# Use of Drone for a Campus Building Envelope Study

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Raheem Ariwoola developed an early interest in Engineering due in part to being born in a family dominated by Engineers. Having enjoyed fidgeting with all electronics equipment found in his surroundings when he was growing up, he developed a curious and inquisitive mind to further his study in the field of engineering. In 2012, he received a degree in BSc Electrical Engineering in Ladoke Akintola University of Technology, Nigeria, with the highest honors. Immediately after graduation, he went ahead to serve his fatherland at Ajaokuta Steel Company Limited, Kogi, Nigeria. After his youth service discharge in 2014, he migrated to United States to continue his studies and presently, he is looking forward to receive is MS in Engineering Technology Department at East Tennessee State University, USA. Raheem participated in a lot of activities during his high school days; he was the head of the Jets club, Science and Technology club, and a proud member of the school's interdisciplinary research committee. After his degree, He participated in some voluntary works as the chief provost of Health, Environmental and Safety club. He is a Level 1 safety professional, and he has a certificate issued by Institute of Safety Professionals Organization of Nigeria (ISPON). This shows how Raheem Ariwoola is multi-talented. At his leisure periods, Raheem enjoys spending his time writing basic computer programs, researching and surfing internet. In few years, he will be able to fulfill his life ambition by earning a Ph.D degree in the field of renewable energy in Electrical Engineering.

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**Abstract**

In 2014, 41% of total U.S. energy consumption was consumed in residential and commercial buildings, or about 40 quadrillion British thermal units according to Commercial Building Energy Consumption Survey. As the number of commercial buildings and floor space increasing, business, industry and government organizations are under tremendous economic and environmental pressures to reduce energy consumption and dollar savings. Building "Envelope" generally refers to those building components (walls, doors, windows and roof) that enclose conditioned spaces and through which thermal energy is transferred to or from the outdoor environment and are significant sources of heat loss. A building envelope study provides a good qualitative and analytical understanding of the thermal performance of major building envelope components, identifies major deficiencies, and helps developing appropriate energy management project to improve performance. In this building envelope study, infrared thermography is used to assess envelope performance of five buildings on East Tennessee State University Campus. Infrared thermography provides a simple, fast, non-destructive, realistic, and reliable technology in determining the spatial temperature distributions of building envelope surfaces. An ArduCopter 3DR Hexa-C Drone and Fluke TI25 infrared hand held camera were used for rapid data collection. The camera was automated to take an image every 2 sec and a 10 minute drone flight captured 300 images covering whole building envelope. Data analysis and reports were carried out with the use of Smartview software and FLIR Reporter pro software. High quality infrared images and the data analysis reveal various insulation defects and heat loss issues through building envelopes. Cost-effective solutions are recommended to all problems detected which will potentially improve long term energy efficiency of the buildings and contribute to sustainable campus infrastructure development.

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## INTRODUCTION

According to data from the U.S. Department of Energy (DOE), residential and commercial buildings are responsible for about 40% of total primary US energy consumption and 71% of total electricity consumption, at a cost of approximately $400B annually [1]. The Building Envelope – walls, doors, windows, roofs, and skylights – through which thermal energy is transferred to or from the outdoor environment is a significant source of heat loss [2]. A "tighter" envelope more effectively keeps conditioned air in, reducing the load on the HVAC system, and therefore increasing the efficiency at which it operates. Energy losses in buildings are primarily due to poor insulation and to air infiltration [2]. Acquiring knowledge about the heat transfer through the components of the building envelope is an important step to assess the energy sustainability of the whole structure of a building [3]. Thus, improving building energy efficiency by using better envelope elements for insulations is a key for cutting the energy consumption in buildings.

Thermal resistance, commonly known as R-value of building envelope components, is a pre-condition in classifying the energy efficiency and performance of a building [4]. A poor building envelope component will have a lower R-value while the better ones will have higher R-values. The building envelope is responsible for about 25% of the total energy loss in all buildings, but can impact up to 42% of energy loss in residential buildings, and 57% of energy loss in commercial buildings [1]. Therefore, improving the building envelope offers significant opportunity for building energy efficiency and can improve occupant comfort and the quality of life. However, there are several obstacles for improving the building envelope for existing buildings:

1. R-values of the building envelope are not constant. Especially, in many campus buildings in the USA which were built in the 1960s, 1970s, and 1980s. R-values change over time because of environmental conditions, material deterioration, and usage. R-value performance can actually change as much as 50% or more [5]. Therefore, there is a need to calculate R-values of the existing building envelope before implementing any building envelope improvement project.
2. Because of the building envelope's huge surface areas, data collection for building envelope is time consuming and slow. As a result, facilities management seldom prioritizes building envelope improvement projects. A rapid data collection process can assist facilities management with identification of the building envelope and insulation issues. Management can then use the data to implement building envelope improvement projects.

This research study devises a method to calculate R-values of existing building envelopes at their current conditions. An ArduCopter 3DR Hexa-C Drone equipped with a Flir Vue Pro infrared camera, and a Fluke TI25 infrared hand held camera, were used for rapid data collection. The process was implemented for five buildings on the East Tennessee State University (ETSU) campus. Based on the data, energy losses for the five buildings through their respective building envelopes, and the potential cost savings if the envelopes were improved to American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) recommended levels, were calculated. Aerial thermography using the drone also identified various insulation issues on the studied buildings.

## METHODOLOGY

This work is divided into two sections. The first section evaluates the thermal resistance (R-value) of various building envelope elements for five buildings on the ETSU campus. The second section utilizes rapid data collection method using an ArduCopter 3DR Hexa-C Drone equipped with a Flir Vue Pro infrared camera.

### *In-situ R-value Measurement*

In order to evaluate the R-value, the overall heat exchanged through the building envelope element and the heat exchanged by radiation with the outdoor environment is used. To have an accurate result, it is necessary that there should be at least a 10℃ (18°F) stable temperature difference between the indoor and outdoor air [6]. The R-value of the target can then be evaluated by calculating the actual amount of heat that is transferred to the target when it is in quasi-steady-state heat transfer conditions [4]. The overall heat transfer rate through the surface of a target with an area (A) and inside and outside temperature difference ($\Delta T$) is illustrated by Ham et al, (2013) and given in equation (1) [4]. Where $\frac{dQ}{dt}$ is the heat transfer rate, and R is the thermal resistance.

$$\frac{dQ}{dt} = \frac{1}{R} \times A \times \Delta T \quad (1)$$

The thermal power ( $\frac{dQ}{dt}$) , due to amount of heat (Q) passing through the target in a time unit, is dissipated from the target surface by means of convection, conduction, and radiation. According to Albatici et al.(2008), the contribution of conduction is not as important a factor as convection and radiation [8]. Fokaides et al. (2011), Ham et al. (2013), hypothesized that the main heat transfer from the target to the sensor of the thermal camera is due to thermal radiation and thermal convection as given in equations (2) and (3) [4,8]. The calculation of the R-value in this research study is based on these hypotheses.

$$Q_{rad} = \varepsilon \times \sigma \times A \times \left(T^4_{Inside,wall} - T^4_{Inside,reflected}\right) \quad (2)$$

$$Q_{conv} = h_{conv} \times A \times (T_{inside,air} - T_{inside,wall}) \quad (3)$$

According to Ham et al. (2013), the R-value can be expressed by combining equations (1), (2), and (3),

$$R = \frac{(T_{inside,air} - T_{outside,air})}{[h_{conv} \times (T_{inside,air} - T_{inside,wall})] + [\varepsilon \times \sigma \times \left(T^4_{Inside,wall} - T^4_{Inside,reflected}\right)]} \quad (4)$$

$All\ temperature\ values\ are\ in\ Kelvin\ (K)$

$\varepsilon\ is\ the\ thermal\ emissivity\ value\ on\ the\ spectrum, and\ varies\ between\ 0.1\ and\ 1.0$ [9].

$\sigma\ is\ the\ Stefan–Bolzmann\ constant\ =\ 5.67\ \times 10^{-8}\ (W/m2\ K4)$

$h_{conv}$ is the convective heat transfer coefficient which is influenced by temperature deviations between the air and the target surface, and the airflow types [4, 7]. The adopted $h_{conv}$ coefficients used in this work are from EN ISO 6946:2007 [10]. All other variables in equation (4) used in calculating the R-value can be collected as a quantitative data from an Infrared thermography technique. The specification of the Fluke infrared camera used in this work is given in Table 1. Also, as part of the thermography process, Extech Model 451181 was used to record the temperature of the inside air, temperature of the outside air, wind velocity, and relative humidity. The main problems experienced are the special technique used for the measurement of emissivity (ε) value of the target surface and the evaluation of the reflected temperature.

Table 1. Technical specification of the Infrared Camera used in this work.

| Name | Fluke TI25 |
|---|---|
| Field of view | 23° x 17° |
| Thermal sensitivity | ≤0.1 °C at 30 °C (100 mK) |
| Spectral range | 7.5 µm to 14 µm |
| Detector type | 160 X 120 focal plane array, uncooled microbolometer |
| Visual camera | 640 x 480 resolution |
| Object temperature range | -20 °C to +350 °C |
| Accuracy | ± 2 °C or 2 % (whichever is greater) |

According to the procedure described by FLIR system (2010) [9], the reflected temperature was measured by using a high reflective surface, like a shining part of an aluminum foil carefully stretched after crumpling. This foil, with shining surface facing outward, was pasted near the surface of the target to be measured and was allowed to be in thermal equilibrium with the surface, usually 3-4 hours. When the emissivity of the infrared camera is set to 1.0, the mean of the temperature data on the crumbled foil as analyzed on Smartview software is the reflected temperature. Figure 1 shows the thermal image (left) and the visible light image (right) for arrangement to evaluate the reflected temperature and emissivity.

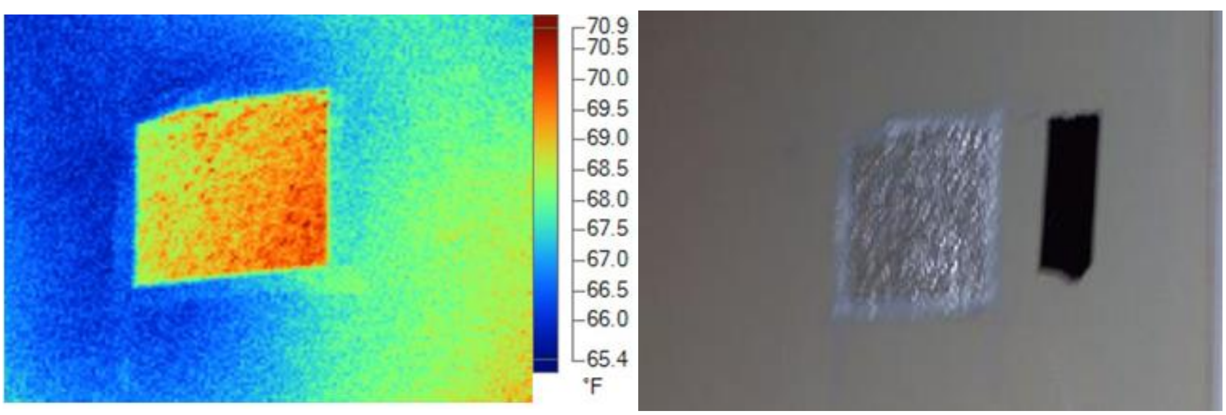



Fig. 1. Experimental arrangement to determine the reflected temperature with a crumpled foil

The emissivity of the targets surface is also an important factor to obtain accurate thermal readings with building infrared thermography [3]. In this work, the emissivity of the target was estimated as suggested by the FLIR system (2010) [9] . This was achieved by using another target with a known emissivity, like a black tape (ε of 0.95) pasted on the building element surface. This black tape was also left fixed on the target for 3-4 hours, in order for the tape to achieve thermal equilibrium with the environment. Now the black tape and the target surface had the same temperature but different emissivity. The post processing of the thermal image from proprietary software (Smartview software by Fluke) gave the exact mean readings of the target temperature when the emissivity was set to the known value (0.95) for the black tape.

For all building envelope elements that are composed of more than a single material (such as windows and doors made of glass, divider, wood or aluminum frame, etc.), the experiment was set-up for each material, and the R-value was calculated separately for each of the materials in an individual element. Then, the weighted mean of the R-values of all the materials that made up the element represents the building envelope element R-value. For example, to estimate the R-value of a window, each experiment is performed separately for the frames, the center of the glass, and the dividers. This is according to the standard given by NFRC 100-2014 (2013) [11]. Thus, the weighted mean R-value can be calculated using equation (5). The same process was done for the wall areas, where some of the wall area was insulated, and other area were uninsulated. The procedures for calculating the areas for the window glazing are illustrated by Finlayson et al. (1993) [12].

$$R_t = \frac{(R_f A_f) \times (R_c A_c) \times (R_e A_e) \times (R_d A_d)}{A_t} \quad (5)$$

Where $R_t = R - value\ of\ the\ building\ element,\ A_t\ is\ the\ total\ area\ of\ the\ element$

$R_f = R - value\ the\ frame,$ $A_f\ is\ the\ area\ of\ the\ frame$

$R_c = R - value\ the\ center\ of\ glass,$ $A_c\ is\ the\ area\ of\ the\ center\ of\ glass$

$R_e = R - value\ of\ the\ edges,$ $A_e\ is\ the\ area\ of\ the\ edges$

$R_d = R - value\ of\ the\ dividers,$ $A_d\ is\ the\ area\ of\ the\ dividers$

***Cost Estimation***

The R-value estimation depicts the level of the heat loss/gain through a building element. A building element with a lower R-value indicates that more heat is transferred through the building envelope element, and as a result, more energy loss is recorded. Therefore, in such a building, heating or cooling requires a greater amount of energy. According to Ham and Golpalvar-Fard (2013), the energy loss due to any insulation when the R-value is known is given by the equation (6)

$$Q_{ins} = \frac{1}{R_{in-situ}} \times Area_{comp} \times \Delta T \times t \qquad (6)$$

$\Delta T \times t\ \ represents\ the\ degree\ days\ estimated\ according\ to\ NOAA, (2013)$

The energy loss costs were also calculated by multiplying the energy loss and the retail price of energy (in this work \$0.0951/kWh was used for electricity, and \$0.081/Therm for the gas used in heating). These price values are found from local suppliers of electricity and gas. The energy loss cost of the insulation is given in equation (7).

Energy Loss cost = $Q_{ins}$ × Retail price of energy (7)

There are proposed R-value standards given by ASHRAE for building elements to be used in different climate regions. These standards were developed to minimize energy loss in buildings. As part of the energy savings strategy, after estimating the energy loss due to estimated R-value using equation (8), this work also estimated the energy loss cost according to the equations (10) & (11) using the R-value proposed by ASHRAE. The difference in the energy loss cost between the ASHRAE R-value and the in-situ R-values gave the amount of annual energy savings for that component. The energy loss costs are estimated separately for heating and cooling. Both the sources of energy used for heating and cooling are different, and the number of heating degree days (HDD) and cooling degree days (CDD) also varies. The HDD and CDD are estimated according to statistics obtained from NOAA website [13].

Therefore, from equation (8) annual energy loss is given as

$$Q_{existing} = \frac{\frac{1}{R_{in-situ}} \times Area_{comp} \times 24 \times (CDD + HDD)}{3413} \tag{8}$$

$Q_{existing}$ is the Existing energy loss (kWh)

and New Energy Loss (kWh) is calculated using equation (9), (if the component is replaced with another one proposed by ASHRAE)

$$Q_{New} = \frac{\frac{1}{R_{ASHRAE}} \times Area_{comp} \times 24 \times (CDD + HDD)}{3413} \tag{9}$$

The existing annual energy cost for heating and cooling for the components are calculated using equations (10), and (11).

$$Q_{heating\ cost} = \frac{\frac{1}{R_{in-situ}} \times Area_{comp} \times 24 \times HDD)}{100{,}000} \times Energy\ price\ (gas) \tag{10}$$

$$Q_{cooling\ cost} = \frac{\frac{1}{R_{in-situ}} \times Area_{comp} \times 24 \times CDD)}{3413} \times Energy\ price\ (electricity) \tag{11}$$

The corresponding new energy costs are calculated for both heating and cooling by changing the $R_{estimated}$ in equations (10) and (11) to $R_{ASHRAE}$. The new constant used in equation (10) is 100,000, which is a conversion rate for Therm to Btu (One therm equals 100,000 Btu) [14]. This work also estimated both the amount of future energy savings and the payback period in order to determine when the new investment evidenced actual savings. The energy savings in any intended number of years compounded annually was calculated according to equation (12)

$$\text{Future Energy savings cost} = \sum_{i}^{n} Present_{cost}(1+r)^{n_i} \qquad (12)$$

$$r \text{ is the interest rate, and } n \text{ is the future years count}$$

The Payback period on the investment was calculated according to equation (13).

$$\text{Payback period} = \frac{Cost_{replacement} \times Area_{component} \times Future\ year\ count}{(Existing - New) energy\ cost\ in\ future\ year\ count} \qquad (13)$$

There are some other critical factors, e.g., the air infiltration rate, and solar heat gain effects, that require consideration when evaluating energy loss, costs, and savings in building envelope diagnostics. These factors were not included in this work. According to Gowri et al. (2009) the ASHRAE 90.1 Envelope Subcommittee has developed a list of component infiltration rates, which can be used to evaluate the overall building air infiltration rate of the entire structure for further building energy analysis[15]. This work only evaluates energy loss costs and savings on improved R-values of building envelope elements.

**PRELIMINARY RESULTS AND ANALYSIS**

Five buildings on ETSU campus have been selected for the pilot project. The selected buildings vary according to location, size, usage, and structure. Most of the buildings are old, and the R-values of the building envelope elements were unknown. Therefore, the above mentioned method was used to estimate R-values for doors, windows, and walls. Table 2 shows the results of the estimated R-values of the building envelope elements obtained by the proposed infrared thermography technique.

Table 2. Estimated R-values of some building elements for five different buildings at ETSU campus

| Building ID | Function | Construction Year | Total Area (sq ft) | Building Element | As-built R-Values | Estimated R-values | ASHRAE R-Values [16] |
|---|---|---|---|---|---|---|---|
| 1 | Lab/Classroom | 1963 | 61,241 | Wall | 4.09 | 3.68 | 9.6 |
| | | | | Doors | 1.06 | 0.99 | 1.30 |
| | | | | Windows | 0.98 | 0.92 | 2.22 |
| 2 | Administrative | 1963 | 98,988 | Wall | 4.09 | 3.72 | 9.6 |
| | | | | Doors | 1.00 | 0.94 | 1.30 |
| | | | | Windows | 1.10 | 0.96 | 2.22 |
| 3 | Lab/Classroom | 1905* | 63,035 | Wall | 5.70 | 4.42 | 9.6 |
| | | | | Doors | 3.53 | 3.24 | 1.30 |
| | | | | Windows | 2.94 | 2.76 | 2.22 |
| 4 | Housing | 1974 | 132524.54 | Wall | 6.76 | 5.38 | 11 |
| | | | | Doors | 1.00 | 0.92 | 1.64 |
| | | | | Windows | 1.89 | 1.72 | 2.86 |
| 5 | Administrative | 1950** | 2,991 | Wall | 2.27 | 2.26 | 9.6 |
| | | | | Doors | 1.16 | 1.04 | 1.30 |
| | | | | Windows | 0.99 | 0.89 | 2.22 |

* Building was renovated in 2011; ** Building was renovated in 1987

As shown in Table 2, the R-values of building envelope elements decreased over time and they are significantly lower than the ASHRAE proposed standards. These data can now draw attention to the facilities management and show enormous energy saving opportunities. A computer application was developed to estimate cost savings if corresponding building elements were replaced with the ASHRAE recommended standards. Table 3 shows annual energy savings in KWh and dollar amount. By improving building envelope elements and insulation issues, an average $4,144 can be saved from the studied buildings.

Table 3. Estimated annual savings after replacing poor elements

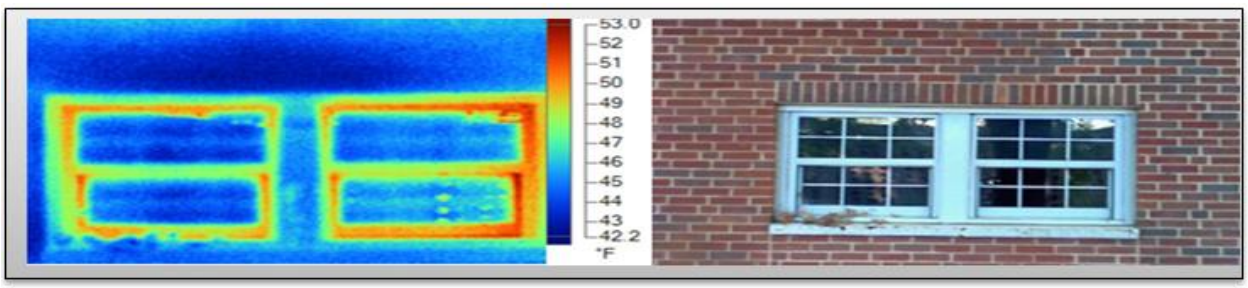
| Building ID | Function | Annual Energy savings (KWh) | Annual savings ($) |
|---|---|---|---|
| 1 | Lab/Classroom | 228,436 | $6,121 |
| 2 | Administrative | 235,002 | $6,298 |
| 3 | Lab/Classroom | 131,036 | $3,511 |
| 4 | Housing | 148,899 | $3,990 |
| 5 | Administrative | 29,718 | $798 |

The next section explains the rapid data collection process to identify energy performance of various building envelope elements and insulation issues. Figure 2 shows equipment used for data collection. The accuracy and quality of the IR images captured depend on the focus, thermal level, thermal span, thermal range, perspective, composition and palette [17].

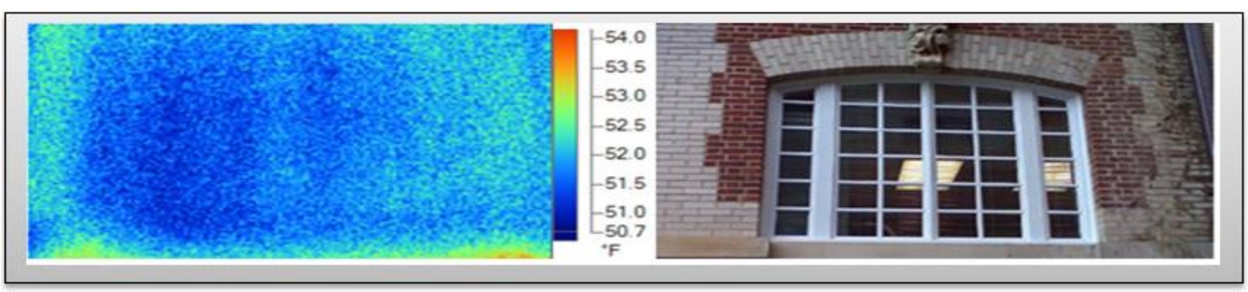
(a) ArduCopter 3DR Hexa-C Drone (b) Extech Model 451181 (c) Fluke Ti25

Fig.2. Equipment used for the data collections

Since rapid data collected during the building inspections are qualitative in nature, precise temperature values of the surfaces were not of concern at the point of capture. The simple procedures used to acquire the data were; Point, Focus, and Capture. All other settings to improve the image quality, such as emissivity correction, reflected and ambient temperature corrections, etc. were done on the software during data post-processing. The emissivity values used for the various data obtained were taken from the list of materials emissivity in the "Smartview" software settings. A detailed list of materials emissivity values can also be obtained from FLIR systems (2010) [9]. Direct view from the camera to the object surfaces were ensured without obstructions. Shiny and reflective surfaces (those unable to be compensated for) were avoided during data acquisition and analysis because they gave false images. Figure 3, 4, 5 and 6 show samples of thermal images taken from the building elements.




(a)




(b)

Fig. 3 (a & b). Samples of thermal and visible light image of a window in building 1 and 3.

The window shown in Figure 3a displays insulation defects around the frames, however, Figure 3b shows a sample of a window that has a very good resistance to heat transfer. Major defects common to doors are exfiltration through openings, edges or perforated holes on door surfaces. Other defects noticed in the building elements are air leaks due to cracks in walls, moisture detection, thermal bridges and improper insulations. Figure 5 shows gradual amount of heat loss through the wall of building 1 due to cracks in the wall. Figure 6 shows IR image of the entrance of a studied building.

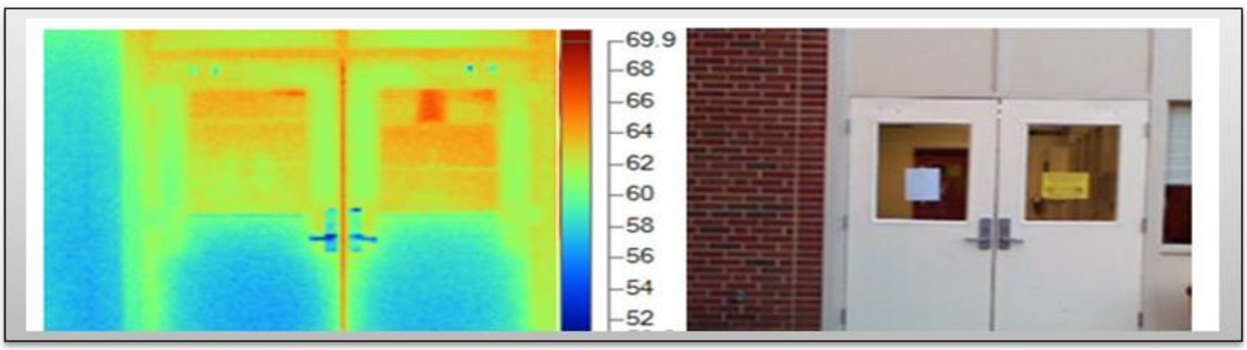



Fig. 4. Sample of thermal and visible light image of a door in building 1.

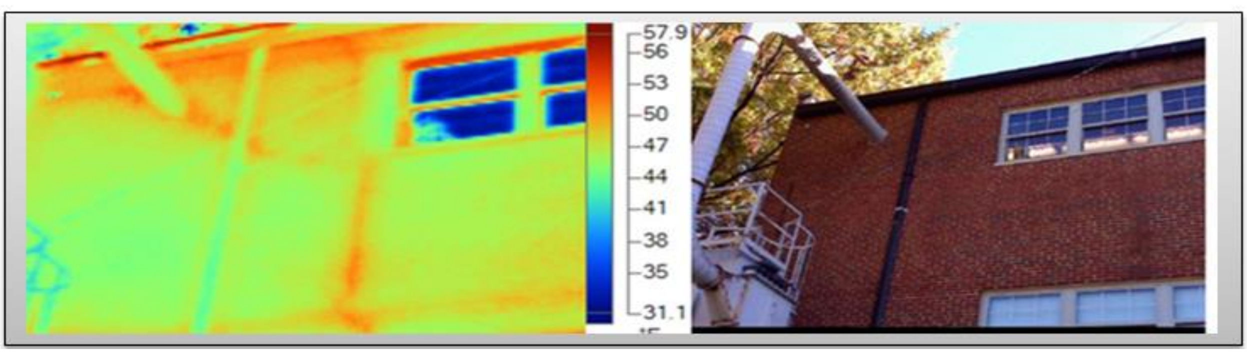



Fig. 5. A thermal and visible light image showing heat loss as a result of cracks in the wall on building 1.

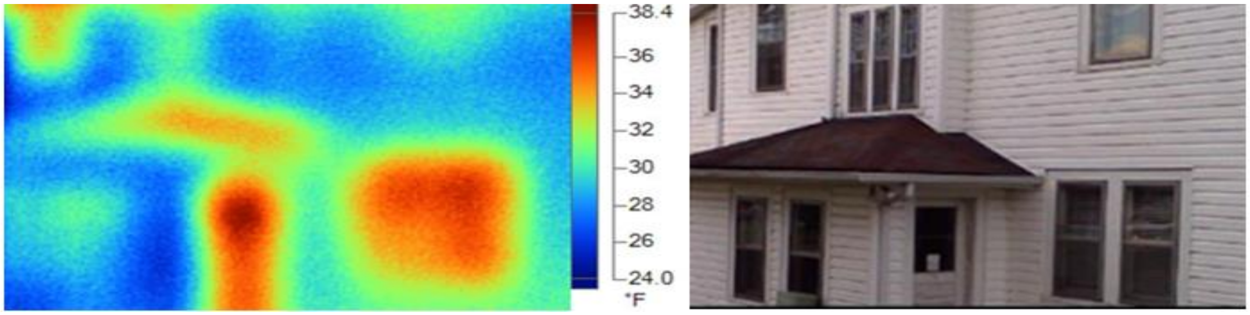



Fig. 6. Sample of thermal and visible aerial image during rapid data collection process

## CONCLUSION

Energy performance of building envelope such as wall, roof, doors and windows significantly impact overall energy use of a building and therefore, offer a significant opportunity for energy-saving. This paper outlines an IR thermography based in-situ R-value calculation method for existing buildings when such values are unknown. The study also presents a rapid data collection process using a drone equipped with Flir Vue Pro IR camera and Fluke handheld IR camera. The study found that R-values of building envelope change over time and are significantly lower than the ASHRAE recommended R-values. Based on the estimated in-situ R-value, this work analyzed the energy loss costs, the future savings to be acquired if the elements that have the poor R-values are replaced with those recommended by ASHRAE. The analyses presented in this study would assist the facilities management to understand in-situ building envelope performance and serve as a catalyst to undertake building envelope improvement projects.

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