible to thermal bridging due to the high thermal conductivity of the steel components. Being able to accurately capture these impacts can provide designers with more realistic information to drive better design decisions in regards to building thermal performance and building energy use.

The American Iron and Steel Institute (AISI) is developing a simplified calculation methodology for determining the thermal performance of generic steel stud assemblies that includes the impacts of thermal bridging. While hot-box testing and computer simulations can produce accurate thermal performance values, the goal is to provide a practical means of calculating U-factors for these assemblies without the direct need for additional software or testing apparatus. As part of the development process of the AISI simplified calculation methodology, a robust 3D thermal modelling analysis was conducted on a variety of steel stud assemblies. This was done to provide accurate values on which the simplified calculation methodology can be based.

For this project, the thermal modelling was conducted using Siemens NX modelling software and TMG Thermal Solver, following the procedures set forth and calibrated in ASHRAE 1365-RP. The software and procedures were further validated for this project using comparisons between simulated values and hotbox data sets from ASHRAE-785 RP and a compilation of 2011-2012 steady-state hot box tests conducted at ORNL.

A sensitivity analysis of the steel conductivity k-value was also conducted. This analysis investigated the potential impact on the assembly thermal performance if this k-value was varied within the typically reported range for galvanized steel.

For the main body of work for this project, the thermal performance of 27 steel stud assemblies was determined. The assemblies varied by insulation thickness, insulation placement and steel stud depth. Multiple fastener patterns for the insulation and sheathings were also examined.

Overall, 127 simulations were run including validation, sensitivity testing and assembly modelling for this project. This report provides a summary of the model validation, sensitivity analysis and overall thermal performance (effective R- and U-values) of the analyzed steel stud assemblies, as well as key temperature indices.

The project monitoring committee (PMC) for this work, formed by AISI, consisted of the following members:

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1. INTRODUCTION AND BACKGROUND

Insulated exterior wall assemblies play a major role in the building envelope in reducing the heat flow between the interior conditioned space and the exterior environment. However, thermally conductive components, typically from structural elements within these assemblies, can create thermal bridging through the insulating layers. This thermal bridging can reduce the effectiveness of the insulation and can lead to impacts on building energy use and localized condensation concerns.

For steel stud wall assemblies with stud cavity insulation, this thermal bridging occurs due to the studs, tracks and other components within the cavity that cuts through the interior insulation. When there is exterior insulation on the assembly, thermal bridging can also occur depending on the method of attaching the insulation and cladding to the substrate.

Methodologies for calculating the thermal performance of building envelope wall assemblies that includes thermal bridging vary, depending on the wall type, material components and complexity of the wall configurations. This includes simplified hand calculation methods, such as parallel path or isothermal planes methods [1]

For steel stud assemblies, due to the high thermal conductivity and shape of steel components, the heat flow paths through the assembly can be complex. These simplified hand calculations may not be robust enough to fully capture this additional heat flow, resulting in reduced accuracy of results. For steel stud assemblies, hot box testing, 2D and 3D thermal modelling approaches can provide accurate U-factor evaluations of these assemblies; however these resources may not be widely available or practical to conduct in every situation, especially for those looking for generic assembly information.

The American Iron and Steel Institute (AISI) is currently developing a new simplified calculation methodology for determining the U-factor for steel stud assemblies. The intent is to provide procedures that reduce the need for additional resources but provide greater accuracy in results over current simplified methods. To further this work, the objective of the project outlined in this report was to conduct more detailed thermal modelling simulations of 27 steel stud assemblies to help inform the development of this simplified methodology.

For this study, Morrison Hershfield Ltd (MH) was contracted by AISI to conduct the thermal performance modelling and analysis. This report is an overall summary of the analysis and outlines the findings from various stages within the study.

The following is a summary of each of the project phases for this work:

Part 1) Formation of the Project Monitoring Committee (PMC)

The Project Monitoring Committee (PMC), consisting of 4 members appointed by AISI, was formed to oversee the project and provide direction where required. This included review of results from each phase of the project and selecting material values and assemblies to be tested during the validation and parametric reviews. The selection process for the PMC is not included in this report.

Part 2) Selection and Validation of Software

For this project, the Siemens NX software and TMG Thermal Solver was used to conduct the thermal modelling, following the procedures previously validated for ASHRAE 1365-RP [2]. The modelling approach is summarized in **Section 2** of this report, as well as additional validation conducted for this project, summarized in **Section 3**.

Part 3) Parametric Review – Steel K-Values

Before the thermal modelling of the 27 steel stud assemblies, a parametric review of the thermal conductivity k-value for the steel components was conducted. As there is a range of reported k-values for steel, this sensitivity analysis was done to determine the impact of the variation in steel conductivity on the overall thermal performance of the assembly. From this analysis a single steel k-value was chosen by the PMC to be used for the remainder of the simulations. This analysis is summarized in **Section 4** of this report.

Part 4) Scenario Modelling

For this project, 27 steel stud assemblies were modelled and simulated for effective R-and U-values, as well as for sheathing temperatures. These assemblies varied by stud spacing/depth, interior insulation thickness, exterior insulation thickness and fastener spacing. The summary of the simulation results are presented in **Section 5** of this report.

Supplemental information for each section of this report can also be found in the Appendices, including additional assembly and material information as well as thermal profiles of selected assemblies.

2. MODEL PARAMETERS

For the modelling in this project, capturing the heat transfer in three-dimensions was required. 3D thermal analysis requires fewer assumptions to account for heat flow through non-continuous thermal bridges (fasteners) and/or thermal bridges in multiple planes (tracks and studs) compared to 2D approaches.

In this project the procedures and software set forth in ASHRAE 1365-RP [2] were extensively followed. Similar to this current work, ASHRAE 1365-RP was conducted to determine the thermal performance of building envelope assemblies using 3D thermal simulations. This approach was selected by MH and further validated for the PMC to confirm its suitability for the current project. The following Section is a summary of the model software, procedures and other conditions. The additional validation is summarized in Section 3, however for more information see Chapter 2 of ASHRAE 1365-RP.

2.1 Software

As required by the PMC, the thermal modelling for this project was to be conducted using publically or commercially available software capable of three-dimensional thermal analysis. Siemens PLM NX 10, was selected, which contains CAD, finite element modelling and thermal simulations. For the thermal solver, NX utilizes the TMG Thermal solver, developed by Maya Heat Transfer Technologies. TMG Thermal uses the finite volume method for solving steady-state heat transfer problems by conduction, convection and radiation. Calculation points are established by the element’s center of gravity and the midpoints of either the two-dimensional face for three-dimensional elements, or the one-dimensional edge of two-dimensional elements. The element nodes are used only to define the element’s geometry but not used as calculation points; the nodal temperatures are interpolated from the elemental values. Basic output data includes elemental and nodal temperatures, thermal gradient, heat flux by conduction and total element heat load/flux. Additional background documentation for the TMG Thermal model can be requested from Maya HTT.

In the context of this project, the Siemens software and TMG Thermal is capable of capturing complex 3D heat flows through building envelope components that contain multiple thermal bridging pathways.

2.2 Material Properties

The thermal modelling was conducted under steady state conditions. Guarded hot-box measurements at different temperature gradients show that the dependency of insulation conductivity to mean temperature can result in up to 6.5% difference in the measured thermal resistance [3]. However, from ASHRAE 1365-RP, it was found that for the typical temperature range for building materials, this dependency was found to have minimal impact on the whole assembly. Further testing was done for this project showing the difference in thermal resistance for selected assemblies in this project was less than 2% using fiberglass and rigid board insulations (see Section 3.4). Temperature dependency of materials was not considered for the project assemblies.

For the project assemblies, material properties were provided by the PMC, mainly taken from material testing data from Appendix D in ASHRAE 785-RP [4] and the ASHRAE HoF [1]. These materials were typically found through testing as per ASTM C-518 [5] at a mean temperature of 75°F. Material properties used are listed in Appendix A.

2.3 Air spaces

For confined, unventilated air spaces, calculating the equivalent conductivity k-value of the air follows ISO 10077 [6]. However, for this project, all insulation materials were assumed to be tightly fit to the sheathings and studs. As such, no air gaps in the insulation or between the insulation and other materials were explicitly modelled. For the planar air space when the stud cavity is empty, the resistance is dependent on the cavity surface temperatures, surface emittances, and geometry. Table 3, Chapter 26, of the ASHRAE HoF provides the thermal resistances of plane air spaces, including the effects of radiation, conduction, and convection. The range of thermal resistances of plane air spaces presented in this table is within 5% uncertainty, similar to the insulation material properties. An equivalent thermal resistance of **0.91 Btu/ hr·ft²·°F** was selected for the planar air in the empty stud cavity.

2.4 Surface Air Film Resistances

Surface air film resistances (and inversely surface heat transfer coefficients) of building envelope components can vary due to many factors, including surface emittance, temperature differences, view factors with adjacent bodies and convection variances due to geometry and environment. Established standards for calculating assembly thermal performance [1] [7] acknowledge that constant heat transfer coefficients still yield accurate predictions of U-values of building envelope components. The values selected for this project were provided by the PMC, and are based on values presented in Table 10, Chapter 26, of the ASHRAE HoF. Table 2-1 below summarizes the heat transfer coefficients applied to the exterior and interior surfaces of the assemblies for this project.

Table 2-1: Summary of Surface Resistances and Conductances Used

Location	Description of Condition	Surface Conductance Btu/h·ft²·°F	Air Film Resistance h·ft²·°F/BTU
Exterior Stucco surface	Surface exposed to 15 mph wind	6.00	0.17
Interior wall surface	Vertical surface exposed to indoor air and surfaces	1.46	0.68

2.5 Boundary Temperatures

As noted in Section 2.1, the material properties were assumed constant and independent of temperature. As such, boundary temperatures were applied as a non-dimensionalized temperature index to create a unit temperature difference across the assembly. The exterior temperature is represented as 0 and the interior temperature is represented as 1. Furthermore, the surface temperatures found in Section 5 are presented as a temperature index and can apply reasonably to any temperature difference within typical building operating conditions (see Section 5.5).

2.6 Contact Resistances

As part of ASHRAE 1365-RP and ASHRAE 785-RP including contact resistances between materials were found to improve the accuracy of thermal models from within 10% of hot box testing values to within 5%. As part of the calibration of ASHRAE 1365-RP, a parametric study of the impact of contact resistances was conducted, comparing tested values to the simulations for U-value as well as localized temperatures. The contact resistance values analyzed were taken from a range of sources, including ASHRAE HoF (Ch 27.4), ASHRAE 785-RP and work conducted at BRANZ [8]. From the parametric study, the following contact resistances shown in Table 2-2, provided excellent agreement and were incorporated into the model.

Table 2-2: Summary of Contact Resistances

Location	Contact Resistance hr·ft^2·°F /Btu
Steel flanges at sheathing interfaces	0.17
Insulation interfaces	0.057
Steel to steel interfaces	0.011

2.7 Other Parameters and Assumptions

Other parameters of the modelling approach, such as the modelled geometry, will depend on a case by case basis. Knowing when a specific complex geometry has influence on heat flow or when it can be simplified without impacting the model is often left to the discretion and experience of the modeler. Typically, modelling in 3D reduces the need for simplifications. Still, there are geometric simplifications that are helpful in reducing modelling and computational time. For instance, the flanged returns and punched holes on the steel studs can be easily incorporated into the model, but including the threads on every fastener would be unnecessary. Simplifications for the geometric modelling in this project are noted in Section 5.3.

For this modelling, the following were considered insignificant or beyond the intent of this project and **not** included:

- Air leakage into the assembly
- Convection within the assembly, other than what was considered in the calculation of the planar airspace k-value.
- Solar radiation
- Impacts of thin sheet weather barriers and vapour barriers

3. MODEL VALIDATION

After the model and software selection, as described in Section 2, the project required the suitability of the approach be demonstrated to the PMC. The approach had been previously validated for ASHRAE 1365-RP [2]. The model was further validated for this project against two publicly available guarded hot-box data sets, provided by the PMC. For this validation, 6 experimental data sets for multiple steel stud assemblies were taken from ASHRAE 785-RP [4] and 21 were taken from a compilation study of steady state hot box tests from Oak Ridge National Laboratory [9]. The tested assemblies from each of these data sets were modelled and the simulated thermal transmittance/resistance values were compared to the experimental results. A threshold of up to +/- 8% difference in simulation vs. tested transmittance value was given by the PMC in order for the model to be considered *validated*. This is a similar threshold value used to demonstrate the accuracy of hot box testing and thermal modelling in similar validation papers [4] [10] [11]. Both the air to air values and surface to surface values were found and presented here, however comparison in this section refer only to the surface to surface values. The results for the comparison were used further for calibration for the project assemblies. The following Section highlights the experimental data sets, comparison to simulated values and additional testing for confirmation of the modelling approach.

3.1 Previous Validation in ASHRE 1365-RP

The modelling approach for this project was benchmarked against a wide assortment of hotbox data sets and well defined reference cases in ASHRAE 1365-RP. Overall, 29 steel stud assemblies from several test reports [4] [11] [12] [13] [14] were simulated and compared to the experimental data. This included similar steel stud data sets from ASHRAE 785-RP, also used in the validation for this project. Based on recommendations in ASHRAE 785-RP, contact resistances were also analyzed based on ranges recommended in the ASHRAE HoF [1] using several of the test assemblies. These tests determined the appropriate values that could be used to improve the accuracy of results for the steel stud assemblies, depending on material interface (values are shown in Table 2-2).

Other validation tests were completed regarding temperature dependence of insulation, thermally massive assemblies and transient simulations. Finally, validation was carried out for 4 well defined reference cases for testing the validity of 3D models for transition details from ISO 10211 [7] and 2 cases for glazing assemblies from ISO 10077 [6].

Overall the validation work in ASHRAE 1365-RP found good agreement between the measured and simulated thermal performance of the selected assemblies (within 5%) and indicated the TMG model will yield high precision results for well-defined problems. For further details on this previous validation, please see Chapter 3 of ASHRAE1365-RP.

The NX software used in this project has been updated since the completion of ASHRAE 1365-RP in 2011, adding additional capabilities and refined meshing options. Regardless, the general modelling parameters and governing equations have remained consistent.

3.2 Validation to ASHRAE 785-RP

The first data sets used for validation for this project was taken from ASHRAE 785-RP [4]. ASHRAE 785-RP contains physical testing of 12 varied steel stud assemblies for thermal transmittance and surface temperatures. The experimental testing was conducted via guarded hotbox apparatus as per ASTM C236 [15] (note ASHRAE 785-RP was completed in 1996 and the ASTM test method used has since been superseded by ASTM C1363 [16]). ASHRAE 785-RP also summarizes thermal conductivity testing of the individual components used in the assembly hotbox test, conducted as per ASTM C518 [5]. For the validation for this project, the PMC requested 6 of the 12 assemblies from ASHRAE 785-RP be simulated. These 6 assemblies are described below in Figure 3-1 and Table 3-1.

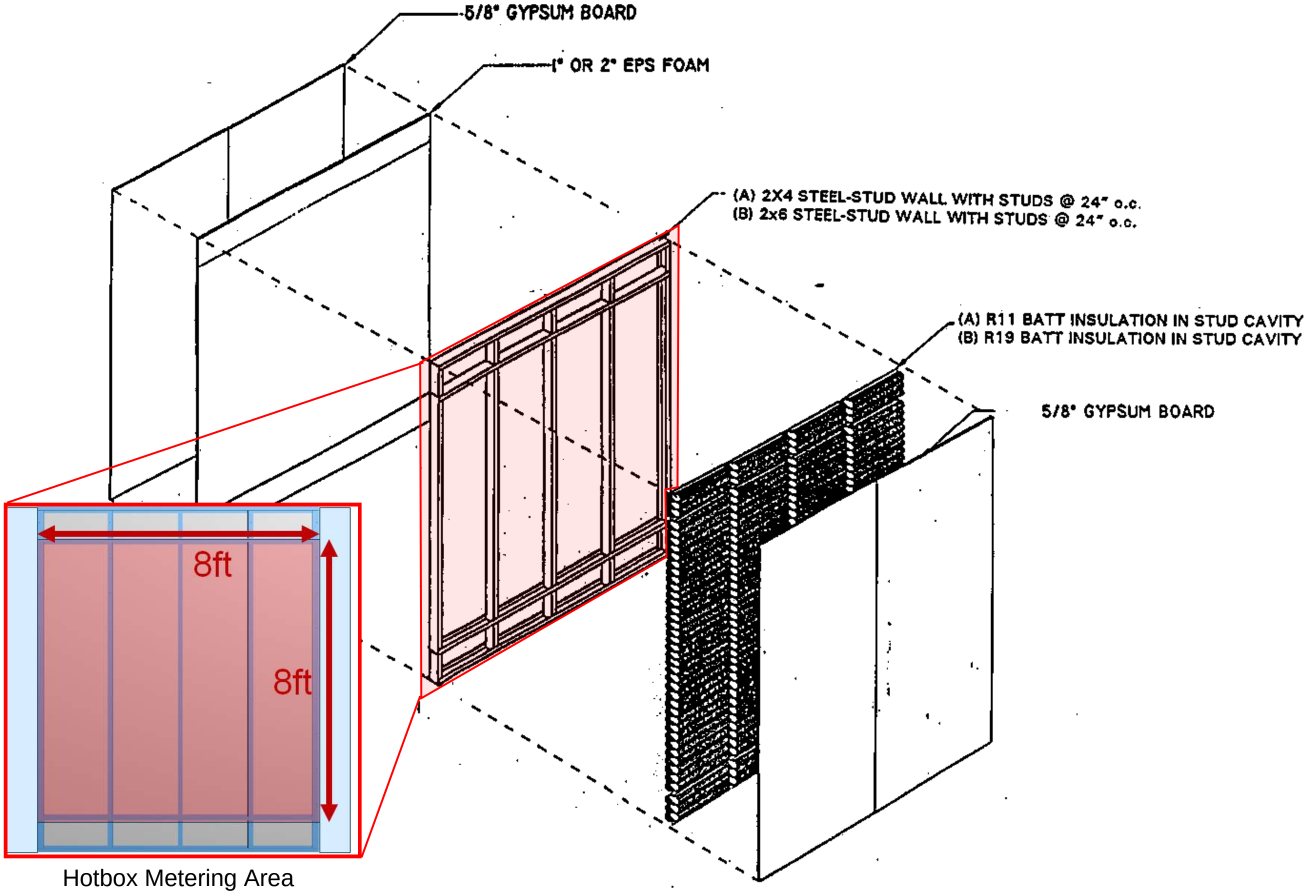


Figure 3-1: Tested Guarded Hot Box Assemblies from ASHRAE 785-RP

Table 3-1: ASHRAE 785-RP Validation Assembly Components

Assembly Ref.	Interior Gypsum	Steel Stud Cavity Depth	Full Width Cavity Insulation Nominal R-Value	EPS Foam Board	Exterior Gypsum
A.1	5/8"	3 5/8"	R-11 Batt	-	5/8"
A.2	5/8"	3 5/8"	R-11 Batt	1.0"	5/8"
A.3	5/8"	3 5/8"	R-11 Batt	1.5"	5/8"
B.1	5/8"	6"	R-19 Batt	-	5/8"
B.2	5/8"	6"	R-19 Batt	1.0"	5/8"
B.3	5/8"	6"	R-19 Batt	1.5"	5/8"

The 6 assemblies were modelled following the approach detailed in Section 2. One modification was made: The exterior conditions within a hotbox test are typically at much lower air speeds than the standard 15mph assumed in the ASHRAE HoF [1], therefore, the air film resistances in the simulations were matched to those calculated from the testing. Regardless, both air to air values and surface to surface values were determined and compared.

The modelled area for the simulations were 8ft x 8ft and matched the active hotbox area from the testing in ASHRAE 785-RP. The studs were spaced at 24"o.c. and flanked on the top and bottom by the steel stud tracks. Fasteners through the insulation and sheathings were included. The perimeter of the assembly was considered adiabatic. The generic modelled geometry for the validation assembly is shown in Figure 3-2.

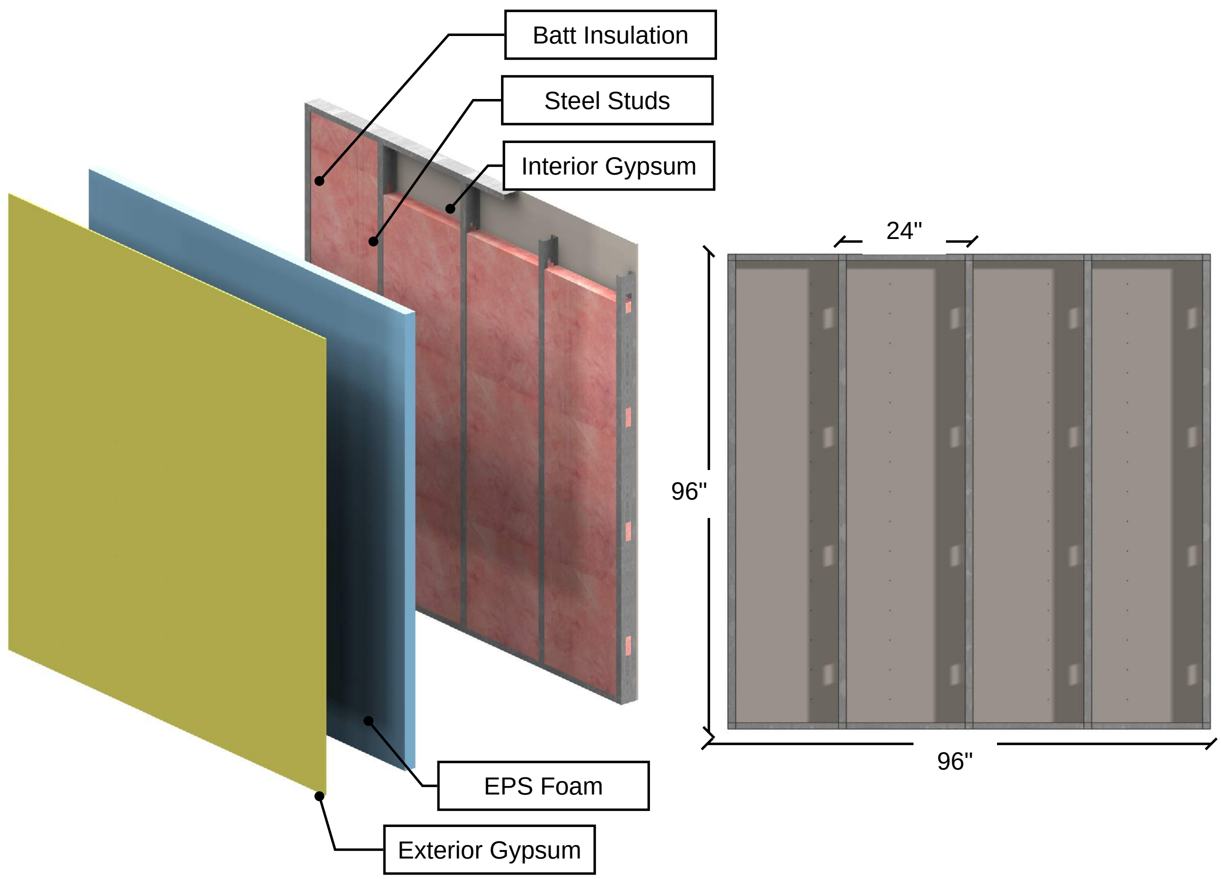


Figure 3-2: Modelled ASHRAE 785-RP Validation Assembly

The material properties, specifically component thicknesses and thermal conductivity k-values, used in the validation simulations were matched with the tested values found in Appendix D of ASHRAE 785-RP, Tables D1a and D1b. Note, this includes the insulation whereby **the tested R-values were used in the simulation**, not the labelled insulation values. These material properties are reproduced and summarized in this report in Appendix A. The simulated assembly R- and U-values for the 6 validation assemblies, along with guarded hotbox values are shown in Table 3-2. This includes air to air and surface to surface values.

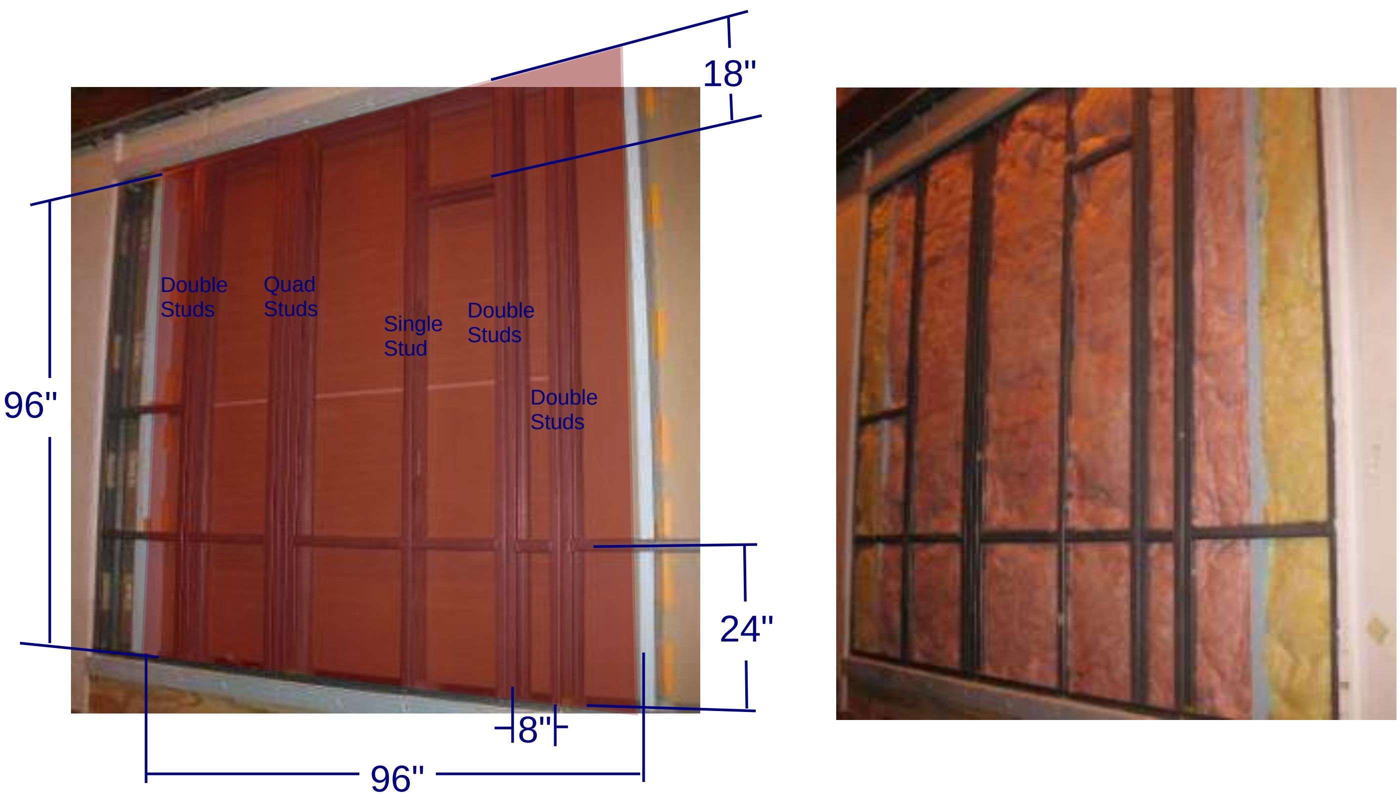
Table 3-2: Tested and Simulated R-Values for the 6 ASHRAE 785-RP Validation Assemblies

Assembly Ref.	Tested Component R-values hr·ft² ·°F/BTU						Assembly Air to Air R-values hr·ft² ·°F/BTU			Assembly Surface to Surface R-values hr·ft² ·°F/BTU		
	Interior Air Film	Interior Gypsum	Tested Cavity Insulation	Tested EPS Foam Board	Exterior Sheathing	Exterior Air Film	Test	Simulation	% Diff	Test	Simulation	% Diff
A.1	0.63	0.49	11.74	-	0.49	0.47	8.88	8.80	**-0.9%**	7.81	7.70	**-1.4%**
A.2	0.76	0.49	11.74	3.81	0.49	0.63	13.90	13.80	**+0.7%**	12.52	12.41	**-0.8%**
A.3	0.76	0.49	11.74	5.39	0.49	0.63	15.27	15.38	**-0.7%**	13.85	13.99	**+1.0%**
B.1	0.57	0.49	18.00	-	0.49	0.39	10.50	10.41	**+0.8%**	9.56	9.45	**-1.1%**
B.2	0.63	0.49	18.00	3.75	0.49	0.41	15.13	15.19	**-0.4%**	14.11	14.15	**+0.3%**
B.3	0.60	0.49	18.00	5.41	0.49	0.42	16.74	17.12	**-2.3%**	15.72	16.11	**+2.5%**

The simulated values show excellent agreement with the tested values, upto +/- 2.5%, well below the +/- 8% threshold for this project. One item of note, as more exterior insulation is added to the assemblies, the error increases in the positive direction. This indicates the simulated values become less conservative compared to the hotbox values with larger amounts of exterior insulation. This is also seen, but in greater impact, with the ORNL validation assemblies. Further discussion on this phenomena can be found in Section 3.4.

3.3 Validation to ORNL Hotbox Compilation Study

The second sets of data used in the validation for this project were taken from a summary report for a series of steady state guarded hot box tests conducted at Oak Ridge National Laboratory [9]. The report details the testing conducted for 21 steel framed wall assemblies according to ASTM 1363. Similarly to the ASHRAE 785-RP report [4], the materials were individually tested for thermal resistance according to ASTM 518 [5]. For the validation for this project, the PMC requested all 21 assemblies from the ORNL Compilation Study be simulated. The general assembly layout image for the ORNL assembly is shown in Figure 3-3 and the components for each of the 21 ORNL assemblies are shown in Table 3-3.



Hot Box Metering Area

With Insulation Installed
(Cover Foam/Sheathing Hidden)

Figure 3-3: Schematic of Tested Guarded Hot Box Assembly from the ORNL Compilation Study

Table 3-3: ORNL Compilation Study Validation Assembly Components

Assembly Ref.	Interior Gypsum	Steel Stud Cavity Depth	Full Width Cavity Insulation Nominal R-Value	Exterior Insulation	Exterior Sheathing	Exterior Finish
1	½" Gyp	3.5"	R-13 Batt	0.5" XPS	-	-
2	½" Gyp	3.5"	R-13 Batt	1.0" XPS	-	-
3	½" Gyp	3.5"	R-13 Batt	1.5" XPS	-	-
4	½" Gyp	3.5"	R-13 Batt	2.0" XPS	-	-
5	½" Gyp	3.5"	R-13 Batt	3.0" EPS	-	-
6	½" Gyp	3.5"	R-13 Batt	3.75" EPS	-	-
7	½" Gyp	3.5"	R-15 Batt	-	½" OSB	-
8	½" Gyp	3.5"	R-15 Batt	0.5" XPS	-	-
9	½" Gyp	3.5"	R-15 Batt	1.0" XPS	-	-
10	½" Gyp	3.5"	-	2.0" EPS	-	-
11	½" Gyp	3.5"	-	2.0" XPS	-	-
12	½" Gyp	3.5"	-	3.0" EPS	-	-
13	½" Gyp	5.5"	R-19 Batt	-	½" OSB	-
14	½" Gyp	5.5"	R-19 Batt	0.5" XPS	-	-
15	½" Gyp	5.5"	R-19 Batt	1.0" XPS	-	-
16	½" Gyp	5.5"	R-21 Batt	-	½" OSB	-
17	½" Gyp	5.5"	R-21 Batt	0.5" XPS	-	-
18	½" Gyp	3.5"	-	2.5" EPS	5/8" Gyp	EIFS
19	½" Gyp	3.5"	-	4.0" EPS	5/8" Gyp	EIFS
20	½" Gyp	5.5"	-	2.5" EPS	5/8" Gyp	-
21	½" Gyp	5.5"	-	4.0" EPS	5/8" Gyp	EIFS

Similarly to the validation in Section 3.2, the 21 assemblies here were modelled following the TMG solver approach, but the air film resistances in the simulations were matched to those calculated from the testing.

The modelled area for the simulations were 8ft x 8ft and matched to the active hotbox area from the testing at ORNL. Fasteners through the insulation and sheathings were included. The perimeter of the assembly was considered adiabatic. The stud configuration was indicated as 24"o.c., however additional framing was present in the hot box assembly to create a framing factor of 23%. The specific arrangement of the steel stud components was not detailed in the paper; however, in recreating the test assembly, the modelled layout was confirmed with the paper's authors. The generic modelled layout for the ORNL validation assembly is shown in Figure 3-4.

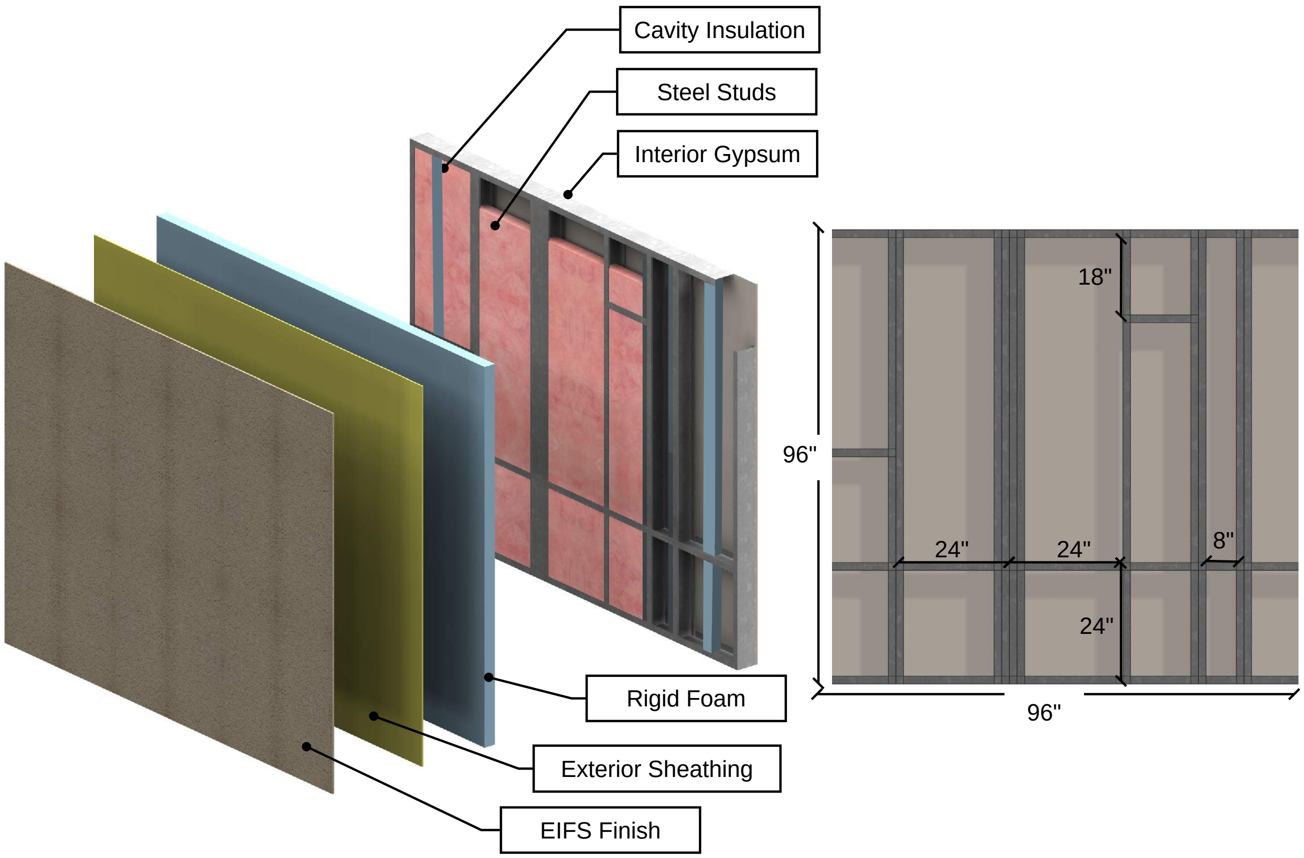


Figure 3-4: Modelled ORNL Validation Assembly

The thermal conductivity of the materials were calculated from the tested material R-values given in the ORNL paper. These values have been reproduced in Appendix A of this report. Values for the steel studs and tracks were not provided in the paper and were assumed to be 430 BTU-in/hrft^{2o}F with contact resistances. The simulated R- and U-values for the 21 validation assemblies as well as the tested values from the ORNL report is shown below in Table 3-4 for both the air to air and surface to surface values. Note, the tested values shown here are for the actual hotbox values, not the “adjusted to insulation label values” also detailed in the ORNL summary report.

From this table it can be seen that the majority of the cases the simulations are within +/- 5% of the hotbox values. There are two cases which are just at the +8% threshold. Similar trends as the ASHRAE 785-RP validation results can be seen, where increasing insulation thicknesses yield less aligned values. Additional testing was completed to determine if there were other factors that may be impacting the results. These adjustments and further discussion are summarized in the following Section 3.4.

Table 3-4: Tested and Simulated R-Values for the 21 ORNL Compilation Study Validation Assemblies

Assembly Ref.	Component R-values hr·ft^2·°F/BTU						Assembly Air to Air R-values hr·ft^2·°F/BTU			Assembly Surface to Surface R-values hr·ft^2·°F/BTU		
	Interior Air Film	Interior Gypsum	Tested Cavity Insulation	Tested Foam Board	Exterior Sheathing	Exterior Air Film	Test	Simulation	% Diff	Test	Simulation	% Diff
1	0.53	0.50	12.8	3.8	-	0.30	10.8	10.7	**-1.0%**	10.0	9.9	**-1.4%**
2	0.58	0.50	12.8	5.0	-	0.28	12.1	12.0	**-0.5%**	11.2	11.2	**-0.2%**
3	0.56	0.50	12.8	7.4	-	0.30	14.2	14.6	**+3.1%**	13.3	13.8	**+3.6%**
4	0.56	0.50	12.8	9.6	-	0.31	16.1	17.0	**+5.3%**	15.2	16.1	**+5.8%**
5	0.55	0.50	12.8	12.1	-	0.28	18.1	19.1	**+5.5%**	17.2	18.3	**+6.2%**
6	0.55	0.50	12.8	15.3	-	0.24	20.1	21.7	**+8.1%**	19.3	20.9	**+8.4%**
7	0.59	0.50	13.50	-	0.50	0.30	7.3	7.0	**-3.6%**	6.4	6.1	**-4.0%**
8	0.57	0.50	13.50	3.8	-	0.25	10.4	10.9	**+4.4%**	9.6	10.0	**+4.5%**
9	0.53	0.50	13.50	5.0	-	0.29	12.2	12.2	**-0.2%**	11.4	11.4	**-0.4%**
10	0.66	0.50	-	8.3	-	0.33	9.8	10.5	**+7.4%**	8.8	9.5	**+8.4%**
11	0.64	0.50	-	9.6	-	0.32	11.9	11.8	**-0.9%**	11.0	10.8	**-1.5%**
12	0.70	0.50	-	12.1	-	0.31	13.0	13.8	**+6.4%**	12.0	12.8	**+6.8%**
13	0.49	0.50	16.30	-	0.50	0.31	7.2	6.7	**-6.3%**	6.4	5.9	**-7.1%**
14	0.53	0.50	16.30	3.8	-	0.31	10.7	11.4	**+6.2%**	9.9	10.5	**+6.3%**
15	0.48	0.50	16.30	5.0	-	0.34	12.5	12.7	**+1.2%**	11.7	11.8	**+1.1%**
16	0.48	0.50	20.40	-	0.50	0.33	7.4	7.2	**-3.2%**	6.6	6.4	**-3.7%**
17	0.51	0.50	20.40	3.8	-	0.33	11.1	11.8	**+6.5%**	10.3	11.0	**+6.6%**
18	0.76	0.50	-	8.4	0.50	0.40	11.4	11.4	**-0.1%**	10.2	10.2	**+0.2%**
19	0.81	0.50	-	13.9	0.50	0.38	16.7	16.9	**+1.2%**	15.5	15.7	**+1.4%**
20	0.84	0.50	-	8.4	0.50	0.37	11.6	11.5	**-1.1%**	10.4	10.3	**-1.3%**
21	0.83	0.50	-	13.9	0.50	0.31	16.7	16.9	**+1.0%**	15.6	15.7	**+0.9%**

3.4 Valdiation with ORNL Hotbox Compilation Study, Adjusted for Temperature

While the vast majority of the ORNL validation assemblies were simulated to within +/- 8% of the tested values, a handful of analyzed assemblies were close to or just at that threshold. One possibility that was discussed with the PMC was the influence of temperature dependence of the R-value of the foam insulation products used. The material properties of the insulation were tested at a mean temperature 75°F, but the resistance of the foam insulation may vary at other temperatures.

The PMC provided a linear approximation showing the potential enhancement or degradation of the R-value of foam insulation away from its base R-value at 75°F. The approximation is shown in EQ1.

$$\%\,R\,Value\,Change = \; -0.2136\,\cdot Mean\,Temperature + 16.201 \qquad \text{EQ1}$$

(for mean temperatures between 20°F to 110°F)

This curve was used to adjust the insulation values in 3 of the ORNL validation assemblies (ORNL #4-6). The previous assembly performance with insulation R-values evaluated at 75°F and insulation values allowed to vary according to EQ1 shown below in Table 3-5.

Table 3-5: Adjusted Values for ORNL Assemblies with Temperature Dependency Added

Assembly Ref.	Evaluated Temperature	Air to Air R-values hr·ft² ·°F/BTU			Surface to Surface R-values hr·ft² ·°F/BTU		
		Test	Simulation	% Diff	Test	Simulation	% Diff
4	Constant at 75°F	16.1	17.0	**+5.3%**	15.2	16.1	**+5.8%**
	Variable	16.1	16.6	**+3.3%**	15.2	15.8	**+3.7%**
5	Constant at 75°F	18.1	19.1	**+5.5%**	17.2	18.3	**+6.2%**
	Variable	18.1	19.4	**+6.9%**	17.2	18.5	**+7.7%**
6	Constant at 75°F	20.1	21.7	**+8.1%**	19.3	20.9	**+8.4%**
	Variable	20.1	22.5	**+11.7%**	19.3	21.7	**+12.2%**

It can be seen that, in general, the R-values are higher using the temperature dependency values with the EPS foams. The difference between the simulated U-values, with and without temperature dependency is less than 3% for the assembly. This is in line with the findings in ASHRAE 1365-RP. With the temperature dependency added for the EPS foams, difference with the tested values gets larger. This indicates the potential temperature dependency of the foam insulation is not a significant influence in the simulation.

Another possible reason for the difference between the simulations and tested values is in the assumed material properties. The steel conductivity values were not provided in this paper and, as discussed in Section 4, published values for galvanized steel can vary. The particular k-value for the steel chosen here may be lower than the actual value of the steel within the test.

Finally, there may be the impact of errors associated with experimental testing itself. This includes with the material testing and the assembly testing. With regards to the sensitivity of monitoring equipment, as more insulation is used the heat flow through the assembly becomes smaller. The resolution of metering box to pick up smaller and smaller amounts of heat flow may have a small impact on calculation of R-values. This may explain the increasing positive difference in the simulations and tested values as more insulation in the system is added.

Overall, the PMC found the validation results acceptable to proceed with further modelling for the parametric study.

4. PARAMETRIC REVIEW – STEEL K-VALUES

For this report, three steel stud depths were analyzed with general dimensions noted in Table 4-1.

Table 4-1: Analyzed Steel Stud Dimensions

Type	AISI Designation	Web Depth (In)	Flange Width (In)	Lip Width (In)	Sheet Thickness (In)
2x4	365S162-43	3.625	1.625	0.5	0.0428" (43 Mil)
2x10	1000S162-43	10.0	1.625	0.5	0.0428" (43 Mil)
2x12	1200S162-43	12.0	1.625	0.5	0.0428" (43 Mil)

For the project assemblies, the largest contributor to thermal bridging is from the steel studs and tracks within the stud wall, which is largely a function of their high thermal conductivity. Reported values of the thermal conductivity k-values for steel can vary by source, testing methodology, gage thickness and galvanization process. As such, a parametric analysis was conducted to determine the impact of steel k-values on the simulated thermal performance values of select steel stud assemblies.

For the ASHRAE 785-RP [4] report, separate thermal conductivity testing was performed on each material used in the test walls, as outlined in Appendix D of that document. For the steel components, the thermal conductivity was determined by the Laser Flash Method following ASTM E1461 [17]. From this testing, it was found that the conductivity varied between 475-495 BTU-in/hr·ft^2·°F for the steel stud and steel track components. From other published sources, values can also vary as low as 350 BTU-in/hr·ft^2·°F [1] [18].

In order to see what potential impact the variation in the steel k-value has on the overall thermal performance of an assembly, a parametric analysis was conducted. For this analysis, a test assembly (Assembly #25 with Fastener Pattern 1) was simulated with varied thermal conductivity of the steel components. This assembly contained 2"x12" steel studs (AISI 1200S162-43) at 16"o.c. with top and bottom steel stud tracks. An equivalent R-38 insulation was included between the studs with stucco only outboard of the gypsum sheathing (no exterior insulation). Fasteners for the gypsum and sheathing were spaced 6"o.c. For more information on Assembly #25, see Section 5 or Appendix A.

For this parametric review, 3 thermal conductivity k-values were provided by the PMC and analyzed. These were assigned in different combinations between the steel studs and steel tracks, resulting in 6 parametric scenarios. The k-values, scenarios and the resulting thermal performance of the 6 simulations for Assembly #25, are shown below in Table 4-2. Note, in parametric scenarios 1-5, contact resistances between materials, including at the stud and drywall/sheathing interfaces, were included. As a further test, scenario 6 was run without contact resistances as a check. See section 2 – Model Validation for more information on the contact resistances used.

Table 4-2: Analyzed variations in galvanized steel thermal conductivity for Assembly #25

Parametric Scenario	Steel Thermal Conductivity K-Value BTU-in/hr·ft^2·°F		Assembly U-value BTU/hr·ft^2·°F	Assembly Effective R-Value hr·ft^2·°F/BTU
	Studs	Tracks		
1	430	430	0.077	13.0
2	430	495	0.077	12.9
3	475	475	0.079	12.7
4	475	495	0.079	12.6
5	495	495	0.080	12.5
6	430 No CR	430 No CR	0.081	12.3

Between the analyzed k-value variations, there was up to a 6% difference in performance values. The largest difference was a result of the influence of the low thermal conductivity and contact resistances vs high conductivity and no contact resistance. The difference in performance due to the use of contact resistances here is similar to those found in ASHRAE 785-RP and ASHRAE 1365-RP.

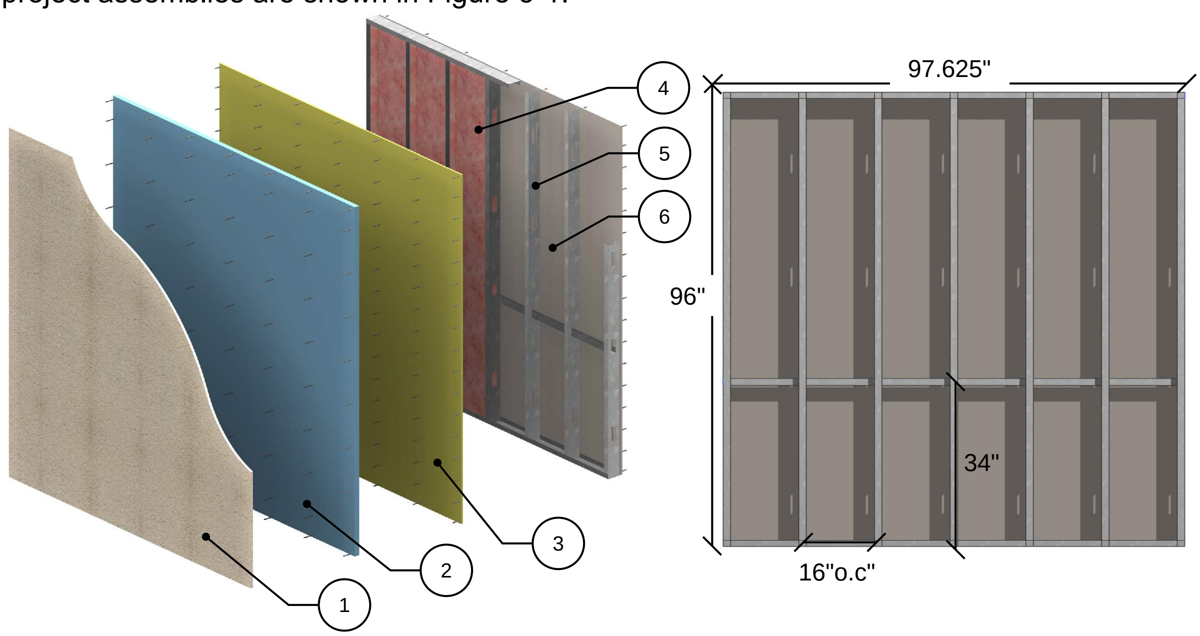
From this parametric analysis, the value of **495 BTU-in/hr·ft^2·°F with contact resistances** (Parametric Scenario 5) was chosen by the PMC to be used for both the studs and the tracks for the remainder of the simulations.

5. SCENARIO MODELLING

With the model validated and the conductivity of the steel confirmed by the PMC, the remainder of the 27 project assemblies were modelled and simulated according to the approach highlighted in Section 2. The following Section highlights the assembly configurations and the thermal performance results from the modelling.

5.1 Wall Configurations

The components of the project assemblies were set out by the PMC at the beginning of the project. The intent was to reflect generic steel stud wall assemblies with a wide range of insulation values typical to current construction. The basic configuration of the steel framed project assemblies are shown in Figure 5-1.



1	2	3	4	5	6
¾ Stucco	Exterior Rigid Board Insulation	5/8" Gypsum Sheathing	Cavity Insulation	Steel Studs, Tracks and C-Channel	5/8" Gypsum Interior Drywall

Figure 5-1: Basic Configuration of the Project Assembly

The thermal conductivities of all modelled components are provided in Appendix A. The overall assembly was modelled at approximately 8' H x 8 ' W and consisted of studs spaced 16"o.c., with end studs on either side [1]. The studs were flanked at the top and bottom by continuous steel tracks. The studs were punched with a 1.5"x4" holes along the centerline at 24"o.c. with a single 1.5" flanged C-channel through the punchouts at approximately 34" from the bottom of the assembly. Several fasteners were included (see Section 5.2). Overall, the stud configuration is similar to the tested assembly in ASHRAE 785-RP [4], but spaced 16"o.c. and with the additional C-channel. To create the 27 unique assemblies for the project, the following components were varied in the configuration:

[1] In order to have the 16"o.c be maintained between studs and include the end studs, the actual dimensions of the assembly were 8'H x 8' 1.625"W. This was to accommodate for the one additional flange width of the end stud.

Table 5-1: Project Assembly Component Variations

Exterior Insulation	Cavity Insulation	Steel Stud Depth
None	None (R-0.9 airspace)	350S162-43 (1.625"W x 3.625"D)
1.5" (R-7.5)	R-19	100S162-43 (1.625"W x 10"D)
3" (R-15.0)	R-38	1200S162 (1.625"W x 12"D)

Note, as directed by the PMC, the insulation values were to be modelled at the stated R-values. The cavity insulations specifically were to be modelled as full depth within the cavity at the stated R-value, acknowledging that the intent was **not** to reflect actual fiberglass batt products that could be compressed within the cavity. The variations in Table 5-1 created 4 insulation configurations for each depth of stud: 1) No Insulation, 2) Exterior Insulation Only, 3) Interior Insulation Only and 4) Split Insulation. These insulation configurations are shown in Figure 5-2. Additional project assembly images, are shown in Appendix A.

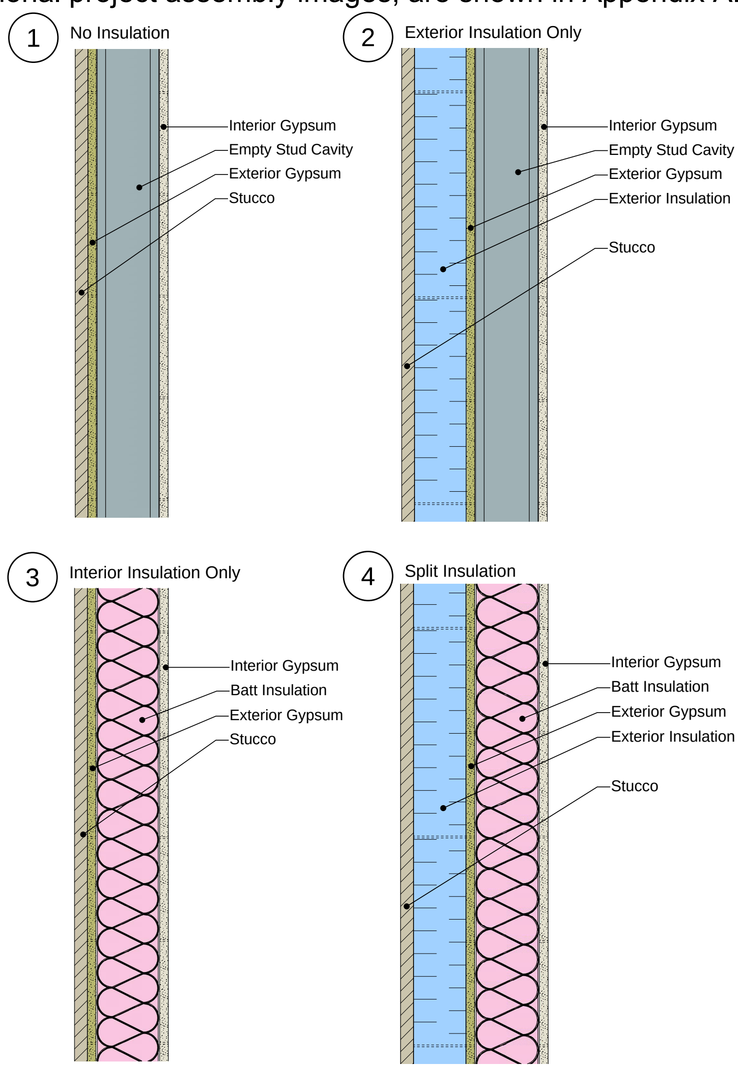
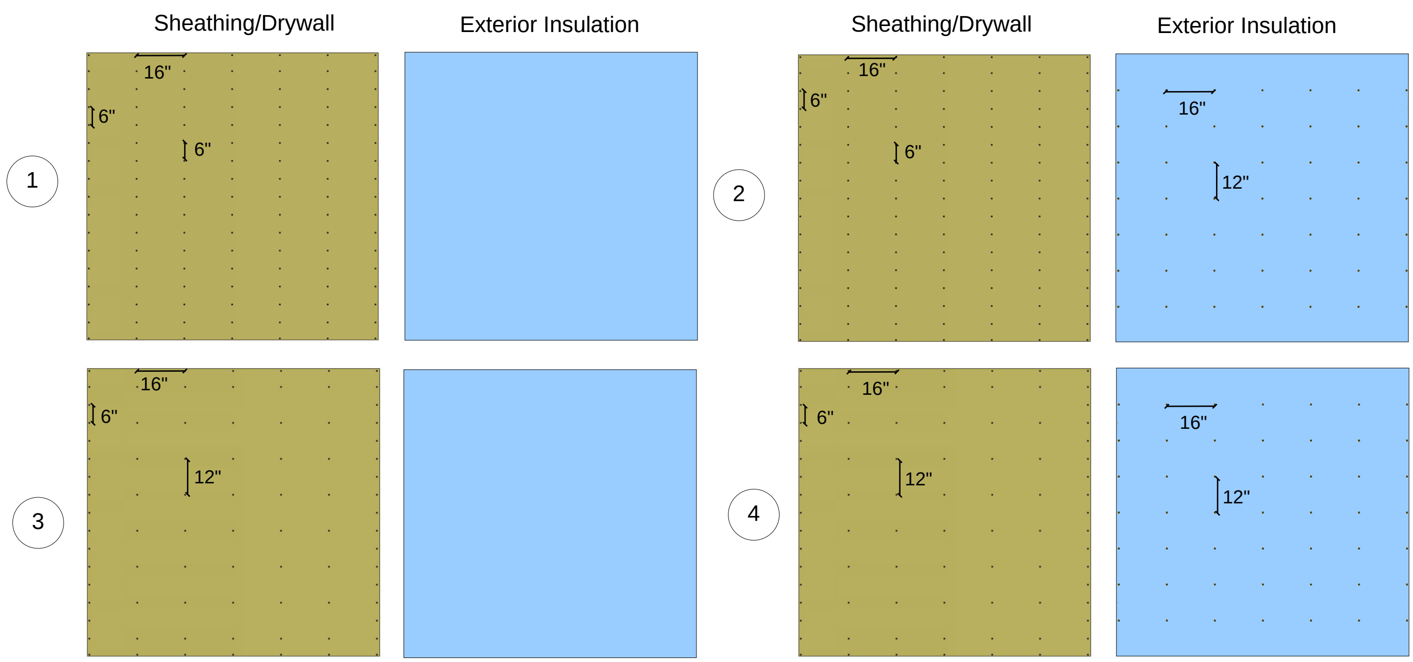


Figure 5-2: Project Assembly Insulation Configurations

5.2 Fastener Patterns

In addition to the variations in Table 5-1, each of the 27 assemblies were also varied with four fastener patterns. This was introduced to assess the sensitivity of thermal performance of the assembly to the fasteners and their spacing. This included fastening through the gypsum (sheathing and drywall) and through the exterior insulation where applicable. The general fastener patterns are shown in Figure 5-3.



Pattern	Gypsum Sheathing and Drywall	Exterior Insulation
1	6"o.c.	None
2	6"o.c.	12"o.c.
3	12"o.c.	None
4	12"o.c.	12"o.c.

Figure 5-3: Fastener Patterns Analyzed for the Project Assemblies

Note, for assemblies that have no exterior insulation, only fastening patterns 1 and 3 apply. For each Scenario, regardless of the fastener pattern, the sheathing and drywall fasteners at the edge of assembly were spaced 6"o.c. along the vertical lengths of the gypsum, in line with the middle of the end studs. Additional fasteners were modelled through the gypsum at the top and bottom of every stud where they are overlapped by the steel stud track. This additional track fastener was placed ¾" from the top or bottom of the assembly. The remainder of the field fasteners for the sheathing and drywall were spaced 6"o.c. or 12"o.c. vertically along the studs according to the fastener pattern scenario. The sheathing fasteners were modelled with #6 screws 0.13" D.

For the rigid board fasteners, the fasteners were spaced 12" o.c. vertically, in line with the middle of every stud with a self-drilling tapping type screw but with a similar 0.13" D as the drywall screws. With these fastener patterns, this creates overall 90 simulations of the 27 assemblies.

5.3 Modelled Geometry Simplifications

To clarify what was included in the model geometry, the following simplifications were made:

- No air gaps were modelled between insulation and other components. The insulation was assumed tight to the gypsum and fit perfectly within the studs and tracks. This includes through the stud punchouts. Contact resistances were still applied.

- Fasteners were simplified as square prisms with the same cross sectional area as the prescribed 0.13" D screws (see section 5.2). No threads or fastener heads were included.

- No metal fasteners were modeled for the stud and track connections or anything specific to fix the C-channel in place.

- The gypsum boards were modelled with no gaps, effectively making them one continuous sheet.

- The stucco was assumed to have a smooth flat finish and modelled as a single solid box (no lathe or trim) with an overall resistance of R-0.08.

5.4 Project Assembly U-Factor and Effective R-value Results

The following Section presents the thermal performance results for all modeled assemblies, insulation variations and fastener patterns that include the impacts of thermal bridging from the steel components. The effective R-values and U-values for the 90 simulations, by fastener pattern and insulation, are shown over the following pages in Table 5-3, Table 5-2 and Table 5-4 for the 350S162, 1000S162 and 1200S162 framed walls respectively. More detailed results, including the R-value of each layer, is shown in Appendix B.

Table 5-2: Simulated R- and U-Values for the 350S162 Steel Framed Project Assemblies

Assembly Ref.	Fastener Pattern	Cavity Insul.	Ext. Insul.	Simulated R-Value
1	1	R-0.9	-	**R-2.9**
	3	R-0.9	-	**R-2.9**
2	1	R-0.9	R-7.5	**R-10.4**
	2	R-0.9	R-7.5	**R-10.2**
	3	R-0.9	R-7.5	**R-10.4**
	4	R-0.9	R-7.5	**R-10.2**
3	1	R-0.9	R-15	**R-17.9**
	2	R-0.9	R-15	**R-17.3**
	3	R-0.9	R-15	**R-17.9**
	4	R-0.9	R-15	**R-17.3**
4	1	R-19	-	**R-9.31**
	3	R-19	-	**R-9.31**
5	1	R-19	R-7.5	**R-18.6**
	2	R-19	R-7.5	**R-18.2**
	3	R-19	R-7.5	**R-18.6**
	4	R-19	R-7.5	**R-18.2**
6	1	R-19	R-15	**R-26.3**
	2	R-19	R-15	**R-25.3**
	3	R-19	R-15	**R-26.3**
	4	R-19	R-15	**R-25.3**
7	1	R-38	-	**R-11.4**
	3	R-38	-	**R-11.4**
8	1	R-38	R-7.5	**R-22.3**
	2	R-38	R-7.5	**R-21.8**
	3	R-38	R-7.5	**R-22.3**
	4	R-38	R-7.5	**R-21.8**
9	1	R-38	R-15	**R-30.3**
	2	R-38	R-15	**R-29.1**
	3	R-38	R-15	**R-30.3**
	4	R-38	R-15	**R-29.1**

Table 5-3: Simulated R- and U-Values for the 1000S162 Steel Framed Project Assemblies

Assembly Ref.	Fastener Pattern	Cavity Insul.	Ext. Insul.	Simulated R-Value
10	1	R-0.9	-	**R-2.9**
	3	R-0.9	-	**R-2.9**
11	1	R-0.9	R-7.5	**R-10.5**
	2	R-0.9	R-7.5	**R-10.3**
	3	R-0.9	R-7.5	**R-10.5**
	4	R-0.9	R-7.5	**R-10.3**
12	1	R-0.9	R-15	**R-18.0**
	2	R-0.9	R-15	**R-17.5**
	3	R-0.9	R-15	**R-18.1**
	4	R-0.9	R-15	**R-17.5**
13	1	R-19	-	**R-9.8**
	3	R-19	-	**R-9.8**
14	1	R-19	R-7.5	**R-18.4**
	2	R-19	R-7.5	**R-18.1**
	3	R-19	R-7.5	**R-18.4**
	4	R-19	R-7.5	**R-18.1**
15	1	R-19	R-15	**R-26.0**
	2	R-19	R-15	**R-25.2**
	3	R-19	R-15	**R-26.0**
	4	R-19	R-15	**R-25.2**
16	1	R-38	-	**R-12.4**
	3	R-38	-	**R-12.4**
17	1	R-38	R-7.5	**R-22.3**
	2	R-38	R-7.5	**R-21.9**
	3	R-38	R-7.5	**R-22.3**
	4	R-38	R-7.5	**R-21.9**
18	1	R-38	R-15	**R-30.1**
	2	R-38	R-15	**R-29.0**
	3	R-38	R-15	**R-30.1**
	4	R-38	R-15	**R-29.0**

Table 5-4: Simulated R- and U-Values for the 1200S162 Steel Framed Project Assemblies

Assembly Ref.	Fastener Pattern	Cavity Insul.	Ext. Insul.	Simulated R-Value	Assembly Ref.	Fastener Pattern	Cavity Insul.	Ext. Insul.	Simulated R-Value
19	1	R-0.9	-	**R-2.9**	24	1	R-19	R-15	**R-26.0**
	3	R-0.9	-	**R-2.9**		2	R-19	R-15	**R-25.2**
20	1	R-0.9	R-7.5	**R-10.4**		3	R-19	R-15	**R-26.0**
	2	R-0.9	R-7.5	**R-10.1**		4	R-19	R-15	**R-25.2**
	3	R-0.9	R-7.5	**R-10.4**	25	1	R-38	-	**R-12.7**
	4	R-0.9	R-7.5	**R-10.1**		3	R-38	-	**R-12.7**
21	1	R-0.9	R-15	**R-18.0**	26	1	R-38	R-7.5	**R-22.4**
	2	R-0.9	R-15	**R-17.4**		2	R-38	R-7.5	**R-21.9**
	3	R-0.9	R-15	**R-18.0**		3	R-38	R-7.5	**R-22.4**
	4	R-0.9	R-15	**R-17.4**		4	R-38	R-7.5	**R-21.9**
22	1	R-19	-	**R-10.0**	27	1	R-38	R-15	**R-30.1**
	3	R-19	-	**R-10.0**		2	R-38	R-15	**R-29.1**
23	1	R-19	R-7.5	**R-18.4**		3	R-38	R-15	**R-30.1**
	2	R-19	R-7.5	**R-18.1**		4	R-38	R-15	**R-29.1**
	3	R-19	R-7.5	**R-18.4**					
	4	R-19	R-7.5	**R-18.1**					

5.5 Surface Temperatures

In addition the assembly R- and U-values, various surface temperatures were found for each assembly related to the interior face of the sheathing and drywall gypsum. The surface temperatures were found at 4 locations in the assembly. These locations are shown below in Figure 5-4.

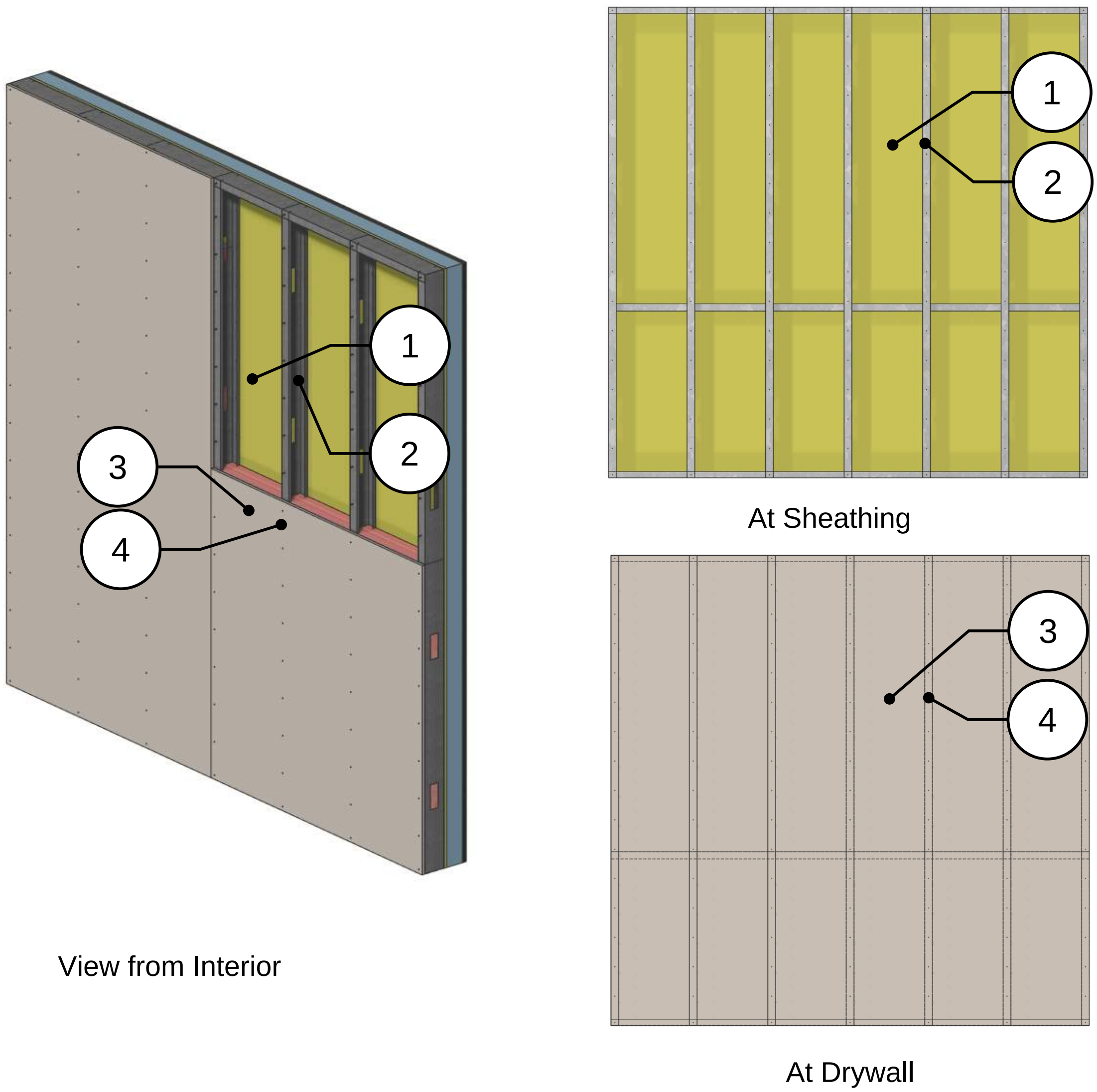


Figure 5-4: Surface Temperature Locations

These locations were chosen as the most likely areas where the coldest temperatures on the sheathing could be. In general, the coldest location on the sheathing is centered between the studs. However, when there is no interior cavity insulation, the coldest location occurs in isolated areas directly at the fastener penetrations. This impact is more prevalent with fastener patterns 2 and 4, when there are also fasteners through the exterior insulation. Regardless, values for all 4 location have been provided for reference.

The modelling was conducted using a temperature index boundary condition, and the surface temperatures are presented in the same format. As discussed in Section 2, the temperature index is the ratio of the surface temperature relative to the interior and exterior temperatures, calculated as shown in EQ 2 below.

$$T_i = \frac{T_{surface} - T_{outside}}{T_{inside} - T_{outside}} \qquad \text{EQ 2}$$

The temperature index has a value between 0 and 1, where 0 is the exterior temperature and 1 is the interior temperature. If T_i is known, EQ2 can be rearranged for $T_{surface}$. This arrangement allows the modelled surface temperatures to be applicable to any climate with the assumption of constant material properties. Note, these indices shown here are for general information only and are **not** intended to predict in-service surface temperatures subject to transient conditions, variable heating systems, and/ or interior obstructions that restrict heating of the assembly. For full limitations of surface temperatures with this modeling approach, see ASHRAE 1365-RP [2].

The various surface temperature indexes are shown in Appendix C along with several example temperature profiles from the simulations.

6. CONCLUSIONS

This report summarizes the work completed for AISI with regards to the simulation of cold formed steel wall assemblies. The report highlights the modelling procedures, validation and simulation results for 90 variations of the project steel stud assemblies.

We believe the information contained within this report meets the objectives of this project. For any further information regarding the material in this report, please contact the undersigned.

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APPENDIX A: Material Properties and Assembly Information

A.1 ASHRAE 785-RP Validation Material Properties

Table A-1: Material Properties Used in ASHRAE 785-RP Validation Simulations

ID	Material	Validation Assembly	Thickness (In)	Conductivity K-Value (BTU-In/hr ft^2 °F)	R-Value (hr ft^2 °F/BTU)
1	Gypsum Sheathing	All	0.64"	1.32	0.49
2	1" EPS Foam	A.2	0.94"	0.247	3.81
	1" EPS Foam	B.2	0.96"	0.257	3.73
	1.5" EPS Foam	A.3, B.3	1.45"	0.269	5.39
3	Fasteners, 12"o.c.	All	#7	346	-
4	3 5/8" x 1 5/8" Steel Stud	A.1-A.3	0.0428" (43 Mil)	475	-
	6" x 1 5/8" Steel Stud	B.1-B.3	0.0428" (43 Mil)	481	-
5	3 5/8" x 1 1/4" Steel Tracks	A.1-A.3	0.0428" (43 Mil)	495	-
	6" x 1 1/4" Steel Tracks	B.1-B.3	0.0428" (43 Mil)	486	-
6	R-11 Batt Insulation	A.1-A.3	3.62"	0.309	11.74
	R-19 Batt Insulation	B.1-B.3	6"	0.333	18.0
7	Gypsum Drywall	All	0.64"	1.32	0.49

Note: ASHRAE 785-RP steel thickness terminology "Ga" has been replaced by "Mils and the inch thickness as per modern cold-formed steel standards

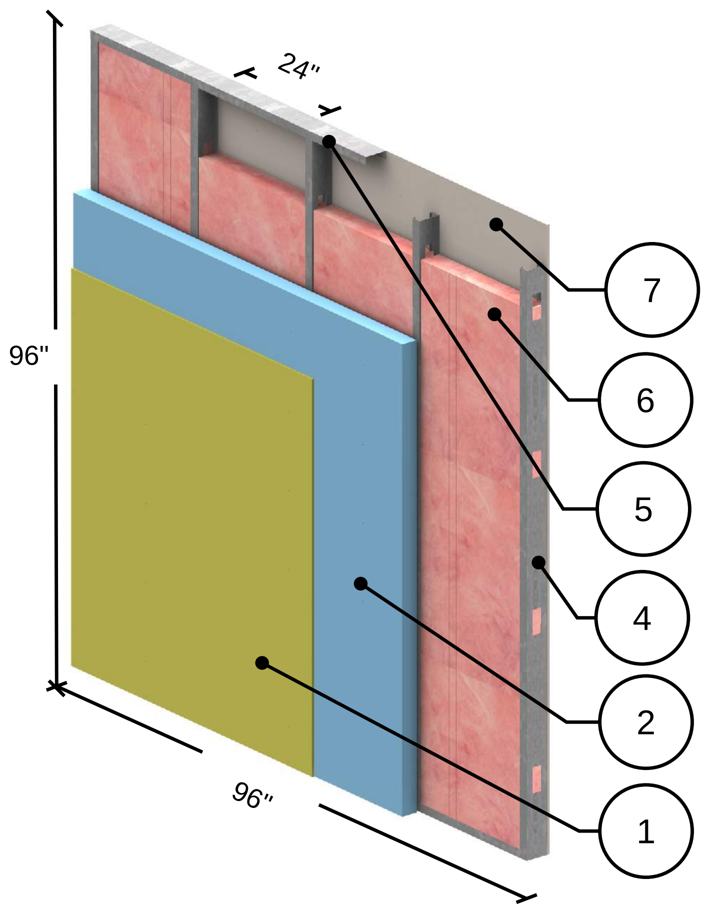

Figure A-1: ASHRAE 785-RP Validation Assembly

A.2 ORNL Compliation Study Assemblies

Table A-2: Material Properties Used in ORNL Compilation Study Validation Simulations

ID	Material	Validation Assembly	Thickness (In)	Conductivity K-Value (BTU-In/hr ft² °F)	R-Value (hr ft² °F/BTU)
1	EIFS Finish	18, 19, 21	3/4"	9.375	0.08
2	OSB Sheathing	7, 13, 16	1/2"	1.00	0.5
	Gypsum Sheathing	18-21	5/8"	1.25	0.50
3	0.5" XPS Foam	1, 8, 14, 17	0.5"	0.132	3.8
	1" XPS Foam	2, 9, 15	1"	0.200	5.0
	1.5" XPS Foam	3	1.5"	0.203	7.4
	2" XPS Foam	4, 11	2"	0.208	9.6
	2" EPS Foam	10	2"	0.241	8.3
	2.5" EPS Foam	18, 20	2.5"	0.298	8.4
	3" EPS Foam	5, 12	3"	0.248	12.1
	3.75" EPS Foam	6	3.75"	0.245	15.3
	4" EPS Foam	19, 21	4"	0.288	13.9
4	Fasteners 12"o.c.	All	#6	346	-
5	3.5" x 1 5/8" Steel Stud	1-12, 18-19	0.0428" (43 Mil)	430	-
	5.5" x 1 5/8" Steel Stud	13-17, 20-21	0.0428" (43 Mil)	430	-
6	3.5" x 1 1/4" Steel Tracks	1-12, 18-19	0.0428" (43 Mil)	430	-
	5.5" x 1 1/4" Steel Tracks	13-17, 20-21	0.0428" (43 Mil)	430	-
7	R-13 Batt Insulation	1-6	3.5"	0.273	12.8
	R-15 Batt Insulation	7-9	3.5"	0.259	13.5
	R-19 Batt Insulation	13-15	5.5"	0.337	16.3
	R-21 Batt Insulation	16, 17	5.5"	0.270	20.4
	Air Cavity	18, 19	3.5"	3.89	0.9
	Air Cavity	20, 21	5.5"	6.11	0.9
8	Gypsum Drywall	All	1/2"	1.28	0.5

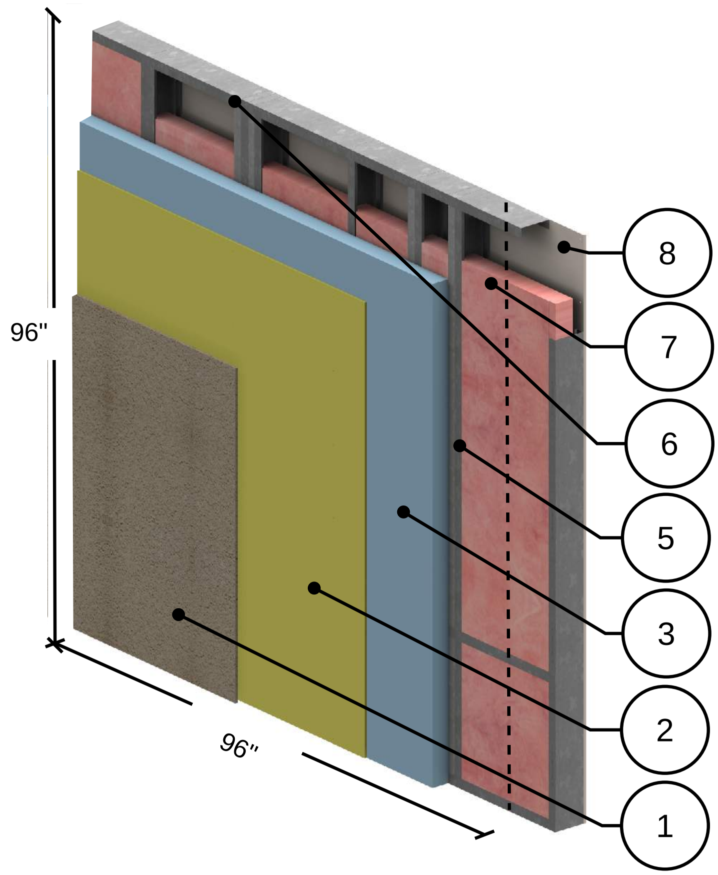

Figure A-2: ORNL Compilation Study Validation Assembly

A.3 Project Assemblies

Table A-5: Material Properties Used in Project Assemblies

ID	Material	Validation Assembly	Thickness (In)	Conductivity K-Value (BTU-In/hr ft^2 °F)	R-Value (hr ft^2 °F/BTU)
1	Stucco	All	3/4"	9.375	0.08
2	1.5" XPS	2, 5, 8, 11, 14, 16, 20, 23, 26	1.5"	0.200	7.5
	3" XPS	3, 6, 9, 12, 15, 18, 21, 24, 27	3"	0.200	15.0
3	Fasteners 6" or 12"o.c.	All	#6	346	-
4	Gypsum Sheathing	All	5/8"	1.11	0.56
5	3 5/8" x 1 5/8" Steel Stud	1-9	0.0428" (43 Mil)	495	-
	10" x 1 5/8" Steel Stud	10-18	0.0428" (43 Mil)	495	-
	12" x 1 5/8" Steel Stud	19-27	0.0428" (43 Mil)	495	-
6	3 5/8" x 1 1/4" Steel Tracks	1-9	0.0428" (43 Mil)	495	-
	10" x 1 1/4" Steel Tracks	10-18	0.0428" (43 Mil)	495	-
	12" x 1 1/4" Steel Tracks	19-27	0.0428" (43 Mil)	495	-
7	1 1/2" x 1 1/2" C-Channel	All	0.0428" (43 Mil)	495	-
8	Air Cavity	1-3	3 5/8"	4.0	0.9
	R-19 Insulation	4-6	3 5/8"	0.191	19
	R-38 Insulation	7-9	3 5/8"	0.095	38
	Air Cavity	10-12	10"	11.1	0.9
	R-19 Insulation	13-15	10"	0.526	19
	R-38 Insulation	16-18	10"	0.263	38
	Air Cavity	19-21	12"	13.3	0.9
	R-19 Insulation	22-24	12"	0.632	19
	R-38 Insulation	25-27	12"	0.316	38
9	Gypsum Drywall	All	5/8"	1.11	0.56

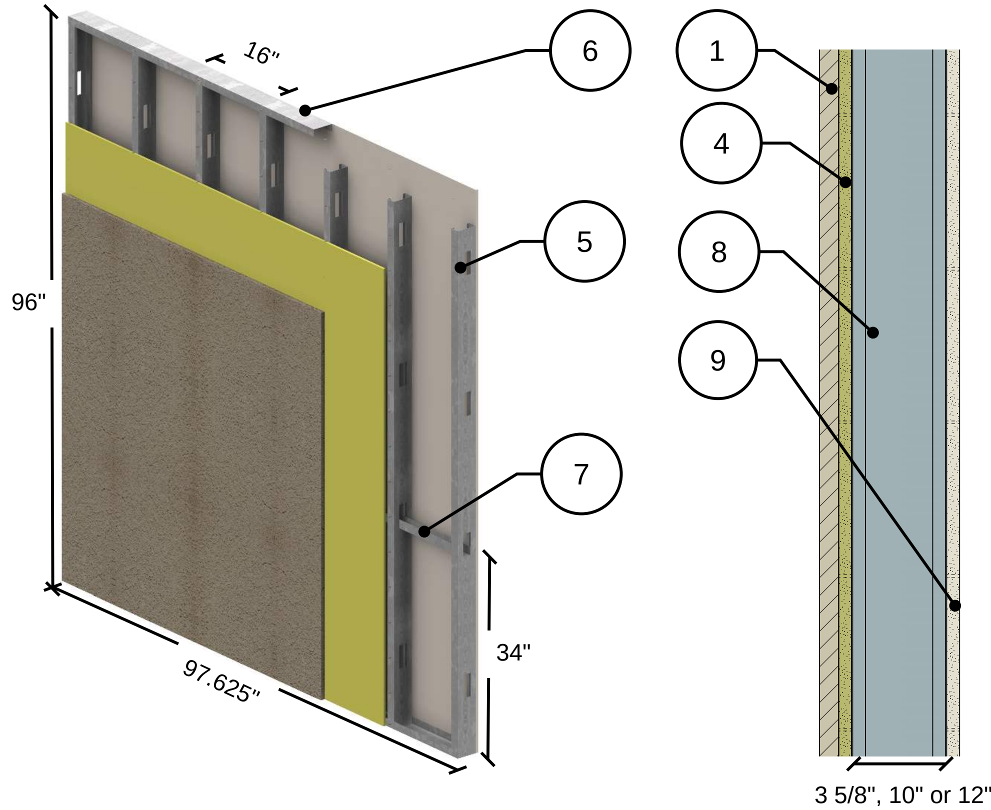

Figure A-3: No Insulation Project Assemblies 1, 10 and 19

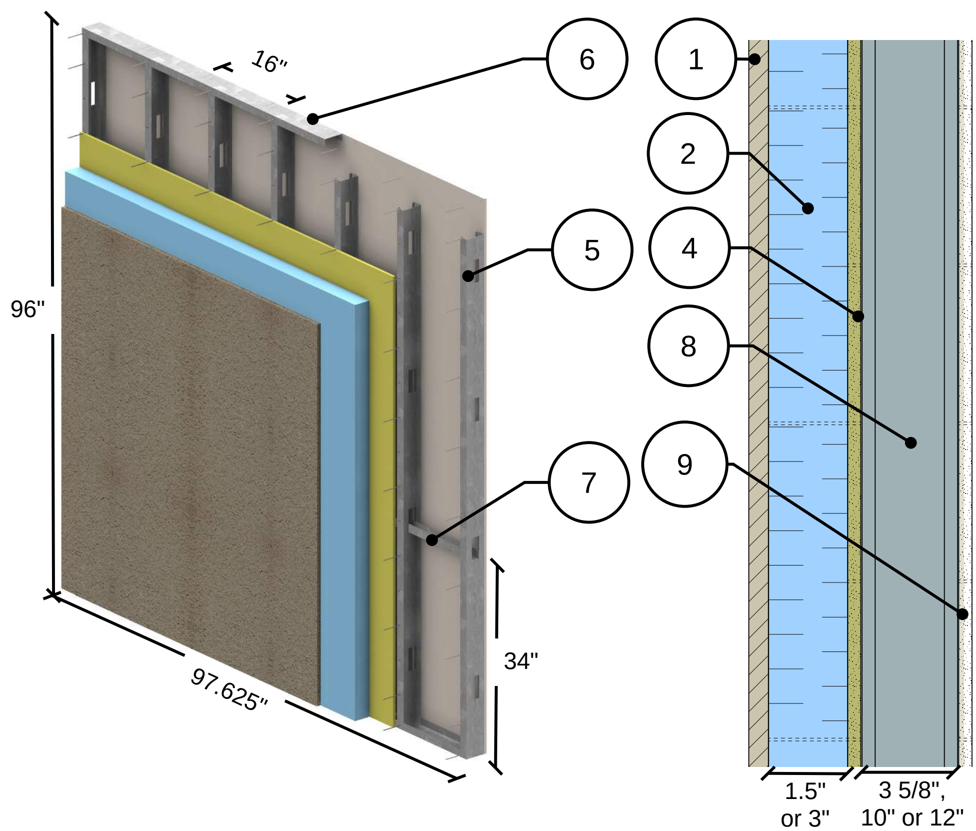

Figure A-4: Exterior Insulation Only Project Assemblies 2, 3, 11, 12, 20 and 21

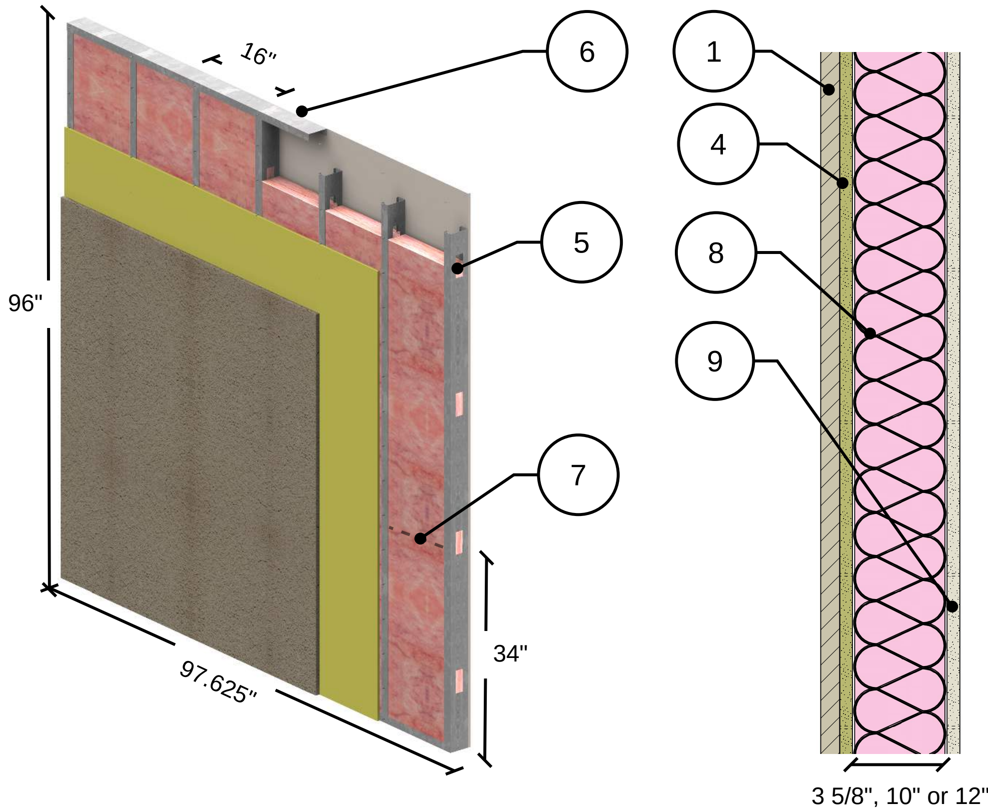

Figure A-5: Interior Insulation Only Project Assemblies 4, 7, 13, 16, 22 and 25

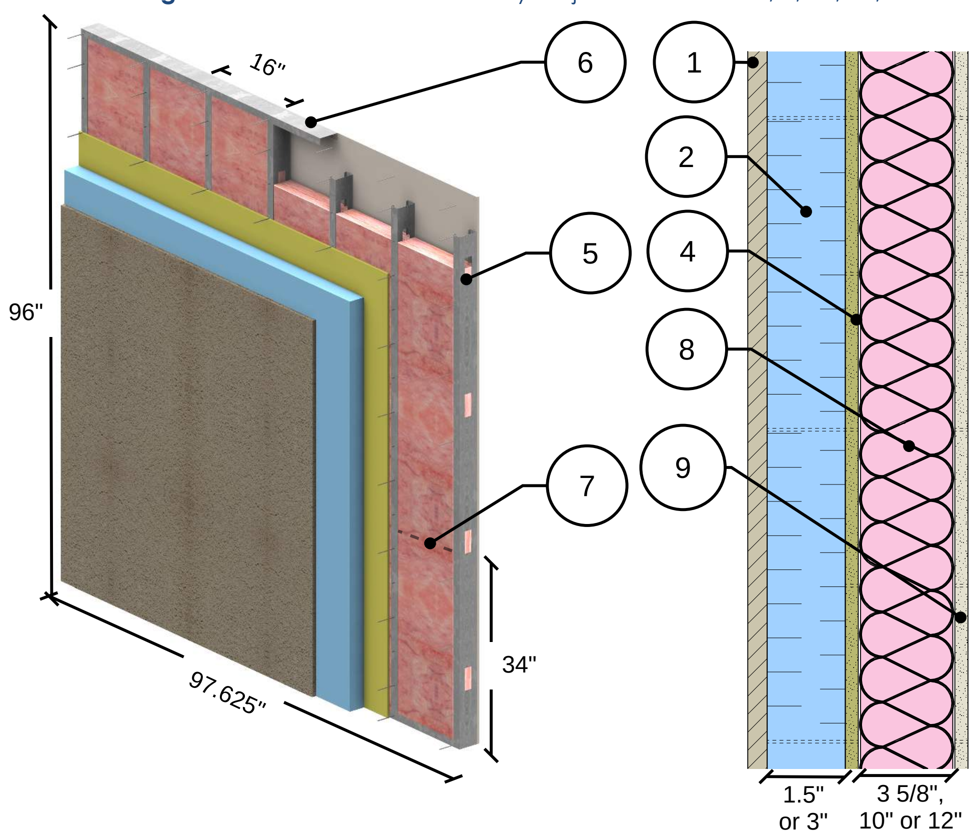

Figure A-6: Split Insulated Project Assemblies 5, 6, 8, 9, 14, 15, 17, 18, 23, 24, 26 and 27

APPENDIX B:
Detailed R- and U-Value Results

Table B-1: Simulated R- and U-Values for the 350S162 Steel Framed Project Assemblies

Assembly Ref.	Fastener Pattern	Gypsum Fastener Spacing	Ext. Insul. Fastener Spacing	Framing 16"o.c.	Component R-values hr·ft^2·°F/BTU (m^{2}K/W)							Simulated R-Value	Simulated U-value
					Interior Air Film	Interior Gypsum	Cavity Insulation	Exterior Sheathing	Exterior Insulation	Stucco	Exterior Air Film		
1	1	6" oc	N/A	350S162	0.68	0.56	**0.9**	0.56	**0**	0.08	0.17	**2.9**	**0.349**
	3	12" oc	N/A	350S162	0.68	0.56	**0.9**	0.56	**0**	0.08	0.17	**2.9**	**0.348**
2	1	6" oc	None	350S162	0.68	0.56	**0.9**	0.56	**7.5**	0.08	0.17	**10.4**	**0.096**
	2	6" oc	12" oc	350S162	0.68	0.56	**0.9**	0.56	**7.5**	0.08	0.17	**10.2**	**0.098**
	3	12" oc	None	350S162	0.68	0.56	**0.9**	0.56	**7.5**	0.08	0.17	**10.4**	**0.096**
	4	12" oc	12" oc	350S162	0.68	0.56	**0.9**	0.56	**7.5**	0.08	0.17	**10.2**	**0.098**
3	1	6" oc	None	350S162	0.68	0.56	**0.9**	0.56	**15**	0.08	0.17	**17.9**	**0.056**
	2	6" oc	12" oc	350S162	0.68	0.56	**0.9**	0.56	**15**	0.08	0.17	**17.3**	**0.058**
	3	12" oc	None	350S162	0.68	0.56	**0.9**	0.56	**15**	0.08	0.17	**17.9**	**0.056**
	4	12" oc	12" oc	350S162	0.68	0.56	**0.9**	0.56	**15**	0.08	0.17	**17.3**	**0.058**
4	1	6" oc	N/A	350S162	0.68	0.56	**19**	0.56	**0**	0.08	0.17	**9.3**	**0.107**
	3	12" oc	N/A	350S162	0.68	0.56	**19**	0.56	**0**	0.08	0.17	**9.3**	**0.107**
5	1	6" oc	None	350S162	0.68	0.56	**19**	0.56	**7.5**	0.08	0.17	**18.6**	**0.054**
	2	6" oc	12" oc	350S162	0.68	0.56	**19**	0.56	**7.5**	0.08	0.17	**18.2**	**0.055**
	3	12" oc	None	350S162	0.68	0.56	**19**	0.56	**7.5**	0.08	0.17	**18.6**	**0.054**
	4	12" oc	12" oc	350S162	0.68	0.56	**19**	0.56	**7.5**	0.08	0.17	**18.2**	**0.055**
6	1	6" oc	None	350S162	0.68	0.56	**19**	0.56	**15**	0.08	0.17	**26.3**	**0.038**
	2	6" oc	12" oc	350S162	0.68	0.56	**19**	0.56	**15**	0.08	0.17	**25.3**	**0.039**
	3	12" oc	None	350S162	0.68	0.56	**19**	0.56	**15**	0.08	0.17	**26.3**	**0.038**
	4	12" oc	12" oc	350S162	0.68	0.56	**19**	0.56	**15**	0.08	0.17	**25.3**	**0.039**
7	1	6" oc	N/A	350S162	0.68	0.56	**38**	0.56	**0**	0.08	0.17	**11.4**	**0.088**
	3	12" oc	N/A	350S162	0.68	0.56	**38**	0.56	**0**	0.08	0.17	**11.4**	**0.088**
8	1	6" oc	None	350S162	0.68	0.56	**38**	0.56	**7.5**	0.08	0.17	**22.3**	**0.045**
	2	6" oc	12" oc	350S162	0.68	0.56	**38**	0.56	**7.5**	0.08	0.17	**21.8**	**0.046**
	3	12" oc	None	350S162	0.68	0.56	**38**	0.56	**7.5**	0.08	0.17	**22.3**	**0.045**
	4	12" oc	12" oc	350S162	0.68	0.56	**38**	0.56	**7.5**	0.08	0.17	**21.8**	**0.046**
9	1	6" oc	None	350S162	0.68	0.56	**38**	0.56	**15**	0.08	0.17	**30.2**	**0.033**
	2	6" oc	12" oc	350S162	0.68	0.56	**38**	0.56	**15**	0.08	0.17	**29.0**	**0.034**
	3	12" oc	None	350S162	0.68	0.56	**38**	0.56	**15**	0.08	0.17	**30.2**	**0.033**
	4	12" oc	12" oc	350S162	0.68	0.56	**38**	0.56	**15**	0.08	0.17	**29.0**	**0.034**

Table B-2: Simulated R- and U-Values for the 1000S162 Steel Framed Project Assemblies

Assembly Ref.	Fastener Pattern	Gypsum Fastener Spacing	Ext. Insul. Fastener Spacing	Framing 16"o.c.	Component R-values hr·ft²·°F/BTU (m²K/W)							Simulated R-Value	Simulated U-value
					Interior Air Film	Interior Gypsum	Cavity Insulation	Exterior Sheathing	Exterior Insulation	Stucco	Exterior Air Film		
10	1	6" oc	N/A	1000S162	0.68	0.56	**0.9**	0.56	**0**	0.08	0.17	**2.9**	**0.344**
	3	12" oc	N/A	1000S162	0.68	0.56	**0.9**	0.56	**0**	0.08	0.17	**2.9**	**0.344**
11	1	6" oc	None	1000S162	0.68	0.56	**0.9**	0.56	**7.5**	0.08	0.17	**10.5**	**0.096**
	2	6" oc	12" oc	1000S162	0.68	0.56	**0.9**	0.56	**7.5**	0.08	0.17	**10.3**	**0.097**
	3	12" oc	None	1000S162	0.68	0.56	**0.9**	0.56	**7.5**	0.08	0.17	**10.5**	**0.096**
	4	12" oc	12" oc	1000S162	0.68	0.56	**0.9**	0.56	**7.5**	0.08	0.17	**10.3**	**0.097**
12	1	6" oc	None	1000S162	0.68	0.56	**0.9**	0.56	**15**	0.08	0.17	**18.0**	**0.056**
	2	6" oc	12" oc	1000S162	0.68	0.56	**0.9**	0.56	**15**	0.08	0.17	**17.5**	**0.057**
	3	12" oc	None	1000S162	0.68	0.56	**0.9**	0.56	**15**	0.08	0.17	**18.1**	**0.055**
	4	12" oc	12" oc	1000S162	0.68	0.56	**0.9**	0.56	**15**	0.08	0.17	**17.5**	**0.057**
13	1	6" oc	N/A	1000S162	0.68	0.56	**19**	0.56	**0**	0.08	0.17	**9.8**	**0.102**
	3	12" oc	N/A	1000S162	0.68	0.56	**19**	0.56	**0**	0.08	0.17	**9.8**	**0.102**
14	1	6" oc	None	1000S162	0.68	0.56	**19**	0.56	**7.5**	0.08	0.17	**18.4**	**0.054**
	2	6" oc	12" oc	1000S162	0.68	0.56	**19**	0.56	**7.5**	0.08	0.17	**18.1**	**0.055**
	3	12" oc	None	1000S162	0.68	0.56	**19**	0.56	**7.5**	0.08	0.17	**18.4**	**0.054**
	4	12" oc	12" oc	1000S162	0.68	0.56	**19**	0.56	**7.5**	0.08	0.17	**18.1**	**0.055**
15	1	6" oc	None	1000S162	0.68	0.56	**19**	0.56	**15**	0.08	0.17	**26.0**	**0.038**
	2	6" oc	12" oc	1000S162	0.68	0.56	**19**	0.56	**15**	0.08	0.17	**25.2**	**0.040**
	3	12" oc	None	1000S162	0.68	0.56	**19**	0.56	**15**	0.08	0.17	**26.0**	**0.038**
	4	12" oc	12" oc	1000S162	0.68	0.56	**19**	0.56	**15**	0.08	0.17	**25.2**	**0.040**
16	1	6" oc	N/A	1000S162	0.68	0.56	**38**	0.56	**0**	0.08	0.17	**12.4**	**0.081**
	3	12" oc	N/A	1000S162	0.68	0.56	**38**	0.56	**0**	0.08	0.17	**12.4**	**0.081**
17	1	6" oc	None	1000S162	0.68	0.56	**38**	0.56	**7.5**	0.08	0.17	**22.3**	**0.045**
	2	6" oc	12" oc	1000S162	0.68	0.56	**38**	0.56	**7.5**	0.08	0.17	**21.9**	**0.046**
	3	12" oc	None	1000S162	0.68	0.56	**38**	0.56	**7.5**	0.08	0.17	**22.3**	**0.045**
	4	12" oc	12" oc	1000S162	0.68	0.56	**38**	0.56	**7.5**	0.08	0.17	**21.9**	**0.046**
18	1	6" oc	None	1000S162	0.68	0.56	**38**	0.56	**15**	0.08	0.17	**30.1**	**0.033**
	2	6" oc	12" oc	1000S162	0.68	0.56	**38**	0.56	**15**	0.08	0.17	**29.0**	**0.034**
	3	12" oc	None	1000S162	0.68	0.56	**38**	0.56	**15**	0.08	0.17	**30.1**	**0.033**
	4	12" oc	12" oc	1000S162	0.68	0.56	**38**	0.56	**15**	0.08	0.17	**29.0**	**0.034**

Table B-3: Simulated R- and U-Values for the 1200S162 Steel Framed Project Assemblies

Assembly Ref.	Fastener Pattern	Gypsum Fastener Spacing	Ext. Insul. Fastener Spacing	Framing 16"o.c.	Component R-values hr·ft²·°F/BTU (m²K/W)							Simulated R-Value	Simulated U-value
					Interior Air Film	Interior Gypsum	Cavity Insulation	Exterior Sheathing	Exterior Insulation	Stucco	Exterior Air Film		
19	1	6" oc	N/A	1200S162	0.68	0.56	**0.9**	0.56	**0**	0.08	0.17	**2.9**	**0.343**
	3	12" oc	N/A	1200S162	0.68	0.56	**0.9**	0.56	**0**	0.08	0.17	**2.9**	**0.343**
20	1	6" oc	None	1200S162	0.68	0.56	**0.9**	0.56	**7.5**	0.08	0.17	**10.4**	**0.096**
	2	6" oc	12" oc	1200S162	0.68	0.56	**0.9**	0.56	**7.5**	0.08	0.17	**10.1**	**0.099**
	3	12" oc	None	1200S162	0.68	0.56	**0.9**	0.56	**7.5**	0.08	0.17	**10.4**	**0.096**
	4	12" oc	12" oc	1200S162	0.68	0.56	**0.9**	0.56	**7.5**	0.08	0.17	**10.1**	**0.099**
21	1	6" oc	None	1200S162	0.68	0.56	**0.9**	0.56	**15**	0.08	0.17	**18.0**	**0.056**
	2	6" oc	12" oc	1200S162	0.68	0.56	**0.9**	0.56	**15**	0.08	0.17	**17.4**	**0.058**
	3	12" oc	None	1200S162	0.68	0.56	**0.9**	0.56	**15**	0.08	0.17	**18.0**	**0.056**
	4	12" oc	12" oc	1200S162	0.68	0.56	**0.9**	0.56	**15**	0.08	0.17	**17.4**	**0.058**
22	1	6" oc	N/A	1200S162	0.68	0.56	**19**	0.56	**0**	0.08	0.17	**10.0**	**0.100**
	3	12" oc	N/A	1200S162	0.68	0.56	**19**	0.56	**0**	0.08	0.17	**10.0**	**0.100**
23	1	6" oc	None	1200S162	0.68	0.56	**19**	0.56	**7.5**	0.08	0.17	**18.4**	**0.054**
	2	6" oc	12" oc	1200S162	0.68	0.56	**19**	0.56	**7.5**	0.08	0.17	**18.1**	**0.055**
	3	12" oc	None	1200S162	0.68	0.56	**19**	0.56	**7.5**	0.08	0.17	**18.4**	**0.054**
	4	12" oc	12" oc	1200S162	0.68	0.56	**19**	0.56	**7.5**	0.08	0.17	**18.1**	**0.055**
24	1	6" oc	None	1200S162	0.68	0.56	**19**	0.56	**15**	0.08	0.17	**26.0**	**0.038**
	2	6" oc	12" oc	1200S162	0.68	0.56	**19**	0.56	**15**	0.08	0.17	**25.2**	**0.040**
	3	12" oc	None	1200S162	0.68	0.56	**19**	0.56	**15**	0.08	0.17	**26.0**	**0.038**
	4	12" oc	12" oc	1200S162	0.68	0.56	**19**	0.56	**15**	0.08	0.17	**25.2**	**0.040**
25	1	6" oc	N/A	1200S162	0.68	0.56	**38**	0.56	**0**	0.08	0.17	**12.7**	**0.079**
	3	12" oc	N/A	1200S162	0.68	0.56	**38**	0.56	**0**	0.08	0.17	**12.7**	**0.079**
26	1	6" oc	None	1200S162	0.68	0.56	**38**	0.56	**7.5**	0.08	0.17	**22.4**	**0.045**
	2	6" oc	12" oc	1200S162	0.68	0.56	**38**	0.56	**7.5**	0.08	0.17	**21.9**	**0.046**
	3	12" oc	None	1200S162	0.68	0.56	**38**	0.56	**7.5**	0.08	0.17	**22.4**	**0.045**
	4	12" oc	12" oc	1200S162	0.68	0.56	**38**	0.56	**7.5**	0.08	0.17	**21.9**	**0.046**
27	1	6" oc	None	1200S162	0.68	0.56	**38**	0.56	**15**	0.08	0.17	**30.1**	**0.033**
	2	6" oc	12" oc	1200S162	0.68	0.56	**38**	0.56	**15**	0.08	0.17	**29.1**	**0.034**
	3	12" oc	None	1200S162	0.68	0.56	**38**	0.56	**15**	0.08	0.17	**30.1**	**0.033**
	4	12" oc	12" oc	1200S162	0.68	0.56	**38**	0.56	**15**	0.08	0.17	**29.1**	**0.034**

APPENDIX C:
Temperature Indices and Example Temperature Profiles

Table C-1: Simulated Critical Surface Temperature Indexes for the 27 Steel Framed Project Assemblies

Assembly Ref.	Fastener Pattern	Temperature Index (T_i)				Assembly Ref.	Fastener Pattern	Temperature Index (T_i)			
		1. Sheathing - Cavity	2. Sheathing - Studs	3. Drywall – Cavity	4. Drywall – Studs			1. Sheathing - Cavity	2. Sheathing - Studs	3. Drywall – Cavity	4. Drywall – Studs
1	1	0.27	0.16	0.57	0.55	10	1	0.27	0.14	0.58	0.58
	3	0.27	0.27	0.58	0.55		3	0.27	0.19	0.58	0.58
2	1	0.80	0.77	0.88	0.88	11	1	0.80	0.76	0.88	0.88
	2	0.79	0.66	0.88	0.88		2	0.80	0.65	0.88	0.88
	3	0.80	0.80	0.88	0.87		3	0.80	0.78	0.88	0.89
	4	0.79	0.66	0.88	0.87		4	0.80	0.65	0.88	0.88
3	1	0.88	0.87	0.93	0.93	12	1	0.88	0.86	0.93	0.93
	2	0.88	0.76	0.93	0.93		2	0.87	0.74	0.93	0.93
	3	0.88	0.88	0.93	0.93		3	0.88	0.87	0.93	0.93
	4	0.88	0.76	0.93	0.93		4	0.87	0.74	0.93	0.93
4	1	0.04	0.12	0.94	0.59	13	1	0.04	0.10	0.93	0.69
	3	0.04	0.19	0.93	0.59		3	0.04	0.15	0.93	0.69
5	1	0.33	0.61	0.95	0.80	14	1	0.36	0.55	0.96	0.83
	2	0.33	0.53	0.95	0.80		2	0.35	0.47	0.96	0.83
	3	0.33	0.64	0.95	0.80		3	0.36	0.58	0.96	0.83
	4	0.33	0.53	0.95	0.80		4	0.35	0.47	0.96	0.83
6	1	0.50	0.72	0.97	0.86	15	1	0.53	0.68	0.97	0.88
	2	0.50	0.63	0.97	0.85		2	0.52	0.59	0.97	0.87
	3	0.50	0.74	0.97	0.86		3	0.53	0.70	0.97	0.88
	4	0.50	0.64	0.97	0.85		4	0.52	0.59	0.97	0.87
7	1	0.02	0.11	0.96	0.59	16	1	0.04	0.10	0.93	0.69
	3	0.02	0.19	0.96	0.59		3	0.04	0.15	0.94	0.69
8	1	0.23	0.58	0.97	0.79	17	1	0.25	0.52	0.98	0.81
	2	0.22	0.51	0.97	0.78		2	0.25	0.45	0.98	0.81
	3	0.23	0.61	0.97	0.79		3	0.25	0.55	0.98	0.81
	4	0.22	0.51	0.97	0.78		4	0.25	0.45	0.98	0.81
9	1	0.39	0.68	0.98	0.84	18	1	0.41	0.64	0.98	0.86
	2	0.38	0.61	0.98	0.83		2	0.41	0.56	0.98	0.86
	3	0.39	0.71	0.98	0.84		3	0.41	0.66	0.98	0.86
	4	0.38	0.61	0.98	0.84		4	0.41	0.56	0.98	0.86

Table C-1 Cont.: Simulated Critical Surface Temperature Indexes for the 27 Steel Framed Project Assemblies

Assembly Ref.	Fastener Pattern	Temperature Index (T_i)				Assembly Ref.	Fastener Pattern	Temperature Index (T_i)			
		1. Sheathing - Cavity	2. Sheathing - Studs	3. Drywall – Cavity	4. Drywall – Studs			1. Sheathing - Cavity	2. Sheathing - Studs	3. Drywall – Cavity	4. Drywall – Studs
19	1	0.27	0.14	0.58	0.60	24	1	0.54	0.67	0.97	0.89
	3	0.28	0.18	0.58	0.60		2	0.53	0.58	0.97	0.88
20	1	0.80	0.76	0.88	0.89		3	0.54	0.68	0.97	0.89
	2	0.80	0.65	0.88	0.89		4	0.53	0.58	0.97	0.88
	3	0.80	0.78	0.88	0.89	25	1	0.02	0.09	0.97	0.71
	4	0.79	0.65	0.88	0.89		3	0.02	0.14	0.97	0.71
21	1	0.88	0.86	0.93	0.94	26	1	0.25	0.50	0.98	0.82
	2	0.88	0.74	0.93	0.93		2	0.25	0.43	0.98	0.82
	3	0.88	0.87	0.93	0.94		3	0.26	0.53	0.98	0.83
	4	0.88	0.74	0.93	0.93		4	0.25	0.43	0.98	0.82
22	1	0.04	0.09	0.93	0.72	27	1	0.42	0.63	0.98	0.87
	3	0.04	0.13	0.94	0.72		2	0.41	0.54	0.98	0.86
23	1	0.36	0.53	0.96	0.84		3	0.42	0.64	0.98	0.87
	2	0.36	0.46	0.96	0.84		4	0.42	0.54	0.98	0.86
	3	0.36	0.56	0.96	0.84						
	4	0.36	0.46	0.96	0.84						

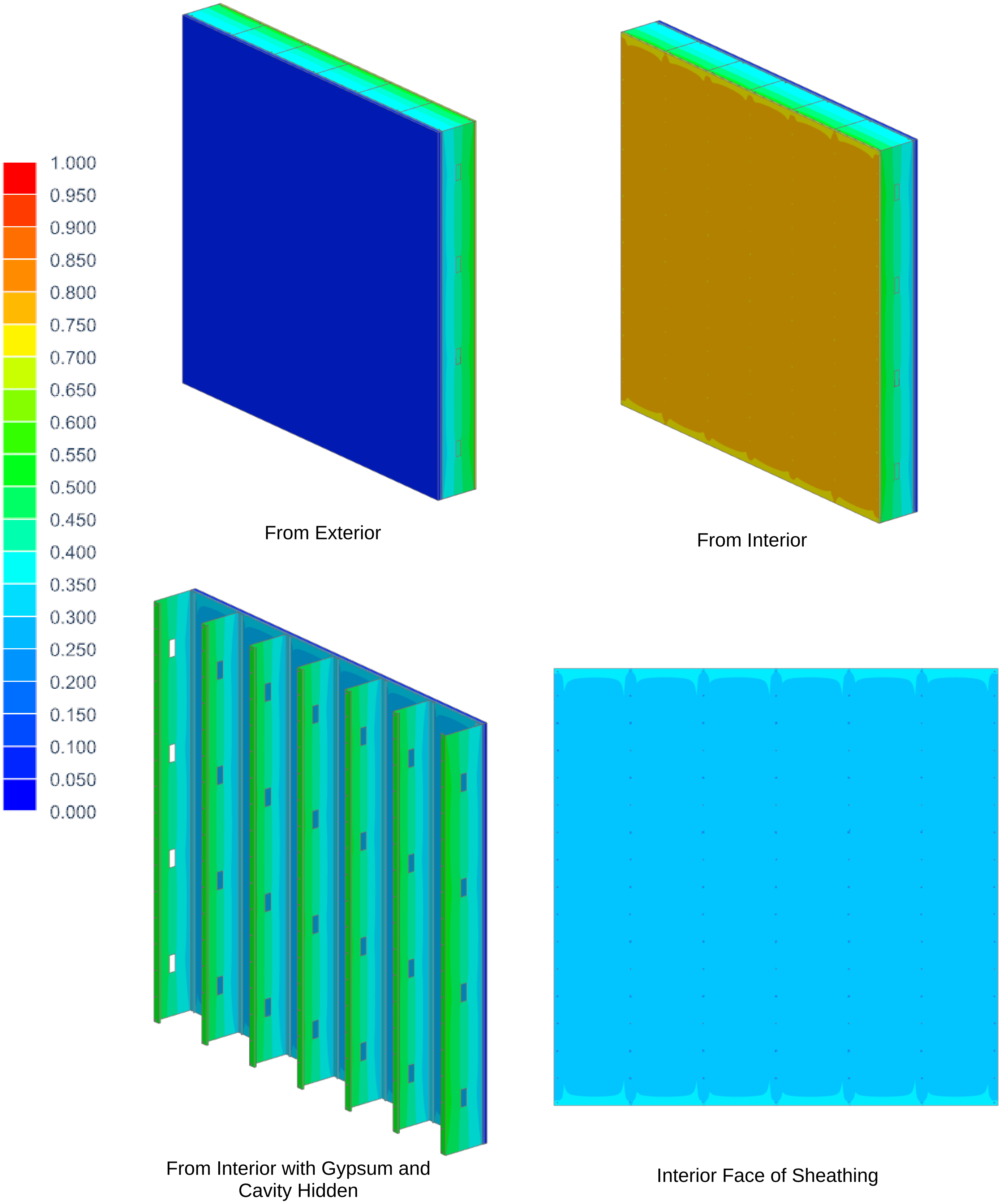

Figure C-1: Temperature Profiles for No Insulation Assembly #10, Fastener #1

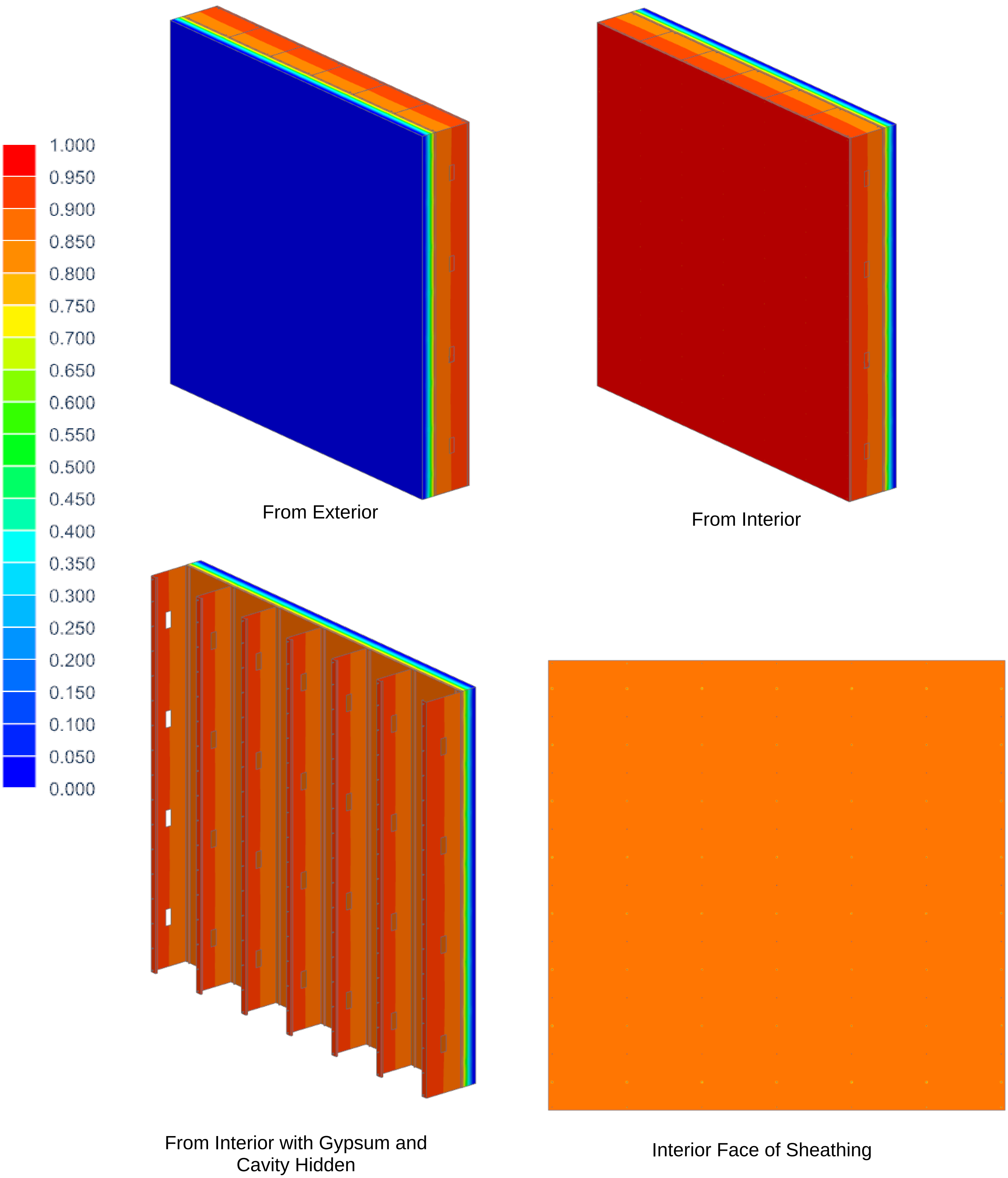

Figure C-2: Temperature Profiles for Exterior Insulation Only Assembly #12, Fastener #2

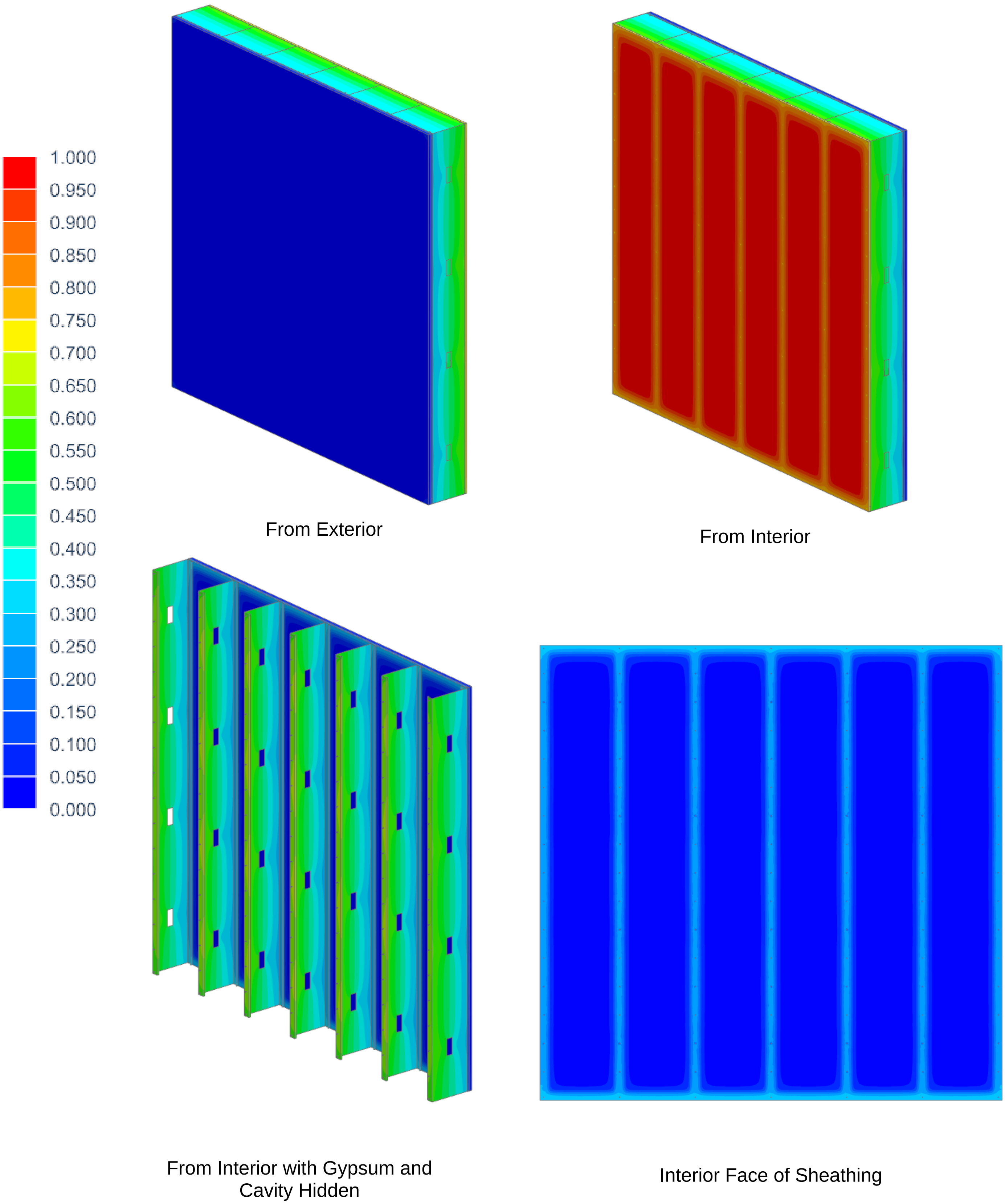

Figure C-3: Temperature Profiles for Interior Insulation Only Assembly #16, Fastener #1

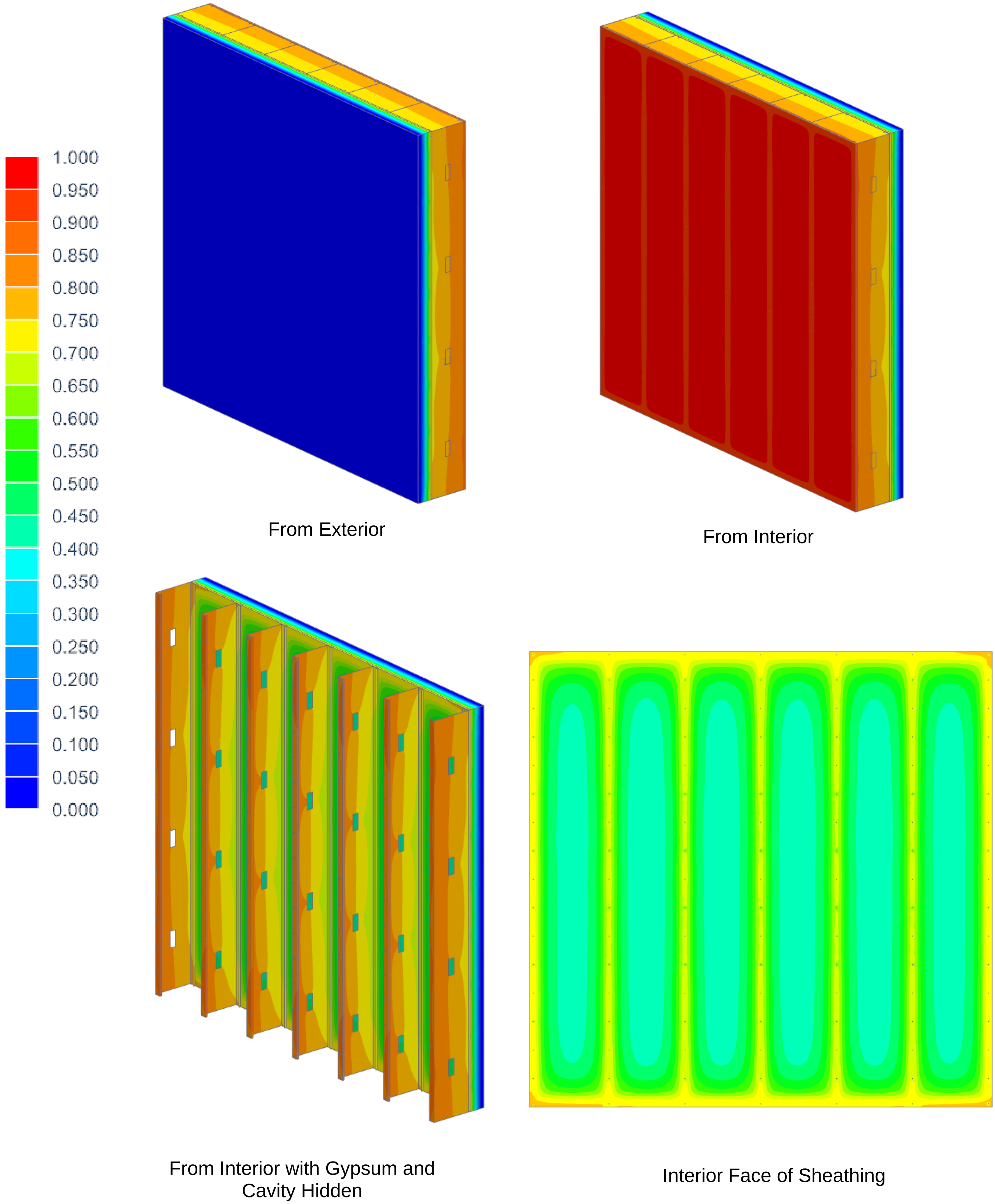

Figure C-4: Temperature Profiles for Interior Insulation Only Assembly #18, Fastener #2

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