Full paper submitted in partial fulfillment of
Arch 563: Building Science Research Topic
Portland State University, School of Architecture

Exploring in situ U-Value thermal performance of glazing with infrared thermography for an urban multifamily housing complex

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Abstract

This study conducts a post-occupancy evaluation of thermal performance on a building envelope. Glazing and doors of an affordable housing high-rise located within the Pearl District of Portland, Oregon are specifically investigated. This research explores an in situ methodology for measuring U-values of glazing and doors which are then compared to provided U-values by manufacturer specification and Oregon Energy Efficiency Speciality Code 2014 (OEESC 2014) requirements. Infrared thermography (IRT) and local weather data information were used to measure envelope performance in Fahrenheit degrees. Measured surface, interior and exterior temperature data were furthermore used in a non-normative experimental U-value calculation specified for IRT from previous literature. Discrepancies and research data collection limitations for in situ U-value calculations are explored in detail. Implications of this research aim at identifying why discrepancies in U-value performance between IRT methodology, manufacture specification, and code requirements may exist. Constraints and variables are then explored for in situ IRT methodology and calculations to bolster future research reliability and validity. Additional implications of this research aim to illuminate issues and challenges in the feedback-loop existing between architects, code requirements, construction process, and measured in situ building performance.

Keywords: IRT, thermal performance, post-occupancy, envelope performance, U-value, OEESC - 2014, in situ IRT, glazing performance

1. Introduction

The architecture industry, in light of environmental concerns and impacts i.e. CO2 emissions and 2030 Challenge have recently concentrated on quantifying the performance qualities, material properties and aspects of building components early in the decision process. The building sector has been found to contribute up to 40% of the overall energy consumption within the United States. Many architecture firms are now seeking to reduce CO2 emissions and overall building energy consumption in the early design phases of the project. There have been great strides in easy to use calculations and software for estimating building material life cycle assessment and predicted energy consumption. However, many advancements can be made in understanding the performance of buildings between the design phases and the built structure. The U-value of building assemblies and glazing have a large contribution to the energy efficiency of the building envelope. However, equations and methodologies for calculating U-values provided by world standardization organizations often determine these equations from strict laboratory testing procedures compared to in situ methodology which contain a more complex understanding of the environment and the data collection tools that relate to determining U-value calculations and results. Many studies have seen deviations in U-values from theoretical (standardized calculations) to in situ (infrared thermography and heat flux meter), which may indicate that national or regional code requirements become more stringent in their regulations for U-values.

The current research performs a POE on thermal performance levels of glazing on a recently built structure in order to determine the efficacy of the glazing energy performance along with evaluating an situ IRT methodology. Specific research questions addressed in this study are as follows:

1. *How is the exterior glazing performing compared to the anticipated U-values.*
2. *Are there any portions of the building envelope that are "thermal holes".*
3. *How does the envelope impact the building's energy use?*
4. *Are there design strategies to make the envelope more efficient?*

To examine the in situ thermal conditions IRT camera technology was used to collect thermal data i.e. images and (F°) readings, specifically on the building's envelope i.e. glazing and doors. Observed on-site data and calculation are compared to manufacturer specifications and OEESC 2014 code. Although Vibrant was designed to exceed the energy performance standards of OEESC 2014, this research aims to test the efficacy of varying U-value calculation methodologies along with the glazing in a in situ POE setting. This research hypothesis that the actual measured and theorized U-values of glazing will vary to that of specification and code requirements. This research aims to identify possible gaps between the design - construction - code - POE building process loop as a means of understanding discrepancies in U-values.

Many international and nationwide building code standards are often updated biannually or even longer intervals of five years. The updating of the building code involves many bureaucratic processes, building trends and advancements in recent technologies and research. In many cases specified building codes experience a latency period or delay of implementation within the AEC sectors because regional codes are derived from national or international building codes i.e. IECC or ASHRAE. This study hypothesizes that through the process of design - construction - measured performance that a reduction occurs in the final energy performance of the building.

While this research attempts to determine how and why this reduction in thermal performance may occur specifically to the Vibrant building structure, furthermore implications of this research elucidate that built structures are performing at lower than expected U-value code requirements in general. Differences in U-Values from manufacture and code have shown deviations from in situ methodology given by the calculations that are used to determine U-values. This implication can assist in evaluating how designers and manufactures may need to exceed code requirements to actually meet these standards in the built environment.

Vibrant is an affordable housing high rise, located in the Pearl District of Portland, Oregon [Figure 1] [Figure 2]. Vibrant was designed to provide affordable and low-income housing to community members [1]. The high-rise apartment complex features 93 units of housing, 40 of these units are reserved from previously house-less tenants, with the remaining 53 units occupied by tenants who live between 30% - 60% of the median income [1].

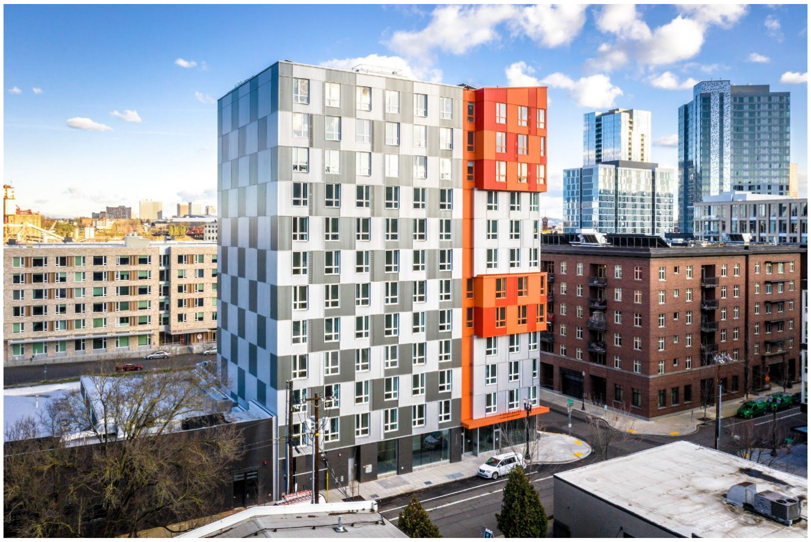


Figure 1: Vibrant! Photograph, Courtesy of Salazar Architects Inc.

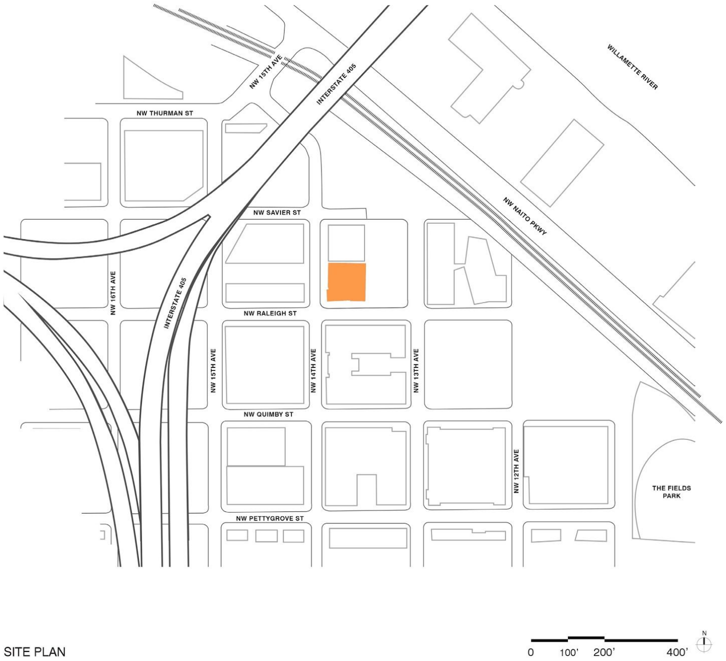


Figure 2: Site Map, Courtesy of Salazar Architects Inc.

2. Literature review

Post occupancy evaluations (POE) provide valuable insights into the performance of buildings. The POE process can illuminate occupants feedback, preferences, and behaviors [2]. POE can specifically indicate how a building system is performing in accordance with users comfort rating [2]. POE research is also conducted to see if users are inhabiting the building in the way that it was designed for. If the building is being used in a way that the designers were not anticipating this may result in lower energy performance of particular systems [2]. Most important POE provides an opportunity for a feedback loop to designers and architecture firms. Many different POE can be conducted with relativity to the qualitative or quantitative aspects desired. In more recent years, as technology advances with accuracy and reliability, more quantitative information through data collection has been desired for architecture firms to learn about the overall “real time” performance of buildings.

The building envelope can be described as the physical separator between the conditioned and unconditioned environments of a building, which additionally include the buildings ability to resist outside conditions i.e. air, water, light and noise [3]. The r-value indicates the resistance to heat flow while the u-value measures how a building material conducts heat or the rate of transfer of heat through a particular area of said material [4]. The relationship of the r-value and the u-value are inverse of each other and can be calculated as such. Thermal bridging is the process of heat transfer through a particular building material from either the inside of the building to the outside or vice versa such as conduction [4]. As heat attempts to follow the path of least resistance, any gaps or holes between building materials can allow for thermal bridging. If thermal bridging occurs in a built structure, occupants or mechanical systems may attempt to regain comfortability levels or equilibrium by inadvertently using mechanical systems i.e. air conditioners or opening windows/doors [4].

R-values and u-values can be calculated using many different calculations and procedures that each vary in their rigor of results, consistency, and reliability. ISO (internal organization for standardization) is one of the worlds most utilized agencies, among many others similar types of agencies i.e. ANSI, ASHRAE IEC for determining and updating u-value and r-value calculations. Similar utilization of (ISO 6946) for determining U-values has been stated in previous research findings with varying degrees of reliability against measured (IRT) data, as the most common equation found [6] [8] [9]. However, ISO calculations have great limitations in that they are reductionist calculations which are determined under laboratory settings with fixed and limited weather conditions [6] [9].

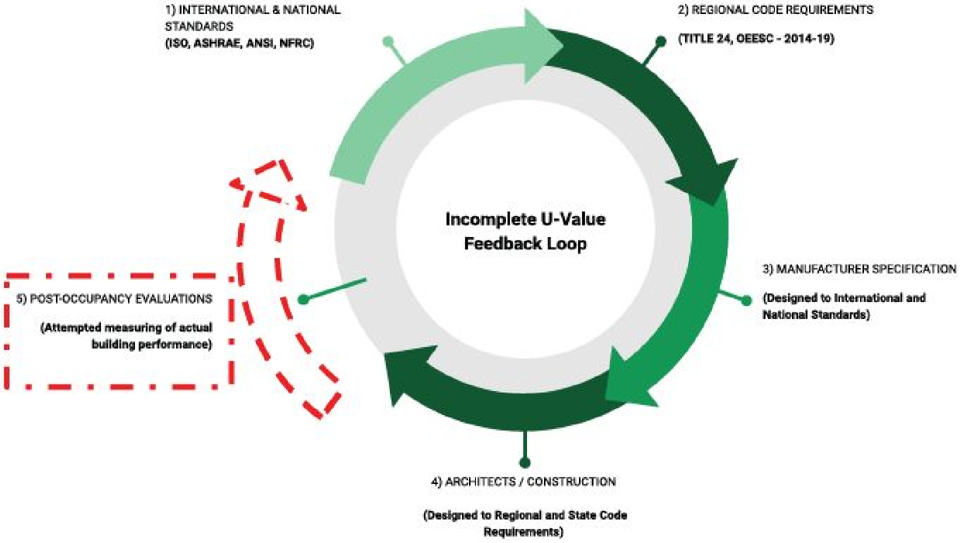


Diagram 1: Incomplete U-value Feedback loop

As [diagram 1] indicates the role of POE within normal industry standards is limited and is not typically conducted leaving the feedback loop of U-value calculations incomplete within industry standards. Through extensive academic research with in-situ methods of data collection researchers are starting to understand the complexities in U-value calculations in real time. The “trickle-down” effect of standardized calculations infiltrate how architects and designers think about building performance. However, the example of U-value calculations can elucidate to other energy performance metrics and values within the construction and architecture industries. If there are large discrepancies in how the A/E/C industries calculate their energy performance for windows this is likely the case for other building materials as well. One of the major limitations for providing and incentivizing POE research is deciding who should pay for evaluations to be conducted. Many real estate investors and building owners would never see a return of investment for a POE study. Furthermore, if the study concluded that the building energy performance was lower than expected, which it might because of the incomplete feed-back loop, then blame might be directed at the architecture firm which can create liability issues along with business relationship challenges.

The NFRC (National Fenestration Rating Certification) program follows the ISO 15099 procedure that determines a center-of-glass, edge-of-glass, frame, and total product U-factor. This program calculated the U-factors at a single set of temperatures (21°C interior and -18°C exterior) with variable surface heat transfer coefficients [10] [17]. Additionally, Passive House uses ISO 10077 which is a very similar calculation, however it does not use a single set temperature for interior and exterior and instead uses the U-value from the entire glass instead of the center-of-glass along with additional equation parameters for calculation [10] [11]. Although both ISO 15099 and ISO 10077 are perhaps more in depth ways to calculate theorized U-values for glazing they are still based off of manufacturing information about the provided U-value of the glazing and frame [10]. Passive House has a specified list of window manufactures that allows them to create more accurate U-value calculations from additional information [11]. Passive House U-value calculations, being more in-depth, may provide more accurate theorized U-value numbers, however these calculations will still be different from in situ methodology and U-value calculations [10].

Many discrepancies and limitations in U-value calculations using IRT methodologies in situ have been explored by the variance of environmental conditions of data collection. Although IRT technology has been around for over 30 years, it is only within the last 10 years that the technology has attempted to quantify observed data compared to historical qualitative analysis of the thermal images alone [13][16]. In order to quantify the IRT temperature data, many researchers have investigated and created experimental calculations for this in situ method [13]. However, many researchers and studies have indicated that IRT is extremely sensitive and calculations are still being developed to accurately determine useful U-value data [6] [9] [13] [16]. A compilation of recent research findings has indicated a range in accuracy from notional ISO 6946 calculations to IRT U-values calculations with deviations up to 80% [9]. However, Dall'O et al. [14] have indicated accuracy ranges between 40% - 45% from that of notional ISO calculations for determining U-values. Fokaides and Kalogirou [15] have indicated variances in U-value calculations using IRT from notional calculations in the 10% - 20% range. Continually deviation percentages in IRT from notional ISO calculations for measuring U-values has become more robust through more research and understanding of the exact variables and sensitivities to the IRT data collection methodologies. However an exact percentage deviation using IRT technology has not yet been established. It is also believed from many research studies that the deviation percentages using IRT from notional ISO calculation should not only be expected but might indicate more accurate U-value calculations [15]. Furthermore, showing that deviations from designed U-values to in situ U-values exist and through more POE architecture research a feedback loop between professionals may be useful in the design process.

In more recent research U-value measurements have utilized multiple procedures i.e. ISO equations, HFM (Heat Flux Meter) and IRT to bolster test reliability and validity of results [6] [8] [16]. Researchers using HFM collections procedures were able to quantify U-value calculations using temperature readings from both inside the structure and outside measuring differences in temperature over an extended period of time [16]. The ISO has created a standardized U-Value calculation for using HFM i.e. ISO 9869. Although, in situ HFM procedures still result in significant deviations from the notional ISO U-value calculations, ranging from 30% - 35% [6].

Furthermore, [6] [13] examines viables most influential on IRT data collection procedures as the emissivity of the surface and reflected ambient temperature (from the target surface). Researches have indicated that overall inconsistencies for determining U-values of building components from nationwide and international formulas compared to in situ recording procedures exist because of known variances in environmental conditions i.e. Solar heat gain coefficient, thermal bridging coefficients of materials, wind velocity, reflected ambient temperature, thermal inertia, and the emissivity of the surface. Additionally, researchers have also included thermal inertia or the degree of slowness with which the temperature of a body approaches that of its surroundings, in U-value calculations as a means of understanding how heat or energy may be stored or depletes from a material over time.

Existing literature has provided many limitations in data collection procedures when using IRT technology that have been addressed by the current research as follows. Precaution was taken during the data collection process to prevent miss readings or inaccuracy of the IRT camera. Thermal images were taken at oblique angles i.e. <5 to >90 from the testing surface to reduce recording reflection from glazing which potentially can present inaccurate results [7]. Existing research has indicated that wind speed (m/s) can alter the accuracy and recording of the (IRT) data [6]. The time of day i.e. duration of solar radiation on the building material should also be accounted for as a possible limitation in variant (F°) recordings with some studies [6][9][13] indicating a difference in ambient temperature from inside to outside should be <10-15 degrees. Other studies have also shown more robust U-value calculations using IRT methods collected over 10 days with recordings made in daytime and nighttime [14]. Additionally, as stated the emissivity of the surface and the reflected ambient temperature also contribute to the accuracy of the IRT procedures. IRT manufacturer i.e. FLIR has indicted a margin of error as +-2% / +-2 degrees for their equipment which will not be adjusted in thermal performance calculations in this research study [7].

3. Methodology

The research scope investigated the exterior and interior building doors, openings, and glazing at the ground level, level 2, and 2 living-area units [Table 1]. Specifically, bike storage, lobby, and entrance areas, at the ground level [Table 1] [Figure 3]. Level #2 consisted of the community room, kids-play room, and bike storage [Table 1] [Figure 4]. Building envelope i.e. solid wall assemblies are not measured in this research. Additionally, only 2 different bedroom living-units glazing were tested for thermal performance. As all window types within the units are from the same manufacturer and model type, testing 2 units established a “typical” thermal performance assumption for the rest of the living-units window conditions. Thermal images were taken of the buildings exterior elevation to understand the performance of the entire building facade, however, U-value calculations were not derived for overall facade conditions.

[Table 1]

U-Value Measurement Locations				
Level:	**Glazing Type:**	**Location I.D.**	**Program:**	**Orientation:**
Ground Level	Curtain Wall	G.L. - Bike	Bike Storage	North
Ground Level	Glass Door	G.L. - Ent. #1	North Entrance	North
Ground Level	Glass Door	G.L. - Ent. #2	West Entrance	West
Ground Level	Curtain Wall	G.L. - Lobby	Lobby	West
Level #2	Glass Door	L.2 - Bike #1	Bike Storage	North

Level #2	Glass Window	L.2 - Bike #2	Bike Storage	North
Level #2	Glass Window	L.2 - Bike #3	Bike Storage	North
Level #2	Glass Door	L.2 - Kids #1	Kids Playroom	North
Level #2	Glass Garage Door	L.2 - Kids #2	Kids Playroom	North
Level #2	Glass Door	L.2 - Comm. #1	Community Room	West
Level #2	Curtain Wall	L.2. - Comm. #2	Community Room	West
Level #2	Glass Garage Door	L.2 - Comm. #3	Community Room	West
Level #3	Glass Window	L.U.308 - Main	Living Unit #308 Main Room	North
Level #3	Glass Window	L.U.308 - Bedroom	Living Unit #308 Bedroom	North
Level #5	Glass Window	L.U.502 - Main	Living Unit #502 Main Room	West
Level #5	Glass Window	L.U.502 - Bedroom	Living Unit #502 Bedroom	West

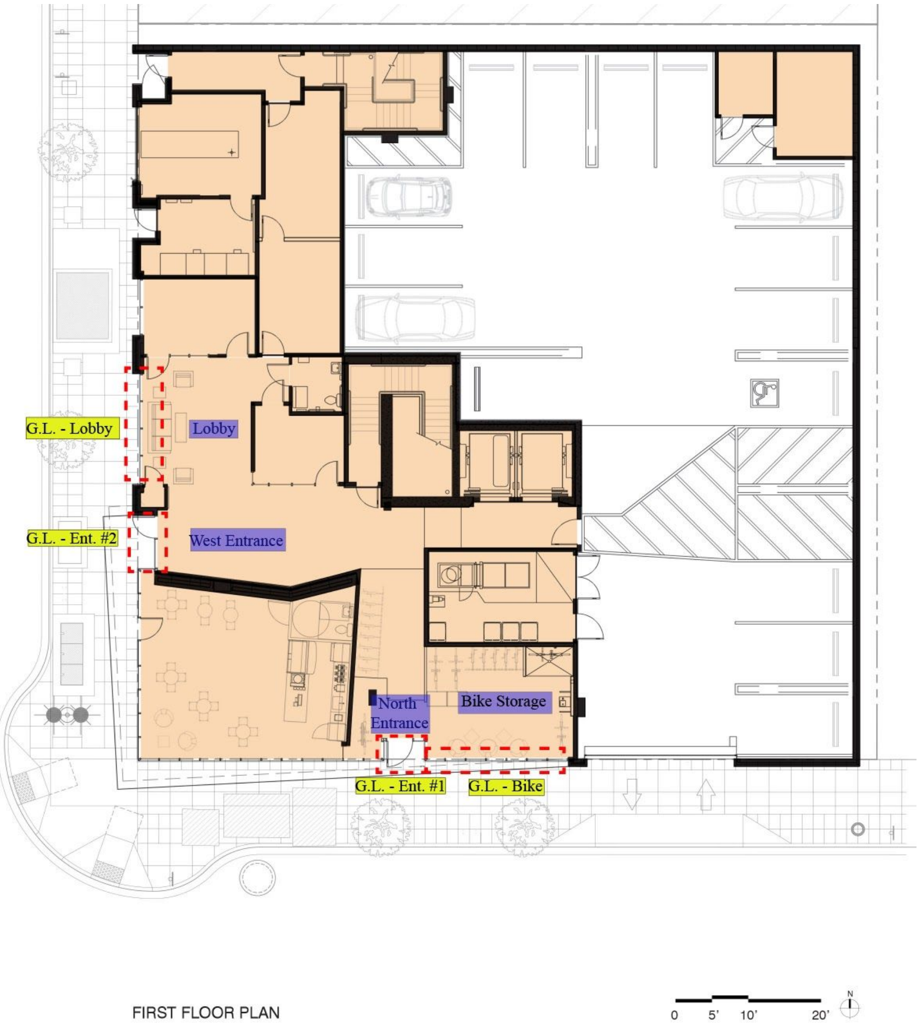


Figure 3: First Floor Plan and U-Value recording locations

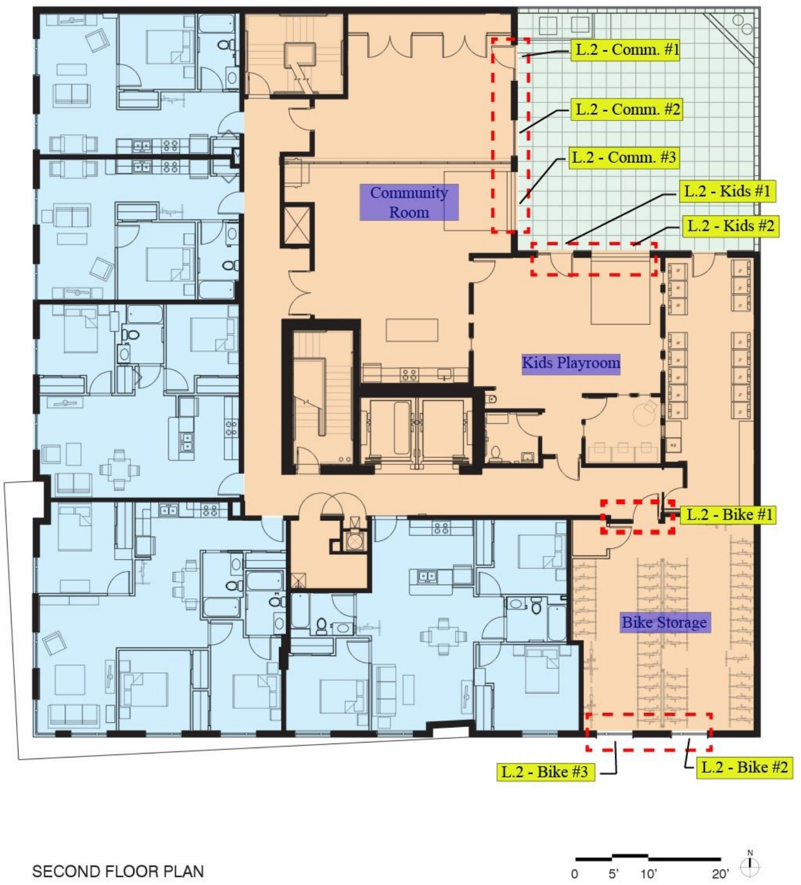


Figure 4: Second Floor Plan and U-Value recording locations

Research methodologies first documented real-time thermal performance, measured in thermal images and temperatures on glazing/doors. In addition, outside ambient temperatures were recorded by local weather data along with the stated indoor temperature from thermostats within the facility [Table 2]. Data was collected on two different days. The first day of data collection all locations [Table 1] were recorded using infrared thermography and outside/inside ambient temperature recording. On the second day of data collection eleven of the sixteen locations were measured for thermal performance using infrared thermography. Living-units #308 and #502, were not recorded on the second day of data collection due to restrictions of access to these facilities. Thermal performance measurements of glazing/door locations were re-measured on the second day of data collection as a test reliability and to create a more robust sample size of data points per glazing and doors.

Infrared thermography equipment, specified as the FLIR E60, a handheld thermal camera provided by Portland State University BUILT Labs. Thermal imaging was conducted with the FLIR E60 of which settings were optimized to take a digital image and thermal image of the same location, simultaneously. Digital images were utilized for determining physical location in references to the thermal images. Additionally, IRT camera settings were modified to collect three individual thermal temperature data points which were furthermore averaged as the total thermal temperature of the measured surface. Temperature data averaging was utilized to bolster the validity of each recorded glazing / door unit rather than collection of a single thermal data point for an entire location.

IRT data collection was scheduled over two different day periods both with varying weather conditions stated in [Table 2].

[Table 2]

Data Collection Information

Date:	Time:	Outside Temperature:	Inside Temperature:	Wind Velocity:	Weather Condition:
2.13.2020	10:30am - 11:30am	43°F	73°F	3.0 m/s	Cloudy
2.21.2020	10:30am - 11:30am	46°F	73°F	1.0 m/s	Sunny

[Image #1]

FLIR Thermal Image: G.L.- Bike

[Image #2]

FLIR Picture: G.L. - Bike

Image #1 and #2 are representative examples of thermal images and regular images taken from both data collection days. Image #1 and #2 were taken from data collection day #1 at G.L. - Bike with a curtain wall window type. Similar images were taken for all of the building program locations specified in [Table 1] and located on [Figure 1] and [Figure 2].

The following non normative formula e.g. equation 1 is utilized for the calculation in determining how the glazing performs compared to the anticipated U-values. Thermal imaging provided the temperature data of the glazing surface for this equation. Temperature recordings in (Farenheit) of the glazing surface temperature *Tw,* inside environment, *T int,* and outside environment temperature as T *out* were used to calculate U-values with the following equation.

$$U = \frac{5.67\,\varepsilon_{tot}\left[\left(\frac{T_w}{100}\right)^4 - \left(\frac{T_{out}}{100}\right)^4\right] + 3.8054\,v\left(T_w - T_{out}\right)}{\left(T_{\text{int}} - T_{out}\right)} \tag{1}$$

U: heat transfer coefficient
ε_{tot}: emissivity of specific material
T_w: surface temperature
T_{out}: ambient outside temperature
T_{in}: ambient inside temperature
V: velocity of wind

5.67: Stefan Boltzmann constant for radiative heat transfer coefficient

3.8054: convective heat transfer coefficient

Thermal imaging temperature recordings were furthermore converted from Fahrenheit degrees to Kelvin degrees to match necessary calculations requirements for the equation. [Table 3] indicates the observed temperature values were collected and calculated in determining the U-value for the glazing/ doors for both Day #1 and Day #2 of data collection.

3.1 Results

The results are cataloged in a [Table 3] for further comparisons between measured U-value performance on Day #1 and Day #2. Recorded surface temperature in Fahrenheit is presented for both data collection days, location, and glazing type. The percentage of U-value difference is documented between day #1 and day #2 of data collection [Table 3]. Additionally, the average deviation in U-value calculations between day #1 and day #2 is 7.4%.

[Table 3]

U-Value using temperature recording from IRT

Location I.D.	Glazing Classification:	Recorded (F) Day #1	U-Value Day #1	Recorded (F) Day #2	U-Value Day #2	Δ U-Values Day #1 & #2
G.L. - Bike	Curtain Wall	59	.82	61	.86	5%
G.L. - Ent. #1	Glass Door	60	.87	62	.92	5%
G.L. - Ent. #2	Glass Door	61	.93	63	.98	5%
G.L. - Lobby	Curtain Wall	62	.98	63	.98	0%

L.2 - Bike #1	Glass Door	n/a	n/a	n/a	n/a	n/a
L.2 - Bike #2	Glass Window	57	.71	57	.63	11%
L.2 - Bike #3	Glass Window	55	.61	58	.68	10%
L.2 - Kids #1	Glass Door	62	.98	63	.98	0%
L.2 - Kids #2	Glass Garage Door	59	.82	59	*.74*	10%
L.2 - Comm. #1	Glass Door	61	.93	61	.86	8%
L.2. - Comm. #2	Curtain Wall	57	.72	60	.80	10%
L.2 - Comm. #3	Glass Garage Door	52	.47	55	.51	25%
L.U.308 - Main	Glass Window	59	.82	n/a	n/a	n/a
L.U.308 - Bedroom	Glass Window	58	.77	n/a	n/a	n/a
L.U.502 - Main	Glass Window	61	.93	n/a	n/a	n/a
L.U.502 - Bedroom	Glass Window	60	.87	n/a	n/a	n/a

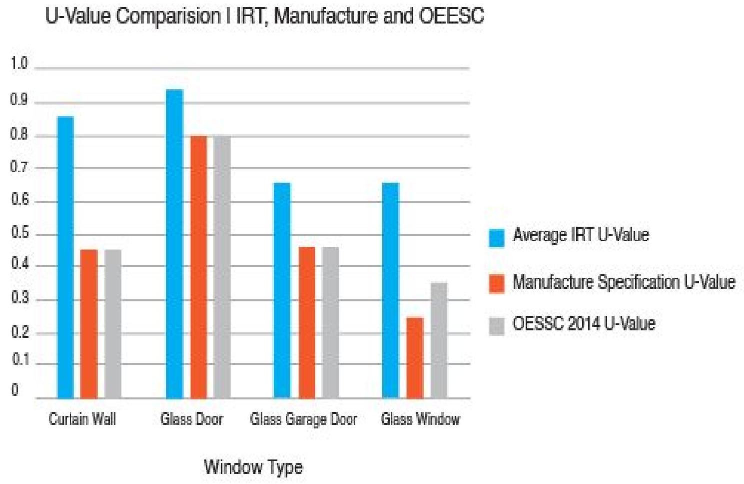
Table 4 shows the averaged U-value calculation between data collection day #1 and day #2 using IRT technology in comparison with the manufacture specification and Oregon Energy Efficiency Speciality Code - 2014. The U-values noted by the manufacturer and OEESC are the same U-value standard with exception of the window type category: Glass window in which the manufacturer specified (.25) and the OEESC specified (.35). Furthermore, deviation percentages are calculated for all window conditions investigated from [Table 1] and [Figure 1 & 2]. It should be noted that averages for the Living Unit locations were not conducted in [Table 4] as mentioned restriction from data collection day #2 provided limitations to these regions. The Living Unit U-values listed in [Table 4] are the same from the listed [Table 3] U-values. Asteriks on [Table 4] denote U-value calculations that are particularly higher than expected, even using IRT technology and will be discussed further in the discussion section of this paper.

[Table 4]

U-Value Comparisons from IRT, Specifications, and OEESC 2014						
Location I.D.	Glazing Classification:	Average U-Value	Specification Sheet U-Value	Deviation Percent	OEESC 2014 U-Value	Deviation Percent
G.L. - Bike	Curtain Wall	.84	.45	-46%	.45	-46%

G.L. - Ent. #1	Glass Door	.90	.80	-11%	.80	-11%
G.L. - Ent. #2	Glass Door	.96	.80	-17%	.80	-17%
G.L. - Lobby	Curtain Wall	.98	.45	-54%*	.45	-54%*
L.2 - Bike #1	Glass Door	n/a	n/a	n/a	n/a	n/a
L.2 - Bike #2	Glass Window	.67	.25	-63%*	.35	-48%
L.2 - Bike #3	Glass Window	.65	.25	-62%*	.35	-46%
L.2 - Kids #1	Glass Door	.98	.80	-18%	.80	-18%
L.2 - Kids #2	Glass Garage Door	.78	.46	-41%	.46	-41%
L.2 - Comm. #1	Glass Door	.90	.80	-11%	.80	-11%
L.2. - Comm. #2	Curtain Wall	.76	.45	-41%*	.45	-41%
L.2 - Comm. #3	Glass Garage Door	.55	.46	-16%	.46	-16%
L.U.308 - Main	Glass Window	.82	.25	-.57%*	.35	-.47%
L.U.308 - Bedroom	Glass Window	.77	.25	-.52%*	.35	-.42%
L.U.502 - Main	Glass Window	.93	.25	-.68%*	.35	-.58%*
L.U.502 - Bedroom	Glass Window	.87	.25	-.62%*	.35	-.52%*

Graph #1: U-value Comparison | IRT, Manufacture and OEESC



Graph #1 shows the comparison of U-value calculation using in-situ IRT methodologies compared to specified U-values from the manufacturer and required U-values from OEESC. As indicated in this graph in situ U-values are higher in all window type categories. The largest deviation window type is glass window followed by curtain wall. The smallest deviation in U-value calculations was from the glass door window type.

Graph #2: U-value Average Deviation | IRT, Manufacturer, and OEESC

Graph #2 indicates the average deviation in calculated IRT U-values from manufacturer and OEESC by window type. The largest deviations are seen in window type Glass window followed by curtain wall, with the least deviations in glass door and glass garage door.

4. Discussion

The United States has indicated that 40% of total energy consumption comes from the building sector. The U-value is an indication of the building envelope performance of energy loss and thus is an important metric to investigate in the pursuit of reducing overall energy consumption for buildings. Communication from POE and academic research is a slow process to determine how standardized testing procedures and calculations can be created to arrive at more accurate results for U-vales specification. In the last 20 years the responsibility and accountability for energy performance has risen for architecture firms rather than strict energy consultants or specialized engineering firms. However, the discrepancies and documented challenges of theoretical calculation to in situ testing are paramount. The current research intentions are to educate architecture firms of this discrepancy in energy performance and to inform that U-values may need to be specified at lower values to obtain appropriate and desired performance expectations.

Previous research has indicated that conclusive results using IRT technology are not yet fully understood with variances in accuracy and reported calculations. Although, IRT was the only method used for data collection for the current research additional equipment i.e. HFM should be utilized in future research to compare measurement results and bolster correlational findings between recording technologies. Extensive literature has examined the deviation in U-value results between the ISO calculation and IRT thermography can range anywhere from 10% - 45% [9]. Furthermore, variances in accuracy and additional complications exist when using IRT recording methods for recording glazing surfaces. Previous literature along with FLIR manufacture documentation has indicated the complexity in measuring surfaces with higher levels of material reflectivity [9] [7].

This research has anticipated some known issues with data collection procedures. Discrepancies between temperature data measurements may be present due to challenges with data collection procedures for the reflective glazing surfaces in scope. Known weather conditions have been stated as a consistent variable and limitation for the data collection process when using IRT technology. It should be noted that the weather i.e. outside recorded temperature and visible sunlight were drastically different between the two days of data collection.

Furthermore, discrepancies in glazing U-value comparisons arise in how the glazing system is defined. For example, the manufacture specification sheet has indicated a particular U-value for the curtain wall and door glazing as a window system, which should be defined as the glazing and the mullion connections as a unit. However, the OESSC - 2014 U-value does specify if the U-value requirements are for just glazing or glazing and mullion window systems. The current research collected data and calculated U-values based on the glazing performance alone. This should be noted as a limitation in the current research and reliability for comparisons between U-value measurements, specifications, and code requirements.

5. Conclusions

Although, all of the window types and glazing conditions in the research resulted in higher U-value calculations than anticipated from specification and code, most of the glazing conditions fall within the deviation percentages expected from IRT in situ literature i.e 40% - 45%. However, it should be noted that some window systems had lower deviations from notional calculations. The window types with the largest deviations are discussed further in understanding the situational conditions that may allude to higher U-value calculation for the glass window and curtain wall window systems.

IRT thermography and temperature recording was collected in reference to L.2 - Bike #1, however the subsequent U-value calculation was not calculated for this building location [Table 3]. L.2. - Bike #1 location is internally located to the building [figure 4], the door does not meet an outside environment condition typical of all other glazing conditions under investigation. Instead L.2 - Bike #1 “outside environment”, is still the interior of the building. Because the U-value calculation [equation 1] requires the difference between *Tint* (interior environment temperature) and *Tout* (outside environment temperature), the U-value calculation for L.2. - Bike #1 was indeterminate and dismissed from recorded results, evident in [Table 3].

Discrepancies in post-occupancy use compared to anticipated occupant usage may be evident for the bike room in general. During data collection day #1, it was observed that L.2. - Bike #2 and L.2. - Bike #3 operable portions of the windows were open. For data collection purposes the windows were closed then a temperature measurement was recorded for both conditions. In addition, during data collection day #2, the same observation i.e. open window was made for both window conditions i.e. L.2. - Bike #2 , #3. Windows were once again closed and then data temperature collection took place. Temperature data results for these two window conditions may be indicative of an abrupt change in temperature. It should be noted that thermal transfer from outside to inside of the building can take many hours to balance out an accurate temperature recording of the inside temperature condition. For the current research this precautionary measure i.e. waiting for a couple hours, was not taken, which may explain large variances in temperature observations along with U-value calculations.

The observation that L.2. - Bike #2, and #3 operable windows were opened, even with a recorded outside temperature of 43° and 46° [Table 2] may indicate occupant behavior patterns about the use of the bike room. Possible implication of these observations may be to create a more desirable thermal comfort level for this particular room within the building or may indicate other occupant usage patterns that were not anticipated during design of the building. A follow up with maintenance staff or occupants i.e. tenants, may allude to reasons why the bike room windows were being opened. It was additionally observed that HVAC units were located directly above and dispersed heated air on the L.2. - Bike #2 and #3 glazing. This might have contributed to the different U-values for these specific windows.

The second largest discrepancy in U-values was from the curtain wall window system. Some possible reasons for this might be that the NFRC and ISO standardization calculations do not take into account the overall size of the glazing. As the curtain wall systems are fairly large compared to a typical window size used in laboratory testing this might explain why U-values for this window type might be higher in in situ measurements compared to theoretical calculations.

In conclusion more research needs to investigate the discrepancies in in situ thermal performance of building stratigraphy and glazing. A very limited amount of research in U-value calculations are applied specifically to glazing conditions. In addition researchers that have investigated glazing using IRT have noted that measuring U-values are particularly challenging with glazing because the material is highly reflective by nature which can skew the temperature reading of the surface.

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