

Validating Thermal Performance of Existing Assemblies Using In-Situ Measurements

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BACKGROUND AND INTRODUCTION

The thermal performance of existing building enclosures is often difficult to determine with a high level of validity. This can create confusion and uncertainty in maintenance or retrofitting projects. For older buildings, the challenge to get information often comes from incomplete or inaccurate documentation. The reasons range from missing drawings to as-built conditions not matching record drawings and undocumented later alterations from previous owners. When information about an existing enclosure is lacking, nondestructive measurement tools can be used in situ to collect data for use in the evaluation of thermal performance.

Before the heat flux sensor technology is applied to measurement conductivities, specialists can use several methods to analyze the thermal properties of building enclosures. Making assumptions based on incomplete record drawings is a valid way to analyze the thermal performance of the existing building envelope. Even without any record drawings, thermal analysis can still be efficiently done in collaboration with a historical expert familiar with the existing buildings' stock in the region. If the uncertainty due to incomplete information can impact the project significantly, destructive probes can be done easily to understand some situations—for example, the existence/thickness of rigid insulation in a roof assembly or the existence of fiberglass batt insulation in the interior metal stud cavities. With an analytical mind, tools like infrared cameras can also aid this process of using incomplete information to conclude the performance estimates. (See the use of the infrared camera in relationship to the heat flux tools in the "Preparing to Implement Field Measurements" section of this article.)

Heat flux transducers (HFTs) and temperature transducers (TTs) can be

especially useful for architects and engineers when there are too many unknowns of the existing envelope. This study wants to position the in-situ measurement toolset as an enhancement to complement the typical workflow using assembly documentation research, infrared scans, and American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) calculations. The field measurements can provide valuable information and confidence in the accuracy of assumptions based on field-collected data instead of dated unverified information. See the summary of the enhanced workflow in **Fig. 1**; it is a typical workflow diagram to determine the thermal performance values of the enclosure assemblies. Using HFTs and TTs is an optional step in the thinking process and acts as an enhancement but not a replacement for the overall thermal analysis.

The outcome of the in-situ measurement is either thermal conductivity (U -factor) or thermal resistance (R -value), depending on the conventions. For most of the wall and roof assemblies, the measured conductivity is converted to R -value at the end of the data analysis process and shown in most of the charts included in this study.

All the case studies included in this study are extracted from measurements completed in the author's office at RWDI. Since adopting the HFTs and TTs set to measure and analyze the conductivities in 2022, the author's team has completed

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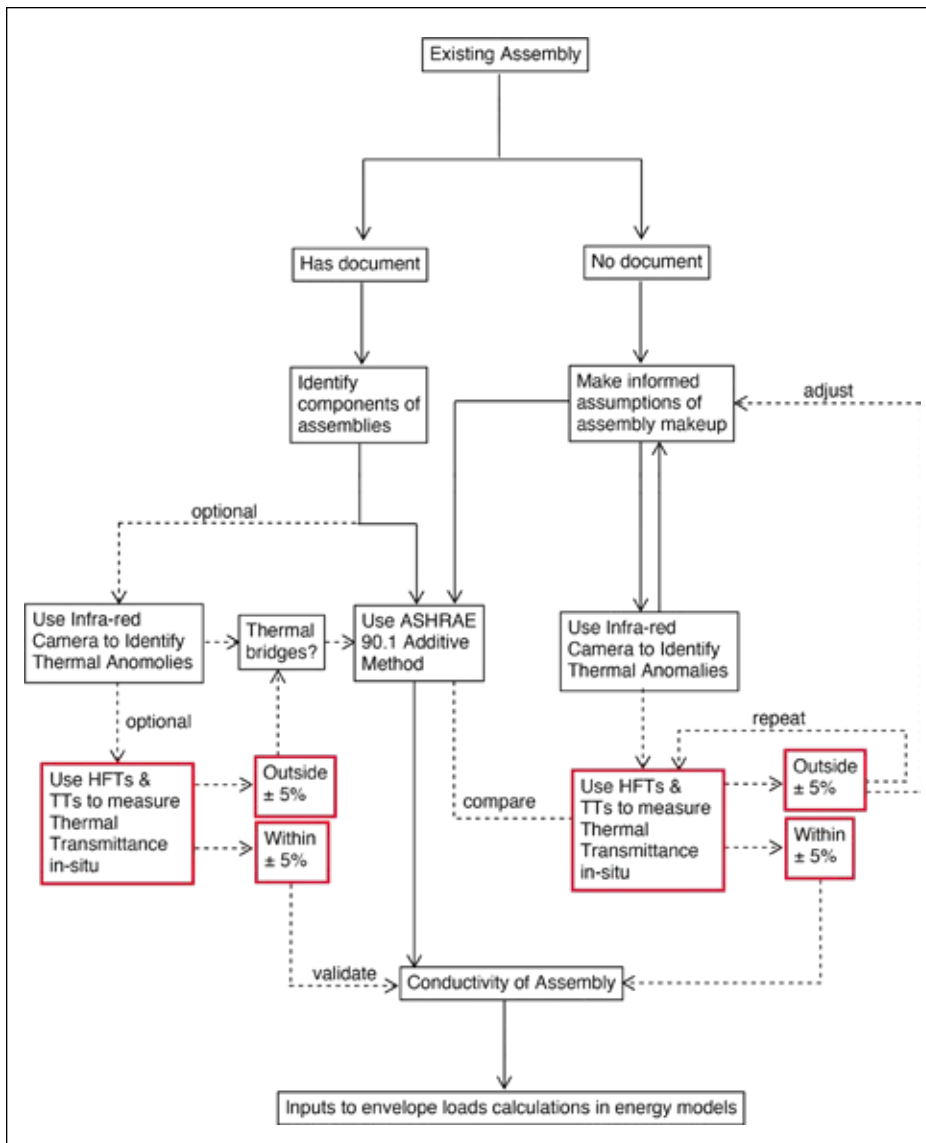


Figure 1. Typical workflow for determining the thermal performance inputs for energy models in known assemblies versus unknown assemblies. HFT = heat flux transducer; TT = temperature transducer.

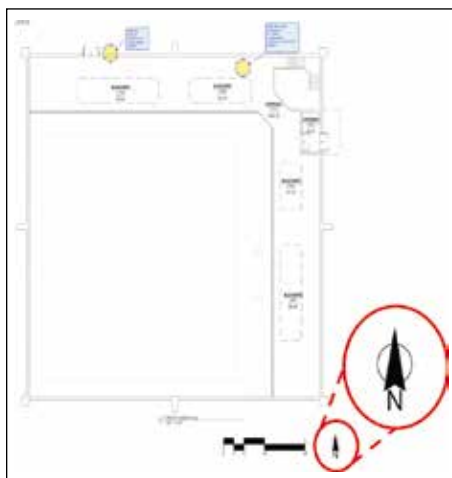


Figure 2. Floor plan of a sports facility; yellow circles are sensor locations.



Figure 3. Install sensors on the north slope under shade (wintertime); red arrow indicates the sensor location.

about 50 sets of measurements on various wall and roof assemblies. Most of the measurements were completed in wintertime, and most of the measured assemblies are opaque walls. A large portion of the measurements was taken amongst the portfolio of a college in Philadelphia, where a campus-wide energy retrofit plan is currently underway. The building uses of the measured assemblies range from office to classroom to residence.

KEY STEPS TO IMPLEMENT IN-SITU MEASUREMENTS

The procedure for using in-situ measurements from HFTs and TTs to validate the conductivity of wall and roof assemblies can be divided into the following five steps.

Step 1: Understand the assembly by going through the workflow diagram presented in Fig. 1. Identify the goal of the measurement. If you have one set of equipment, prioritize the measurement of the field conductivity outside of the thermal anomalies. If multiple sets of equipment are available, expand the goal to include different thermal conditions adjacent to each other.

Step 2: Select measurement locations. Avoid direct solar radiation by deploying sensors in the north (Fig. 2) or use shades (Fig. 3). The next section will discuss the use of a thermal camera in more detail to aid in selecting specific locations.

Step 3: Install equipment. See Fig. 4 and 5. Input conversion factor S as defined by the sensor manufacturer. Verify that the absorption rate of the HFTs matches the adjacent interior surface or surfaces. Validate initial readings 15 minutes after the sensor installation.

Step 4: Collect data for more than 72 hours. The length of the measurement is 1) required if the results need to meet ISO 9869:1, *Thermal Insulation—Building Elements—In-Situ Measurement of Thermal Resistance and Thermal Transmittance*,¹ and 2) more likely to produce a reliable result compared to a shorter measurement period. Record the weather conditions during the measurement period. Control the interior conditions to be as constant as possible. Protect the equipment from being removed or damaged.

Step 5: Retrieve equipment and process data. To meet the criteria of standard ISO 9869:1, the measured U -factor (see Eq. [1]) at the end of the test should deviate less than $\pm 5\%$ of the value obtained 24 hours at the beginning of the stabilized measurement; the first two-thirds of the overall measurement period should deviate

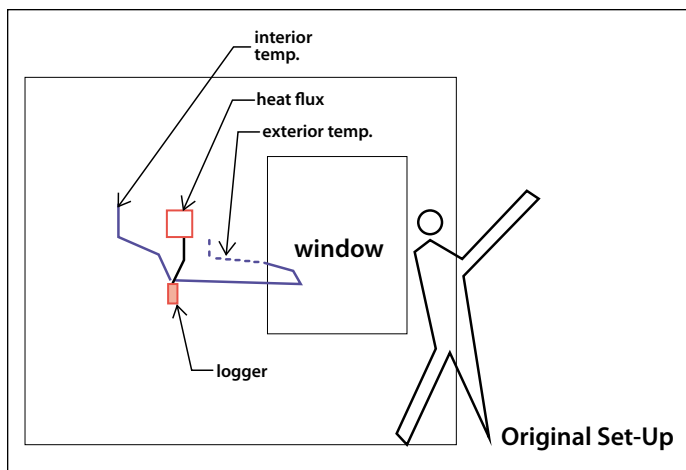


Figure 4. How to connect sensors at fenestrations.

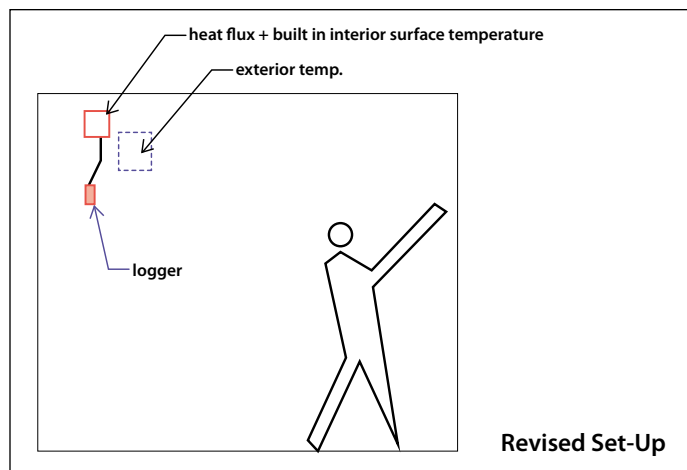


Figure 5. How to connect sensors without fenestrations.

Table 1. Example of converting measured data to desired result, following Equation 1.

Time	Te	Ti	W/m ²	Temperature Differential	W/m ² K	BTU/h-ft ² °F	R-value
1/20/23 12:34	9.88	24.75	13.20	14.87	0.8875	0.1564	6.39
1/20/23 12:35	9.84	24.81	13.20	14.97	0.8819	0.1554	6.43

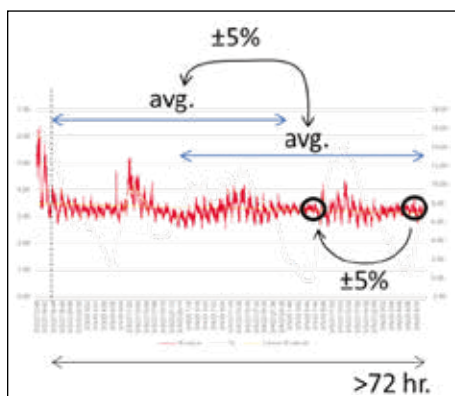


Figure 6. Example of a result chart with stabilized data.

less than $\pm 5\%$ of the last two-thirds of the overall measurement period. The overall standard deviation of the U -factor should be within 10% of the average value (Fig. 6 and Table 1).

Equation 1

$$U\text{-factor} = \frac{\sum_{j=1}^n q_j}{\sum_{j=1}^n (T_{ij} - T_{ej})}$$

where

q_j = heat flux at time j

T_{ij} = inside air temperature at time j

T_{ej} = outside air temperature at time j

PREPARING TO IMPLEMENT FIELD MEASUREMENTS

Before installing those tools, it is recommended by the standard practice guidelines^{1,2} to gather in-situ information with an infrared camera. This field measurement tool can be used to identify thermal anomalies in opaque and nonreflective building enclosures, as it provides a two-dimensional temperature map of an exterior or interior surface in real time. Although the infrared camera reads specific surface temperatures, it tells if one section of the envelope is colder or hotter than the adjacent section, but it does not measure the conductivity of each section. For example, for a heated building, the lack of insulation in a portion of the exterior wall will likely show up as a hotter surface in winter from the outside. The infrared camera may show the hotter portion being 5° warmer than the adjacent portion. Therefore, the information is usually used only to compare qualitative conclusions.

Thermal imaging can help identify conductive components of an opaque enclosure. For example, Fig. 7 is an infrared image of the exterior of a Philadelphia college dormitory, built in 1981, with a slate roof, a stucco wall at dormers, a stone wall, and wood-framed windows. The image was taken in the winter, and analysis of the thermal patterns should exclude the reflection of the cold surroundings and the sky at the insulated glass units (IGUs)



Figure 7. Exterior infrared image of a dormitory building at a college in Philadelphia, Pennsylvania, originally built 1981.

and metal downspouts (note the examples crossed out with white lines). Looking at the thermal image, it is apparent that the stone wall is conducting interior heat to the exterior more than the roof and the dormers. Therefore, the most conductive component of this building enclosure is the stone wall.

Thermal imaging can also help identify the presence of insulation within a stud cavity. For example, Fig. 8 shows an infrared image of an exterior wall taken in late winter from the interior of an office. The drawings on record indicated that the building, built in 1989, had metal studs at the interior. When analyzing the thermal image, the transmission of the cold surroundings



Figure 8. Interior infrared image of a wall of a college performance center and office in Philadelphia, Pennsylvania, originally built 1989.

or the sky should be excluded at the IGU (examples are crossed out with white lines). In this thermal image, profiles of the metal studs are apparent. Note that the field temperature between the metal studs is very close to the interior temperature captured at the interior wall surface to the left (72°F [22.2°C]). From this observation, it can be deduced that the heat loss to the exterior is very slow, and, therefore, the cavity between the metal stud walls is insulated.

Without quantitative values of the conductivities of the wall or roof, information from thermal images cannot be used directly as inputs to calculate enclosure loads in energy models. However, it serves an important role in determining where the heat flux sensor should be deployed because of two reasons:

- 1) Understanding the thermal anomalies helps identify the components in the wall assembly. By itself it can add values to the workflow shown in Fig. 9.
- 2) To know the locations of thermal anomalies, so that the specific HFT's location can be selected.

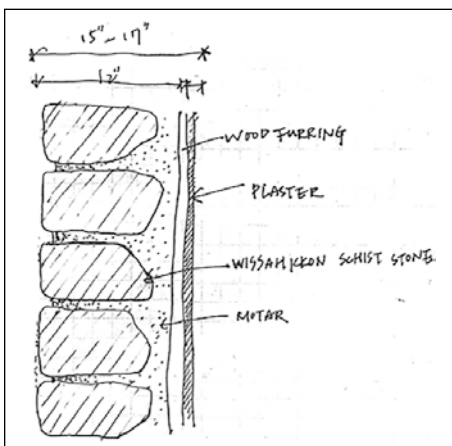


Figure 9. Assumptions about masonry assembly. Sketch by RWDI.

WAYS TO IMPROVE MEASUREMENT BASED ON TWO CASE STUDIES

Field measurements of the HFT and TT will vary due to key factors such as weather conditions, interior air temperatures, thermal mass of the measured assemblies, and thermal profiles of the assemblies in question. The following case studies present a variety of real-world examples of these anomalies.

Case Study 1: Identifying the Conductivity of a Mass Masonry Wall

Being part of a campus aiming for net-zero carbon by 2035, the project architect is looking to reduce the heating and cooling loads by insulating the existing envelope. The first step of the team was to understand the performance of the current envelope so that the energy modeler would have adequate parameters to run analysis.

For a historic home built in 1724, there was no record of the construction or modifications to date. Based on the age of the building, it was assumed to be load-bearing masonry. Assuming there is no interior insulation, the overall *R*-value is estimated to be *R*-1.5 ft²·°F·h/BTU (0.264 km²/W).

An infrared camera was used to identify the presence of insulation within the cavity (Fig. 10). Because the surface temperature between the metal studs is lower than the



Figure 10. Interior infrared image of a historic home and office at a college in Philadelphia, Pennsylvania, originally built 1724.

interior temperature captured at the ceiling (72°F [22.2°C]), it was assumed that the heat loss at the cavity was faster than the wood furring, and therefore the cavity between the metal stud walls was uninsulated.

The HFTs and TTs tool set was deployed at the colder surfaces between the wood furring to eliminate the thermal bridging of the studs. Because the assembly is highly conductive, the tool set contributes to more than 1% additional resistance to the construction. The thermal resistance of the HFT and adhesion tape was removed from the measured results based on ASTM C1046-95, *Standard Practice for In-Situ Measurement of Heat Flux and Temperature on Building Envelope Components*.¹ The average measured thermal resistance with adjustment was *R*-1.71 ft²·°F·h/BTU (0.301 km²/W). The standard deviation in the measurement of the thermal transmittance is 11.4%, which exceeds the standard allowance for error (10%). The average measured thermal resistance is 12% greater than the assumed resistance based on the assumptions of the assembly materials. The existing assembly is measured to be slightly more insulating than the additive method prediction, which could be contributed to a thicker stone or the wood furring.

As demonstrated by this case study, using in-situ HFT and TT tools cannot replace the process of component-based thermal analysis, but the field measurements can validate the outcome of the thermal analysis (Fig. 11).

Case Study 2: Identifying the Conductivity of an Insulated Concrete Masonry Unit Wall

For a lecture hall built in 1995, the documentation indicated that the wall assembly was constructed of steel and concrete masonry units, exterior rigid insulation, and stone cladding over metal supports (Fig. 12). The documentation also revealed many thermal bridges at the structural steel, corners, perimeter of fenestration, and penetrations that made a simple clear field value difficult to identify. The clear field area was so small that the

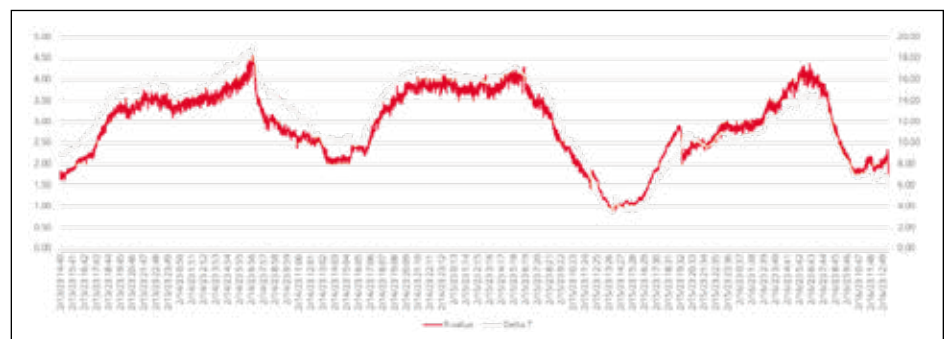
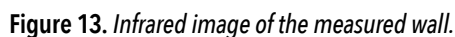
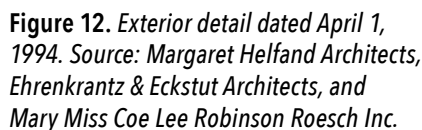
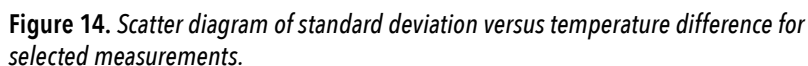


Figure 11. Thermal resistance based on measurements from heat flux and temperature transducers.



At first, the author's team was only using one set of HFTs, which was deployed outside of thermal anomalies based on the thermal imaging (**Fig. 13**). When multiple sets became available, one of the sensors could be deployed at the thermal anomalies to understand the effect of thermal bridging. If the additive method specified in Section A9.4 of ASHRAE 90.1, *Energy Standard for Buildings Except Low-Rise Residential Buildings*,³ were used on its own, it would produce an optimistic estimated *R*-value of 12.2 ft²·°F·h/BTU (2.15 km²/W), whereas the measured conductivity was only as high as 7.7 ft²·°F·h/BTU (1.36 km²/W). To capture the thermal bridges, multiple locations were selected, and a total of four measurements were taken to provide a relatively accurate measurement of the average conductivity of the exterior wall. This procedure eliminated the need to simulate the thermal bridges using a computer

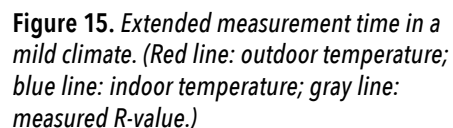


program developed by Lawrence Berkeley National Laboratory called THERM (or similar heat transfer simulation software programs developed for calculating conductivities of certain geometries and materials in two or three dimensions). The simulation process has yet to be automated, which can result in a more labor-intensive process to input a complex set of geometry into the model.

FACTORS INFLUENCING THE PRECISION OF MEASUREMENTS

The Difference Between the Exterior and Interior Temperatures Differential

Below is a scatter diagram (**Fig. 14**) showing most of the measurements land within the 10% deviation range and have at least a 10°F temperature differential. However, a few cases also managed to achieve the lower deviation with a much lower temperature differential. These were the cases where the assembly only



When the 15°F (8.3°C) temperature differential could not be maintained consistently due to daily temperature changes, it was useful to double the measurement time to capture more data. Many of the selected installation conditions had noticeable day and night temperature differences. For example, all the summer measurements in Philadelphia faced the challenge of inconsistent indoor-outdoor temperature differential (**Fig. 15**). The daytime temperature difference can usually reach 15°F but not always constantly greater than 15°F in the mornings and afternoons. At night the temperature differences sometimes can reverse, where the outdoors becomes cooler than the indoors. It sometimes means the data was

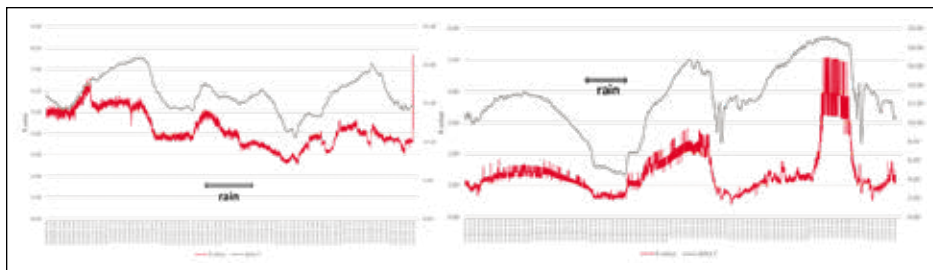


Figure 16. Comparison of two R-value measurements at the location of a masonry wall on different days. (Red line: R-value; gray line: temperature difference.)

skewed, especially around the tipping points of zero temperature differential. However, successful measurements meeting the ISO/ASTM standards^{1,2} were completed at these challenging conditions before with extended time.

Selectively choosing data over a longer period does not meet ISO/ASTM standards,^{1,2} and this method cannot be used to solely identify assembly thermal resistance. However, when dealing with fluctuating temperature differences, selectively cropping out data around zero-temperature-differential time can be useful in understanding the overall dataset. This is especially true for the assemblies that already had drawings and just needed an order of magnitude for validations.

Weather Events That Had Limited Impact on Measurement

When rain coincided with temperature changes, it appeared to have impacted the HFT measurement. However, when comparing two sets of measurements at the same location during different time periods, it was discovered that that rain event is not necessarily impacting measurements (Fig. 16).

LIMITATIONS OF HEAT FLUX AND TEMPERATURE TRANSDUCERS AND ALTERNATIVE WAYS TO OBTAIN THE THERMAL PERFORMANCE OF EXISTING ASSEMBLIES

Translucent Assemblies

Like infrared cameras, HFTs and TTs are not suitable for use on translucent assemblies. Even when HFTs are deployed at a shaded site, they will pick up heat transfer from ambient radiation, more than the conduction from the glass surface. Modifications can be made, such as taping or masking the outside of the glass, but the modifications inevitably will change the original states of the assembly.

The most direct way to identify the properties of an IGU is to find the glass label by the manufacturer that is typically etched into a corner of the IGU. Alternatively, a glass thickness gauge

meter can be used to identify the components within the glass unit; this meter usually can provide a reliable assumption of the low-emissivity coating, the location(s) of the coating(s), and the width and type of gas of the gap. Information from a glass gauge meter is sufficient to provide a relatively accurate assessment of the thermal properties at the center of the glazing.

Metal Components

With HFTs and TTs, it is also tricky to measure metal components, either metallic surfaces or steel structures, because of the multidimensional heat flows created by highly conductive components. To clarify, the tool set can be used on metal stud walls or roofs with steel decks, where metal components are not in direct contact with the exterior or the HFTs and have a consistent heat flow pattern. This situation can be overcome by using the infrared camera to identify the locations of the thermal bridges created by metal components within (see Case Study 2). Multiple measurements can be used to increase confidence in the results. However, if the interior surface is metallic, such as a curtainwall frame, the lateral conduction or interior radiative exchange can alter the measurement with numerous rapid fluctuations and make it difficult to identify heat flow patterns.

CONCLUSION

Taking in-situ measurements using the combination of HFTs and TTs is a useful nondestructive method to determine the baseline thermal resistance for a range of existing building wall and roof assemblies. For an assembly with detailed documentation, these field measurements assist in validating the U-factor estimates. If the field-measured U-factor consistently varies from the calculated prediction, those measurements prompt further study. For an assembly with unknown makeup, successful field measurements can provide approximate U-factor evaluation, confirm assumptions, or identify anomalies requiring further investigation.

Setting up the HFTs and TTs in the field is critical to the success of the measurements.

Skipping a step will likely result in inconclusive data or misinterpretation of the measurements. When the result does not meet the recommended 10% standard deviation by ASTM C1046-X4,¹ the tool set will still reflect the real-time thermal behavior of the assemblies in question and provide insight into the thermal performance related to thermal mass or other factors that impact the heat transfer. 

REFERENCES

1. International Organization for Standardization (ISO). 2014. *Thermal Insulation—Building Elements—In-Situ Measurement of Thermal Resistance and Thermal Transmittance*. ISO 9869-1:2014. Geneva, Switzerland: ISO.
2. ASTM International. 2021. *Standard Practice for In-Situ Measurement of Heat Flux and Temperature on Building Envelope Components*. ASTM C1046-95 (2021). West Conshohocken, PA: ASTM International.
3. American Society of Heating, Refrigerating and Air-Conditioning Engineers. 2022. *Energy Standard for Sites and Buildings Except Low-Rise Residential Buildings*. ASHRAE 90.1-2022. Peach Tree Corners, GA: ASHRAE.

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A highly motivated building enclosure consultant with RWDI's Philadelphia team, Shibe Huang possesses technical skills specific to high-performance buildings, energy code compliance, assembly performance analysis, and construction administration. With a

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