Summer studentship final report – 2020/21 Anna O'Leary

Assessing of the real-world performance of low-e window films in commercial buildings using an infrared camera

1. Aim

Due to new greenhouse gas emission reduction targets, the University of Otago aims to improve the energy efficiency of their buildings in order to help reduce energy consumption and therefore emissions. We explore the use of infrared (IR) thermography of windows with and without a low emissivity (low-e) film to determine the thermal transmittance (U-value). When applied to a window, low-e films are able to reduce heat loss by reflecting the radiation (or heat) back into the room. Applying a low-e film to existing windows is a cost-efficient method to improving the insulation value of the window and therefore the building, the alternative is to replace all existing windows with double glazing which can be expensive. The aim of this summer studentship project was to develop a low cost and efficient method to evaluate theenergy performance of low emissivity (low-e) films on windows.

2. Introduction

Windows are usually the weakest element in a building's thermal envelope. Single pane windows for example, can be responsible for up to 50 % of heat loss.[i] Therefore, by improving the insulation of windows, less energy will be required to maintain internal temperature. To replace all single pane windows with double glazing would be expensive; hence, retrofitting existing windows with low-e films is one promising low-cost approach.

Low-e films allow visible light through while stopping infrared light, otherwise known as heat. Therefore, when they are applied to a window they are able to reflect the heat back inside during winter; this also works in summer, the outside heat is reflected allowing for a cooler room temperature inside. This is demonstrated in Figure 1. A low-e film would be beneficial in locations such as Central Otago due to their cold winters and extreme summer temperatures. Emissivity (ε) is a measure of how effective a surface is at emitting radiation in the IR region, the lower the ε of the film the higher the reflection of the radiation. From Kirchhoff's law of thermal radiation, it is found that:

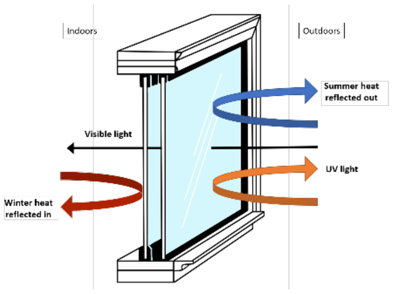


Figure 1, Window with applied low-e film, this demonstrates the heat being reflected while letting visible light through.

$$\varepsilon + reflection = 1$$

The ε of an object can depend upon wavelength and the surface. For example, shiny metals are known to have a low ε whereas surfaces such as soil and water have a high ε and can therefore absorb a greater amount of radiation.

3. Short literature review

Low emissivity glazing first appeared on the market in 1979,[ii] since then it has had many developments in application and lowering of the emissivity value. Today the option of applying a low-e film to an existing window is much cheaper than installing double or triple pane windows to increase the energy performance of a building. Before retrofitting an entire building with low-e films, it is possible to model the energy savings using software. For example, S. Abolghasemi Moghaddam[iii] was able to model the retrofitting of 3M Thinsulate Climate Control

75 (CC75) low-e film to a 200-year-old building in Sweden. In another paper by Amirkhani et al.[iv] an existing UK hotel was modelled with the same low-e film, CC75, on EDSL TAS software. Both modelling papers showed that the low-e film can reduce energy consumption for energy usage; for the Swedish building and the UK hotel space heating was found to be reduced by 6 % (including hot water) and 3 % respectively. For the UK building, it is in a much warmer climate, the cooling consumption with the low-e films was found to be reduced by 20 %. In order to model the effectiveness of the low-e film, the thermal transmittance (or U-value) has to be determined.

The thermal performance of the low-e films is given by its U-value. The U-value for a material (through a wall) has the general ratio seen in Equation 1, this ratio is between the thermal power (P) and the inside and outside temperature difference.

$$U = \frac{P}{T_{in} - T_{out}}$$

Equation 1

There are various methods to determine the U value experimentally. In the paper by Soares et al.[v] different methods such as heat flow meter (HFM), the hot box (HB) and infrared thermography (IRT) are all compared on how they are able to evaluate the U-value for walls, windows andconstruction elements. All of these methods were performed in a controlled environment. It states that IRT was previously only used to help aid the positioning of sensors such as flow meters for other techniques, however, in recent years the IRT technique has advanced. This has led to utilizing the IRT as a method of its own instead of in combination with another.
The IRT methods have become increasingly more common over the years in determining the U-value of a wall. In papers by Albatici et al.[vi] along with Albatici and Tonelli,[vii] both used IRT methods and Equation 2 to calculate the U value. The components in this equation are the surface temperature of the element (T_i), the inside temperature (T_{in}), the outside temperature (T_{out}) and convective heat transfer from the Jurge's equation, $3.8054v$.

$$U = \frac{5.67\varepsilon\left(\left(\frac{T_i}{100}\right)^4 - \left(\frac{T_{out}}{100}\right)^4\right) + 3.8054v(T_i - T_{out})}{T_{in} - T_{out}}$$

Equation 2

In 2011, Fokaides and Kalogirou[viii] used a slightly different equation to calculate the U-value of a building including the glazing. Equation 3 was used in this study, here a new component was taken into consideration, the reflected temperature (T_{ref}). In this equation, σ represents the Stefan Boltzmann constant, h_{in} is the thermal convection coefficient and T_s is the wall/element temperature. The h_{in} was determined by EN ISO 6946:1997.[ix]

Equation 3

$$U = \frac{\left[4\varepsilon\sigma {T_s}^3\left(T_s - T_{ref}\right) + h_{in}(T_s - T_{in})\right]}{(T_{in} - T_{out})}$$

The paper by Soares et al. references the research done by Fokaides and Kalogirou, however, Soares et al. stated that the equation used by Fokaides and Kalogirou was Equation 4. This is inconsistent with Equation 3. For example, Soares et al has used the outside surface temperature for the element whereas it was not specified by Fokaides and Kalogirou. The top line is also inconsistent between Equations 3 and 4, if it is indeed consistent it was not stated how. It should be stated that Equation 4 is in fact identical to that of Equation 2, with the small exception of how the surface temperature of the element is taken.

$$U = \frac{\varepsilon\sigma\left({T_{s,out}}^4 - {T_{out}}^4\right) + 3.8054v(T_{s,out} - T_{out})}{T_{in} - T_{out}}$$

Equation 4

In a recent paper by Kou et al.[x] the effects of low-e film on a window are investigated. This paper has modelled a window with an air gap between the glass and the low-e film. Even though there is no gap in between the window and low-e film in this project, how they have broken down each component of the model is very insightful (this can be seen in Figure 2). For example, the Prandtl (Pr), Grashof (Gr), Nusselt (Nu) and Rayleigh (Ra) numbers have been considered. These numbers take into account the characteristics of air; for instance the Pr is a ratio between momentum diffusivity to thermal diffusivity (this is around 0.71 for air); Gr is free convection; Nu is the thermal conductivity of air and the Ra is the product of Gr and Pr which defines heat transfer by natural convection.[xi]

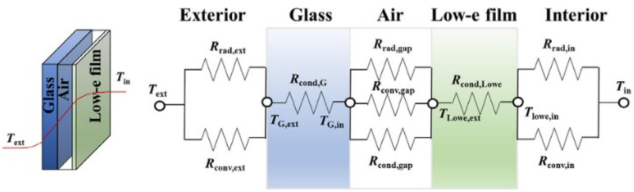


Figure 2, Glass and low-e film model referenced from Kou et al.

The research completed by Kou et al. was conducted in an environmental chamber to control and achieve the U-value of the glass model proposed. The results showed a 3.91 W/m^{2}K reduction in the U-value when applied to a single glass pane, it was also found that further U-value improvements could be made if the air gap was increased or if emissivity of the film was lowered.

In 2019, Bienvenido-Huertas et al.[xiii] constructed a review paper of in-situ methods for calculating the U-value of walls. The different methods that were compared were the theoretical, HFM, simple hot box-heat flow meter (SHB-HFM), thermometric (THM) and the quantitative infrared thermography (QIRT) method. For each method reference papers were compared and evaluated, the QIRT was of great interest as all significant IRT reference papers were compared. This included the papers by Fokaides and Kalogirou, Albatici et al. and Tejedor et al. The paper by Tejedor et al. proposed an equation that uses the Ra, Pr and Nu numbers to approximate for the convective coefficient instead of the Jurges equation, this can be seen in Equation 5.

$$U = \frac{\overbrace{\varepsilon\sigma\left({T_{refl}}^{4} - {T_{s,in}}^{4}\right)} + \overbrace{\frac{k \cdot Nu}{L}\left(T_{in} - T_{s,in}\right)}}{T_{in} - T_{out}}$$ Equation 5

Heat transfer: —— Radiation —— Convection

The Nu number can be calculated from the Ra and Pr numbers in Equation 6, 7 and 8. In these equations k is the thermal conductivity of air, L is the length of glass measured and $T_{s,in}$ is the temperature of the glass surface on the inside.

$$\beta = \frac{1}{(T_{in} + T_{s,in})}$$ Equation 6

$$Ra = (3.18 \times 10^{10}) \cdot \beta \cdot (T_{in} - T_{s,in}) \cdot L^3$$ Equation 7

$$Nu = \left\{ 0.825 + \frac{0.387 Ra^{\frac{1}{6}}}{\left[1 + \left(\frac{0.492}{Pr}\right)^{\frac{9}{16}}\right]^{\frac{8}{27}}} \right\}^{2}$$ Equation 8

4. Method

The equipment utilized in the data collection is listed below:

- Flir i7 Infrared camera
- Two tripods
- Kestrel 5500 Link
- Black electrical tape
- Tin foil

The equation used in this study to determine the U-value of the windows with and without the low-e film will be Equation 5. Therefore, it was necessary to record the inside, glass, reflected and outside temperatures, along with the outside pressure. The conditions in which the data were recorded were in local wind speeds under 2.0 m/s as recommended by Dall'O et al.[xiii] (to minimize the heat convection from the wind) and in the evening when there was no solar irradiation stated by Albatici and Tonelli. The local wind speed was also recorded to ensure it did not interfere with the collected data.

The two locations with low-e film that were assessed was lab 1.N10 in the Richardson building and an office in Abbey College. Once in position, the emissivity (ε) of the windows with and without low-e film were found by use of the black electrical tape on the glass as a reference. The black electrical tape has a known ε value of 0.95, with the IR camera ε set at 0.95 the temperature of the tape is recorded as demonstrated by Fokaides and Kalogirou. This temperature is the true temperature of the glass, the ε value on the camera was then lowered until the temperature of the glass met the true temperature. When the temperature of the glass was equal to the temperature of the tape, the ε value set on the camera is that of the glass. The length of each window was also recorded.

The reflected temperature can be found by setting the ε value of the IR camera to 1.00 and recording the temperature from tin foil that has been attached to the glass as stated by Tejedor et al. The inside temperature was found by taking temperature readings from around the room with an ε value of 0.95 and then taking the average. Every two minutes the data was collected for a 20-minute period for each window; this included the glass and reflected temperature recorded from the IR camera while the outside temperature, wind speed and pressure were recorded from the Kestrel positioned outside. This was done every two minutes to allow the IR camera to automatically calibrate.

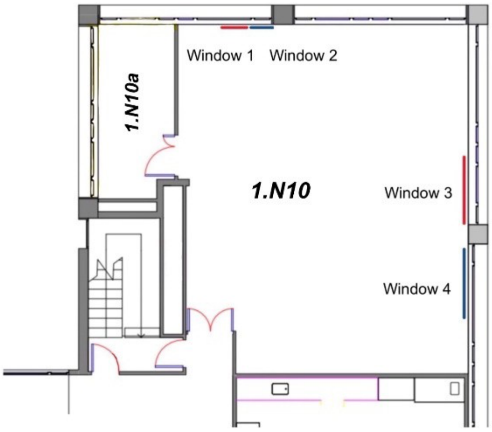


Figure 3, , This layout of Lab 1.N10 shows the location of each window used. The red line indicates the low-e film and the blue is the control window

In lab 1.N10, four windows were used for data collection as seen in Figure 3. Windows and 3 had the low-e film applied, while windows 2 and 4 were used as the control.

Once the data collected the U-value was calculated via Equation 5 on excel and double checking using MATLAB. The K value for each value was calculated from an online calculator[xiv] using the outside temperature and pressure

5. Results

Currently the University of Otago has installed three variations of this low-e film across a few different buildings, these can be seen in Table 1 below.

Table 1, Low-e films and their location and specifications

Film type	Location	Manufacturer emissivity value	Manufacturer U value (Winter – W/m^{2}K)	Manufacturer U value (Summer – W/m^{2}K)
VEP70	Abbey College	0.09	3.464	2.498
ICM-1307	Richardson Building Te Pa College of Education	0.49	4.76	-
Titanium T1316	Te Pa	0.6	5.28	-

Lab 1.N10 – Richardson Building

5.1 On the 4th of December a trial run of the measurements were made in Lab 1.N10. The ε value of window 1 with the ICM1307 film was found to be 0.56, this was found from the results in Table 2.

Table 2, Emissivity values of window 1 on the 4/12/20

ε	Glass surface temperature (°C)	Tape temperature (°C)
0.95	17.2	15.6
0.7	16.3	-
0.6	15.8	-
0.56	15.6	-
0.55	15.5	-
0.5	15.1	-

Window 2 was used as the control for window 1, this window was found to have an ε value of 0.85 which can be found in Table 3 below.

Table 3, Emissivity values of window 2 on the 4/12/20

ε	Glass surface temperature (°C)	Tape temperature (°C)
0.95	16.8	15.9
0.85	15.9	-
0.84	15.8	-

The recorded data on this evening was taken every minute for five minutes for each window, the average for each value was then taken. Using Equations 5-8, window 1 with a length of 1.65 m had the average U-value of 3.072 W/m^{2}K. Whereas window 2 had a length of 1.6 m and was found to have the average U-value of 4.108 W/m^{2}K.

5.2 On the 7th of December another round of measurements were recorded. Again the ε values were checked to ensure they were found correctly on the first night; Window 1 had the values found in Table 4 and window 2 had the values found in Table 5. No changes in the ε values were observed.

Table 4, Emissivity values for Window 1 on the 7/12/20

ε	Glass surface temperature (°C)	Tape temperature (°C)
0.95	18.0	16.5
0.6	16.8	-
0.56	16.5	-
0.55	16.3	-

Table 5, Emissivity values for Window 2 on the 7/12/20

ε	Glass surface temperature (°C)	Tape temperature (°C)
0.95	18.2	16.8
0.9	17.2	-
0.85	16.8	-
0.84	16.6	-

All recorded data for window 1 appeared consistent; however, in window 2 a few outliers were observed. This can be seen in Figure 4 below.

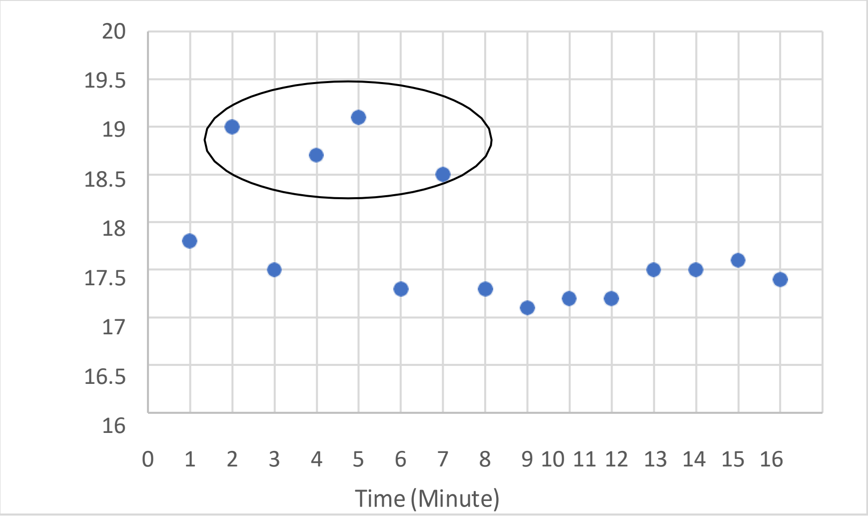


Figure 4, This graph plots the glass temperature against the time. The circle indicates the outliers

These four outliers are due to the automatic calibration on the IR camera, these higher glass temperatures carry over when the U-values are calculated. This can be seen in Figure 5, the U-values from the outliers result in a lower U-value for the window.

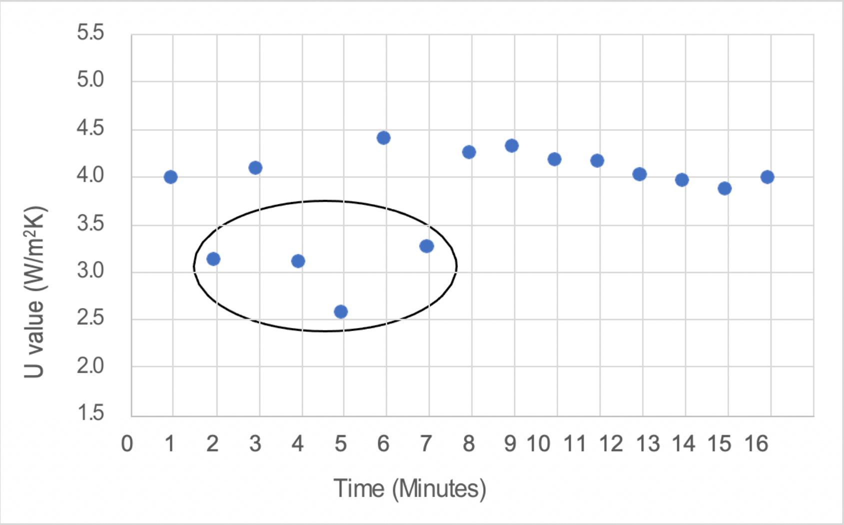


Figure 5, The U-values vs time for Window 2

5.3 On the 8th of December, the recording of data was altered to lower the calibration issue. Data was measured every two minutes for a 20-minute time period. The ε values were checked for the third and final time, they were again consistent with previous results. Bienvenido-Huertas et al. does state that “Emissivity only needs to be measured once because it will remain stable throughout a measurement because it is not affected by temperature changes”.

With the new alterations to the method, no calibration issues were observed. Further measurements were recorded on four more nights of windows 1, 2, 3 and 4. The ε value of window 3 and 4 were identical to that of windows 1 and 2 respectively.

5.4 Comparing the results

5.4.1 Window 1:

Seen in Figure 6 below, the U-values of window 1 are shown against their outside temperature.

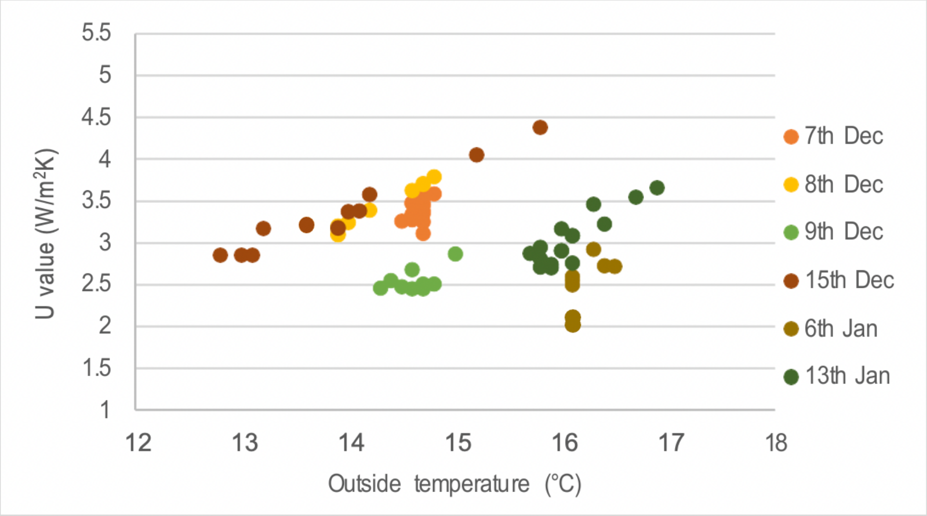


Figure 6, U-values of window 1 plotted against their recorded outside temperature

Below in Figure 7, the frequency of the calculated U-values for window 1 are shown. Individual nights have been separated by colour to show their consistency.

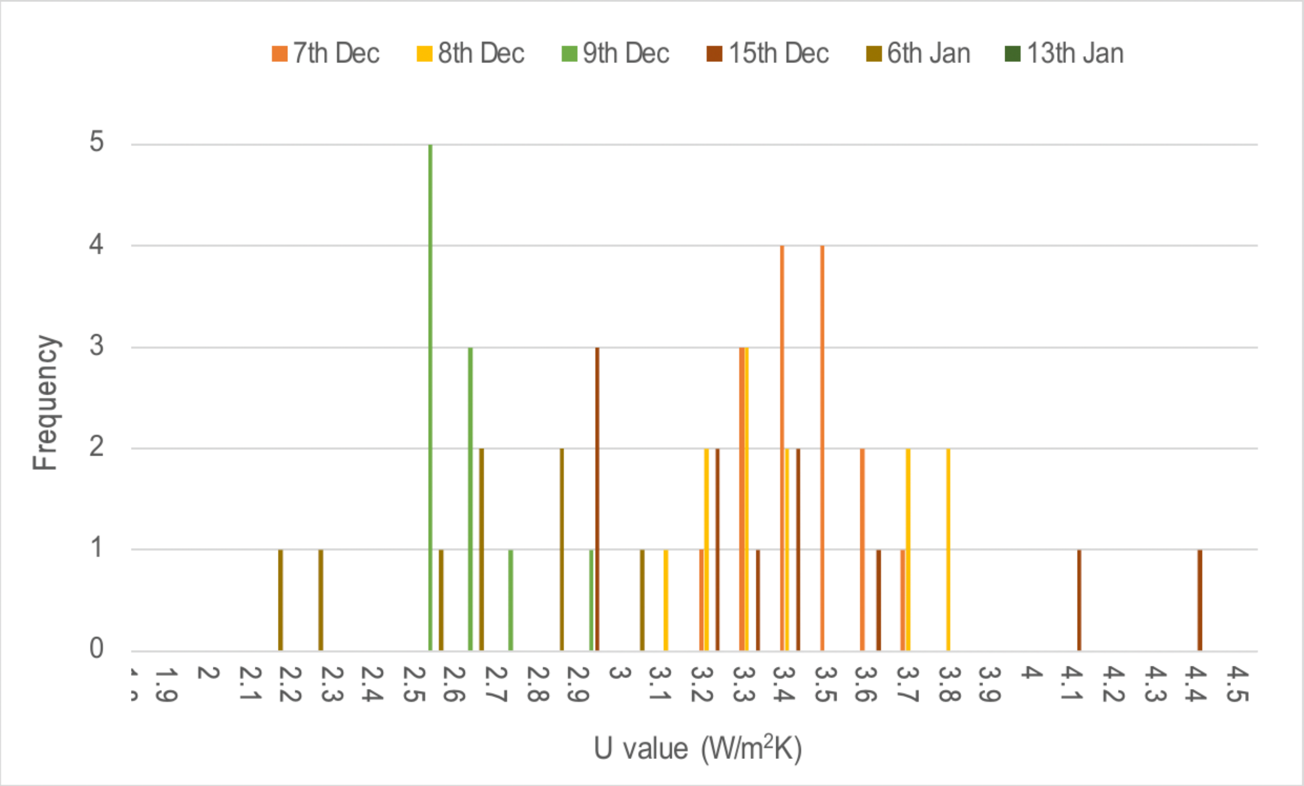


Figure 7, Frequency of the calculated U-values for window 1

It should be noted that a light rain occurred during the measurements on the 6th of January. Rain could interfere with the heat transfer of the window during the measurements and cause inaccurate results.

Window 2:

Figure 8 shows the U-values of window 2 against their outside temperature.

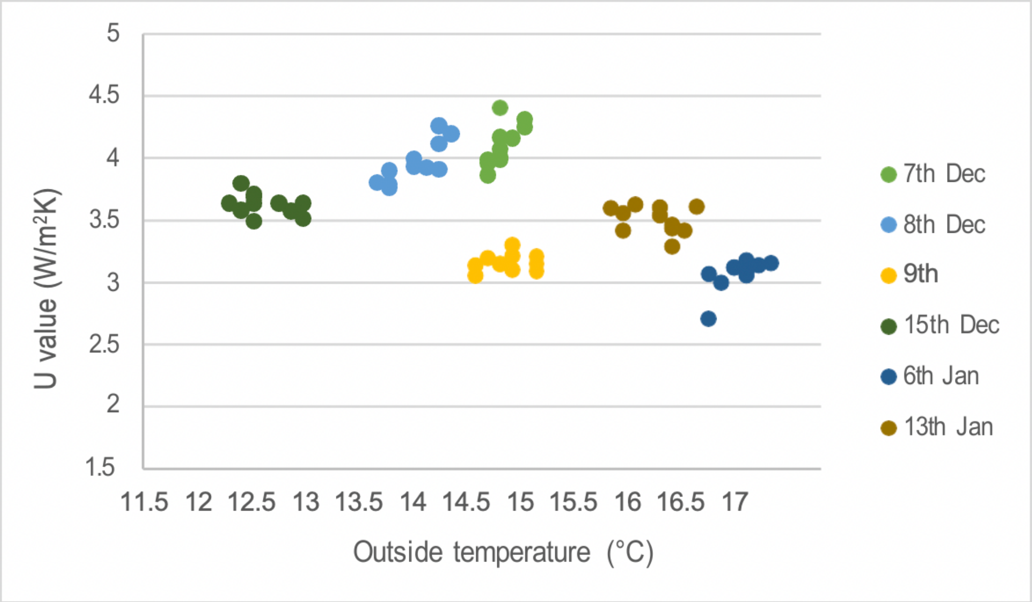


Figure 8, U-values of window 2 against their recorded outside temperatures

Shown below in Figure 9 are the calculated U-values of window 2 and how frequent they were.

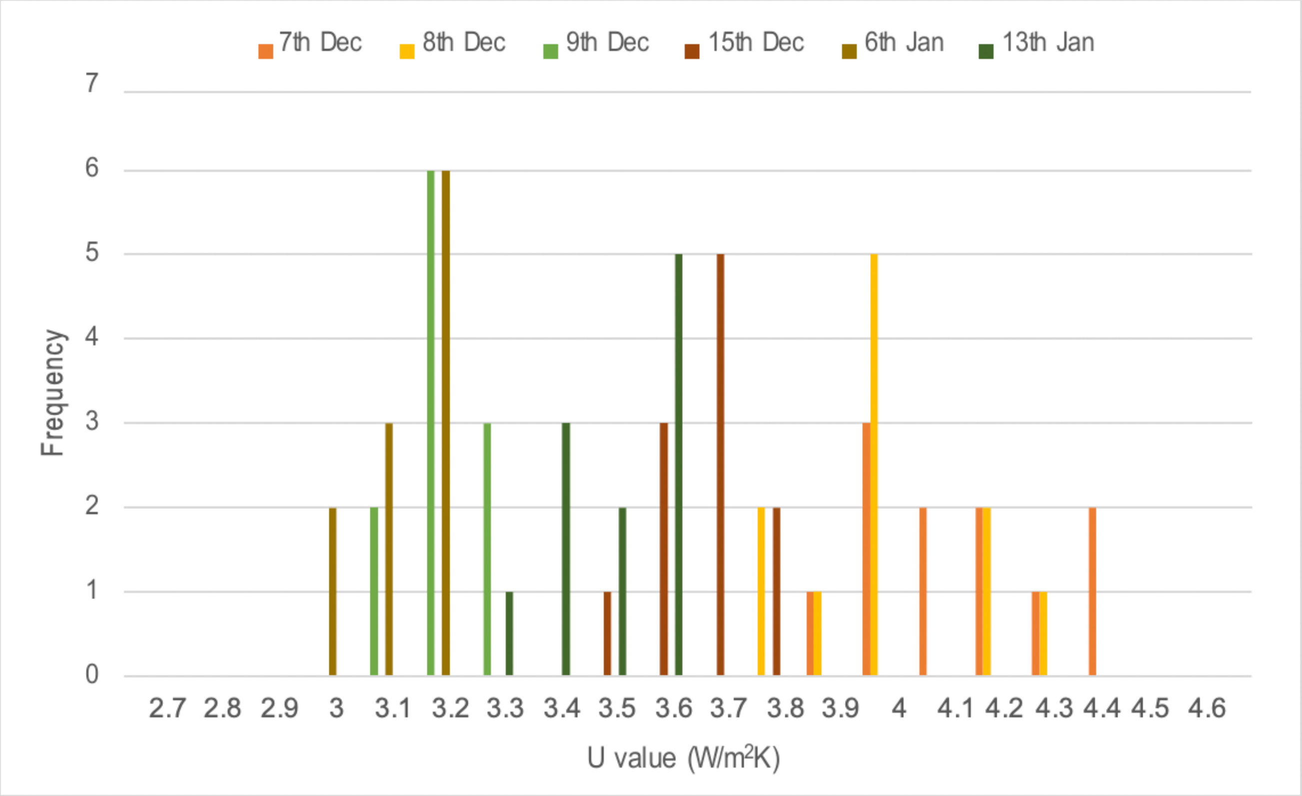


Figure 9, Frequency of the calculated U-values for window 2

Window 3:

Below in Figure 10 shows the U-values of window 3 against their outside temperature.

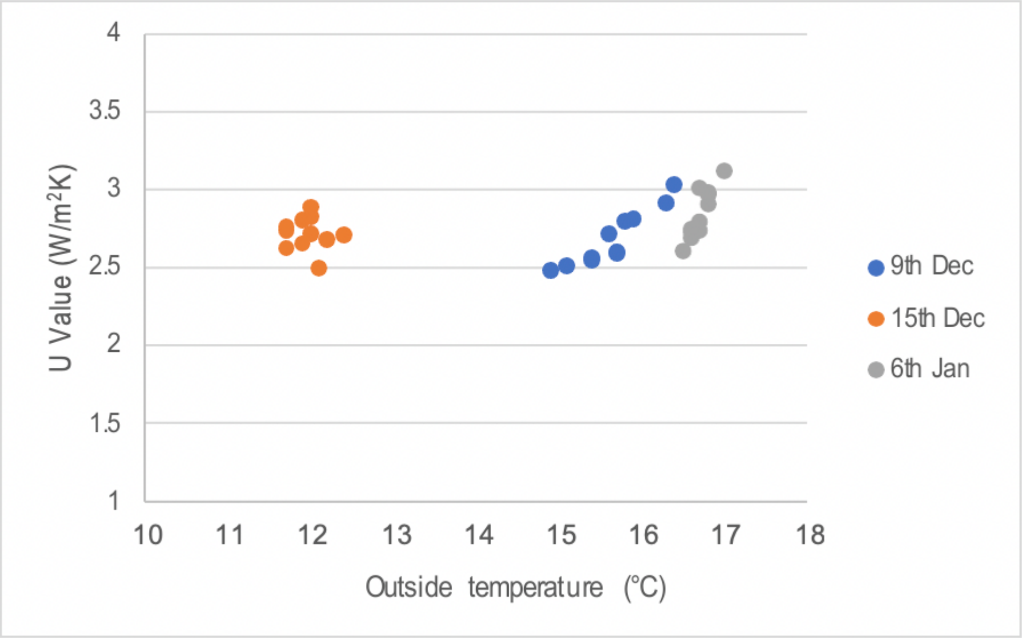


Figure 10, U values from window 3 against the outside temperature

Figure 11 shows the calculated U-values and their frequency for window 3.

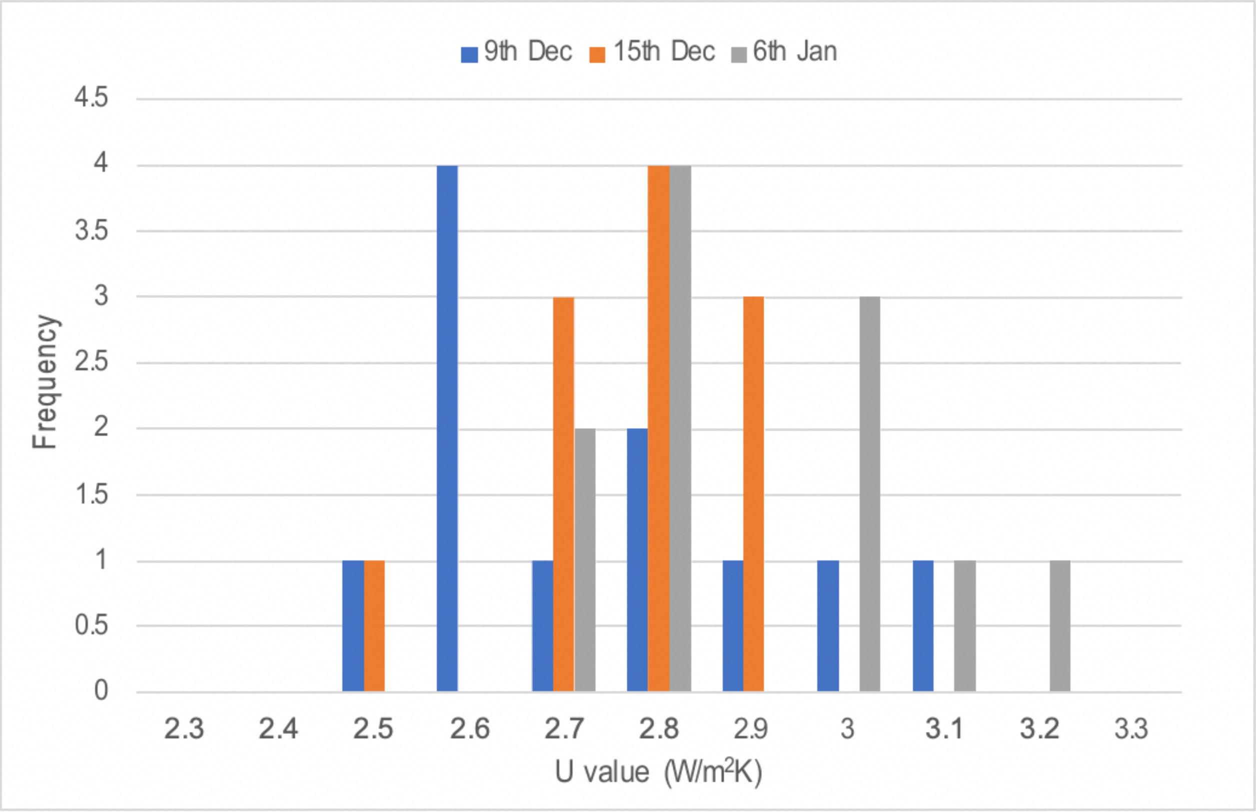


Figure 11, The frequency of U-values for window 3

Window 4:

Below in Figure 12, the U-values are plotted against their outside temperature.

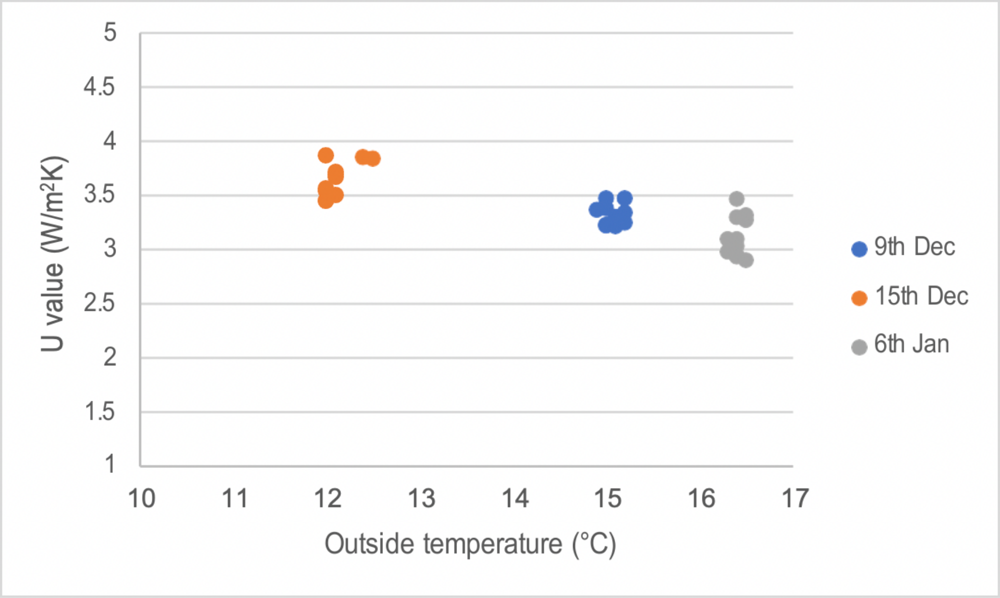


Figure 12, U-values of window 4 plotted against their outside temperature

Figure 13 shows the calculated U-values and their frequency for window 4.

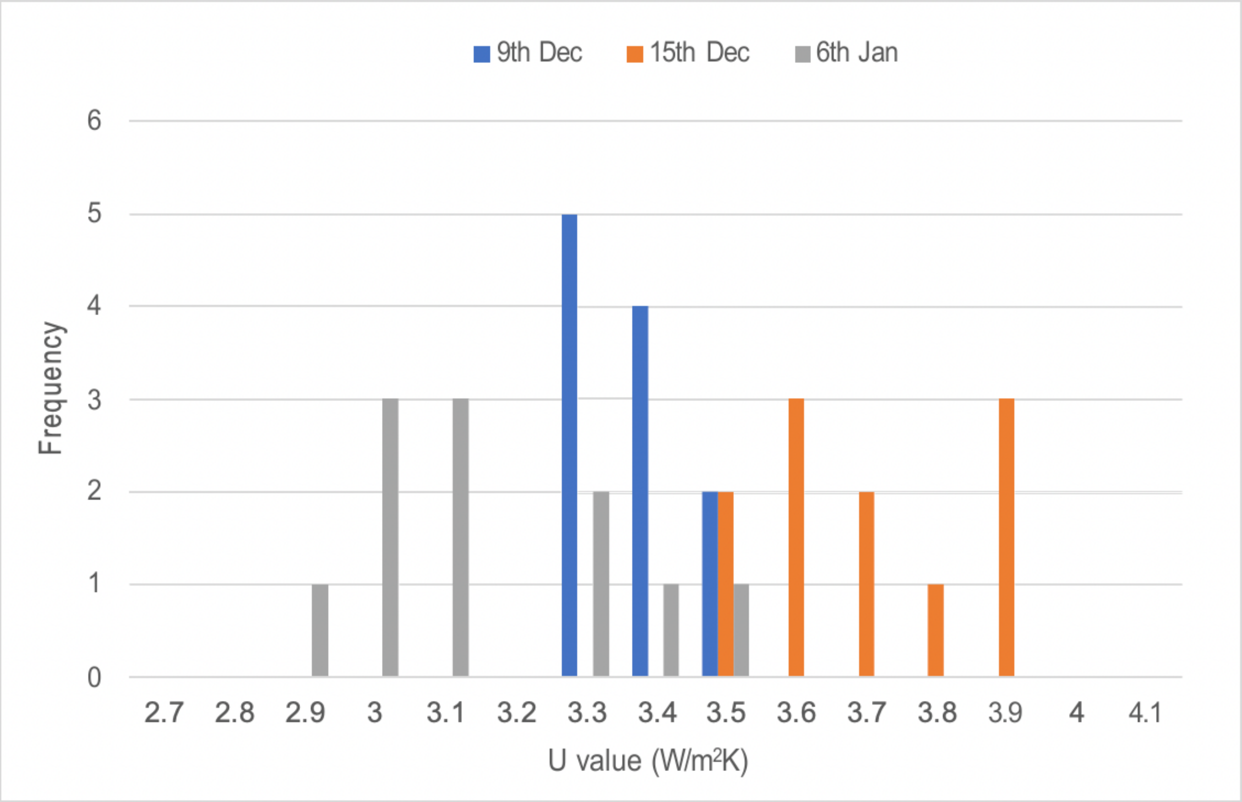


Figure 13, Frequency of U values for window 4

5.4.2 Window 1 and Control Window 2

Below in Figures 14 and 15, the U-values of both windows are plotted against each other to show their difference. Figure 14 plots the recorded results from the night of the 8th of December, while Figure 15 plots the data taken from the 15th of December. These two nights were taken and plotted to show the general trend of the windows on each night

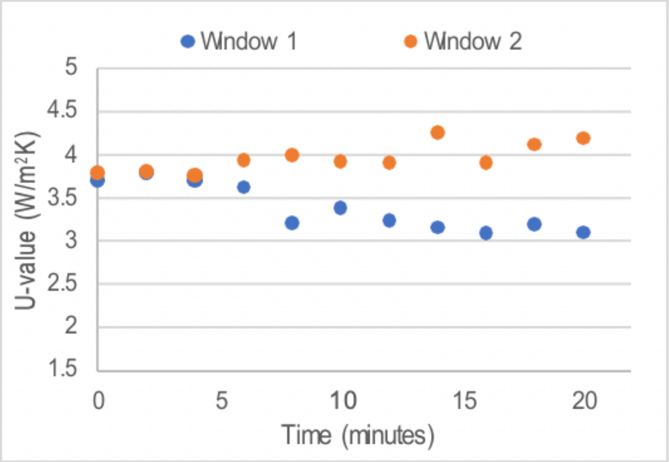


Figure 14,This shows the U-value of each window over the time period taken on the 8/12/20

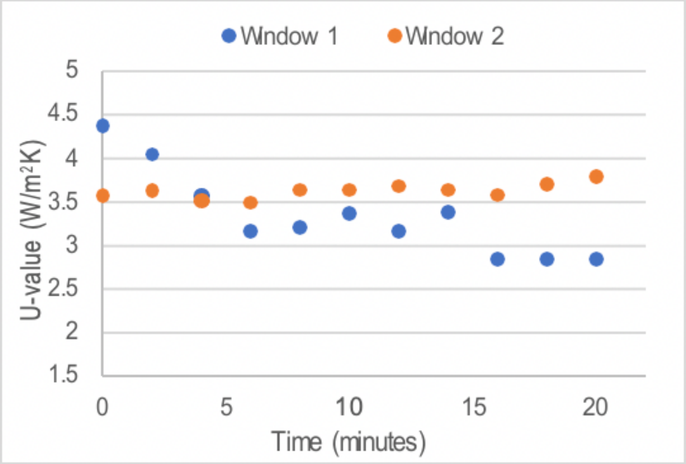


Figure 15, This shows the U-value of each window over the time period taken on the 15/12/20

Window 3 and Control Window 4

In Figures 16 and 17 seen below, they both show window 3 and the control window 4 plotted against time on two different nights. Figure 16 has the data taken from the 9th of December and Figure 17 shows the data recorded on the night of the 15th of December.

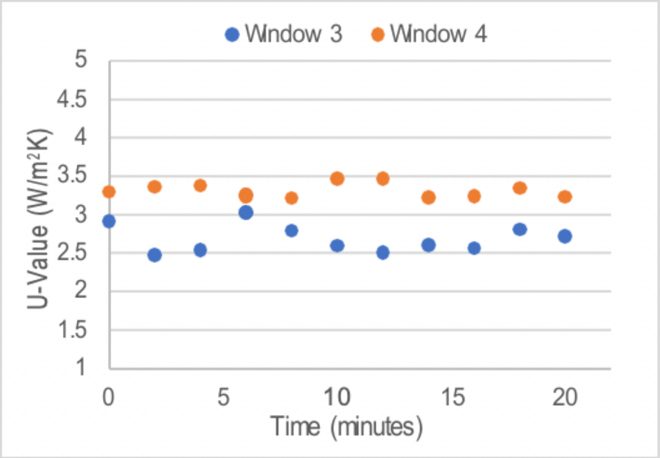


Figure 16, This shows the U-values of window 3 & 4 plotted over time on the 9/12/20

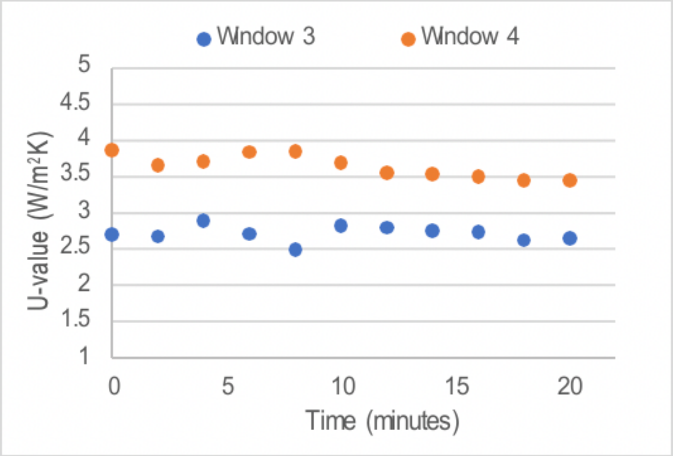


Figure 17, This shows the U-values of window 3 & 4 plotted over time on the 15/12/20

5.4.3 Low-e film vs No film

Below in Figure 18, all of the windows are plotted. The blue indicates the U-values of window 1 and 3 that have the low-e film applied, whereas the grey represents the windows with no low-e film.

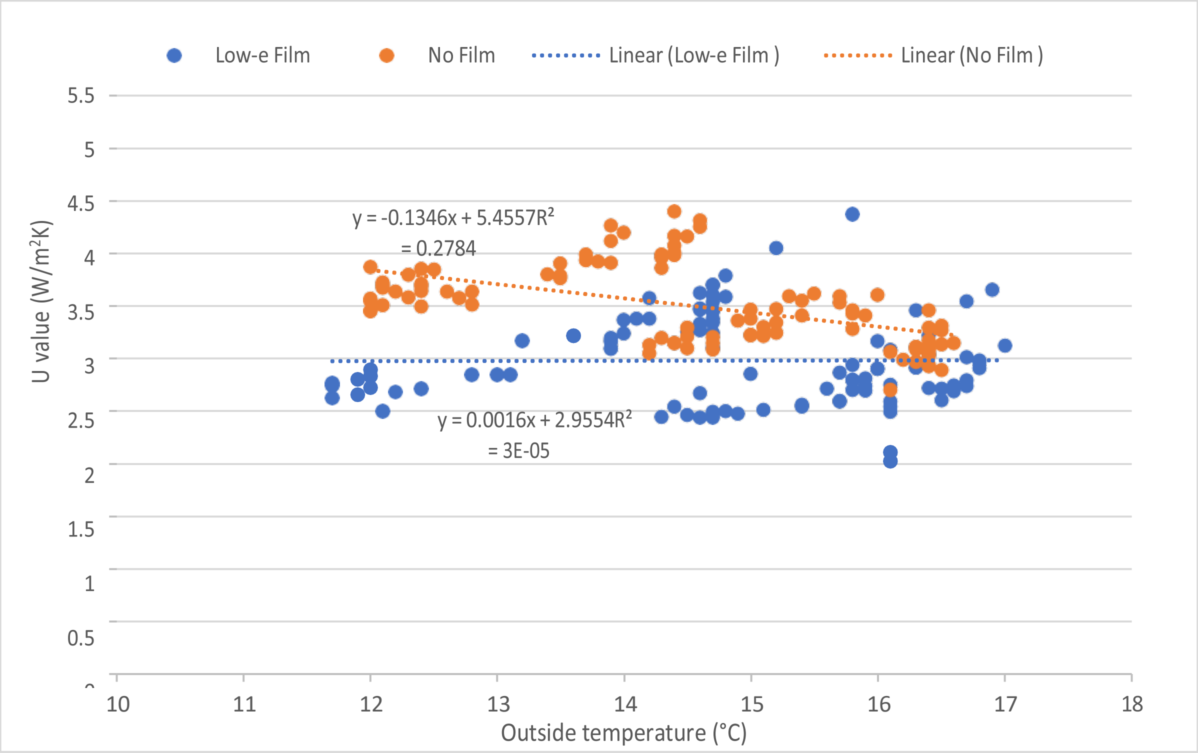


Figure 18, All window U-values with and without low-e film plotted against the outside temperature

Figure 19 shows what would happen if the data from the night of the 6th of January was removed due to the rain.

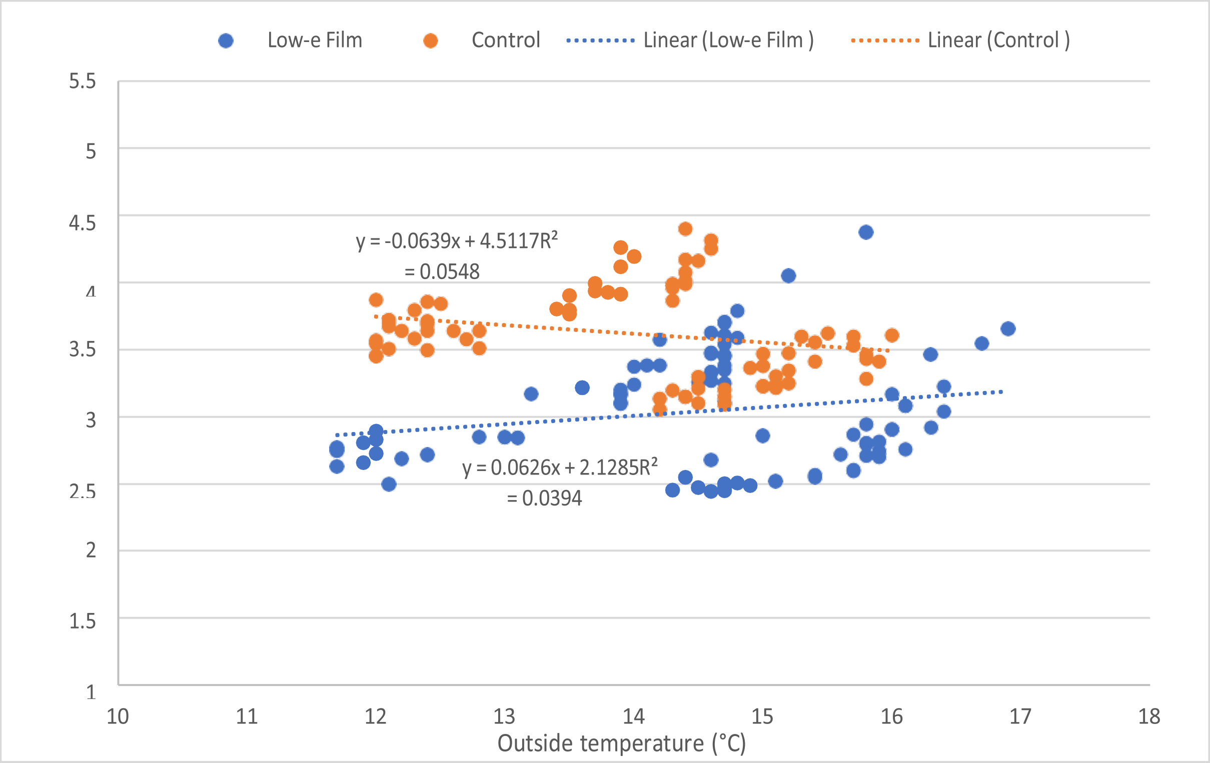


Figure 19, U-values excluding the data taken from the 6/1/21 with and without low-e film plotted against outside temperature

5.5 How emissivity affects the U-value

To evaluate just how sensitive the equation used in this study is to the emissivity of the window, different set conditions were taken and used to plot emissivity against U-values using Tejedor et al.’s equation. The used temperatures and thermal conductivity of air (K) for each condition can be found in Table 6, the plotted results can be observed in Figure 20.

Table 6, The set condition and their values used to plot Figure 19

Set Condition	Inside temperature (°C)	Glass temperature (°C)	Reflected temperature (°C)	Outside temperature (°C)	K (W/mK)	Gradient
Lowest	22.03	16.3	21.2	12.8	0.02514	0.334
Average	22.6	17.9	22.4	15.0	0.02530	0.299
Highest	24.2	20.0	24	16.9	0.02545	0.313

The gradient for each line can be found in Table 6, it appears that the lowest set conditions have the highest gradient whereas the average temperature values have the lowest. Each condition was taken from the recorded values from windows 1-4 in lab 1.N10.

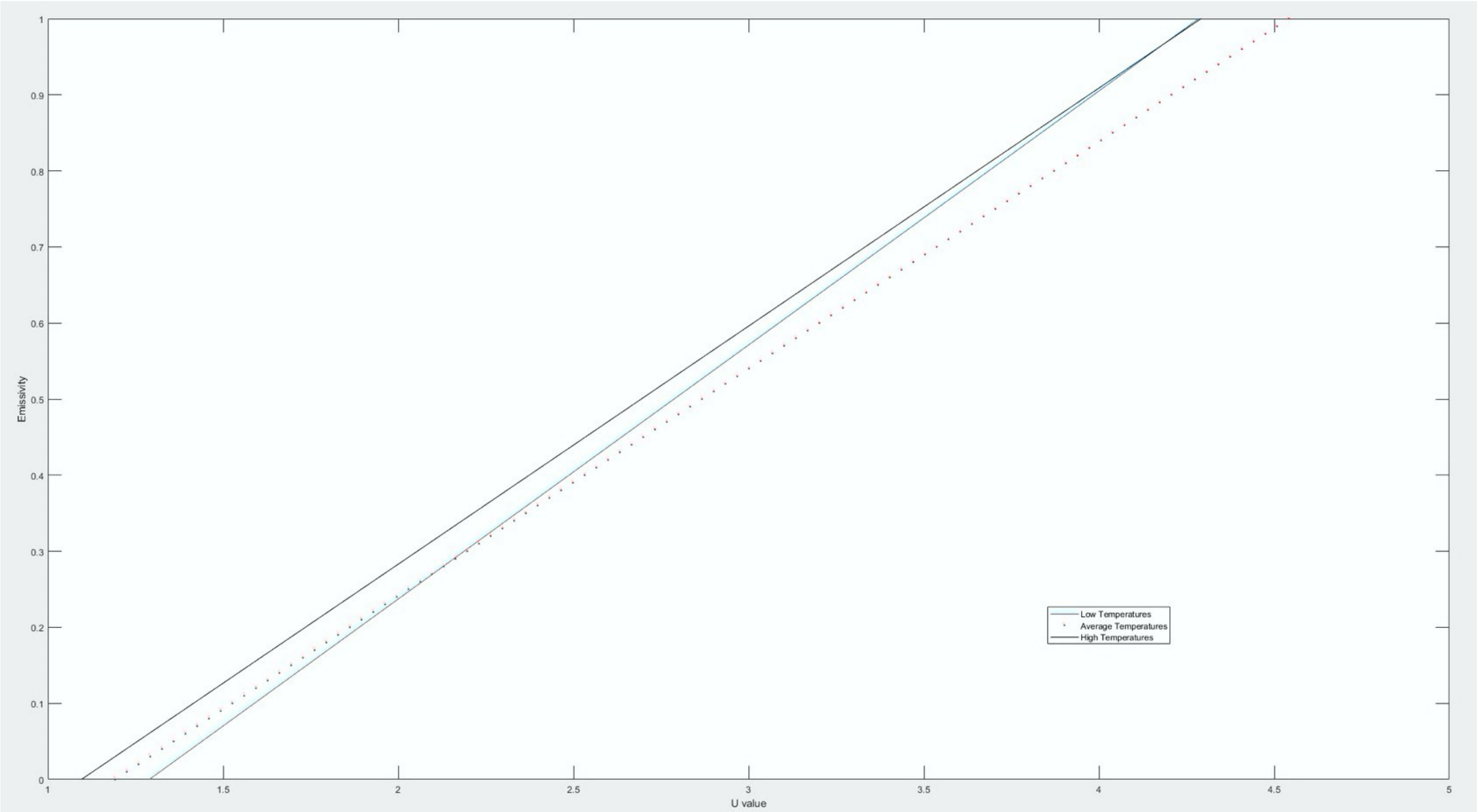


Figure 20, This figure plots the emissivity against U-value with set conditions

Abbey College

5.1 The film located in Abbey college is the VEP70, this was measured on the 11th and 12th of January. The emissivity value of the low-e film was found on the 11/1/21 to be 0.34, this was concluded fromthe data in Table 7 below.

Table 7, Emissivity values for the VEP70 film at Abbey College

ε	Glass surface temperature (°C)	Tape temperature (°C)
0.95	18.4	16
0.5	17.6	-
0.4	16.3	-
0.35	16.2	-
0.34	16.0	-
0.30	Values jumped around too much	

The recorded values from the windows at Abbey college from the night of the 11th are plotted in Figure 21 below. The measurements for the control window were cut short due to time restraints.

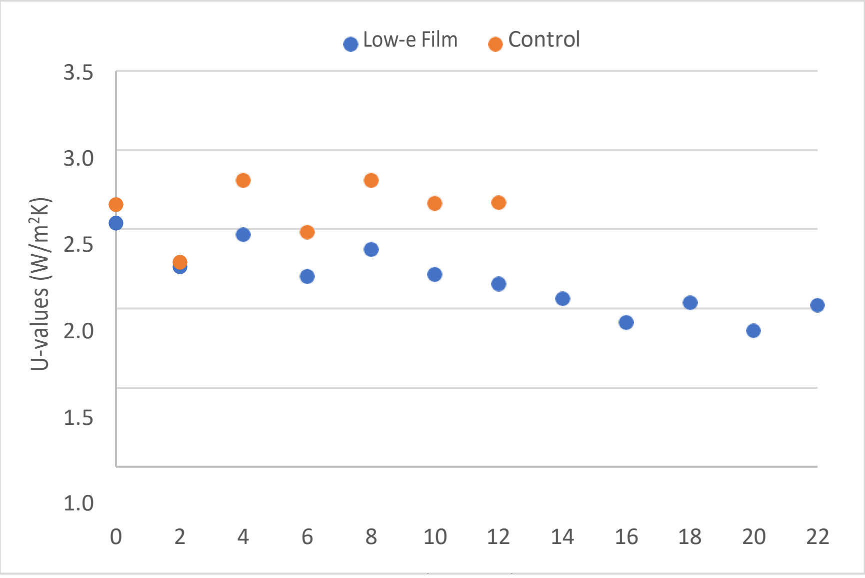


Figure 21, Values from low-e film, VEP70 and the control on the 11/1/21

On the 12th the emissivity value for the VEP70 window was checked again, however no result could be taken due to inaccurate readings.

Table 8, Emissivity values from VEP70 on the 12/1/21

ε	Glass surface temperature (°C)	Tape temperature (°C)
0.95	20.6	17.8
0.4	Ranges from 20.5 – 21.3	-
0.35	Ranges from 19.1 – 20.3	-
0.30	Ranges from 20.4 – 21.1	-
0.25	Ranges from 19.8 – 20.6	-
0.20	Ranges from 19.9 – 20.8	-

Figure 22 shows the plotted U-values from the low-e film and its control on the 12/1/21.

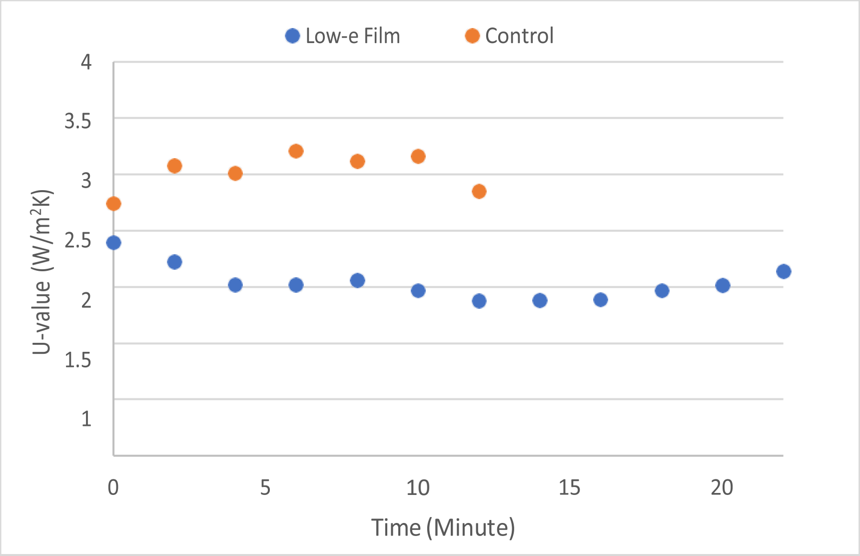


Figure 22, Plotted U-values from the VEP70 and its control on the 12/1/21

The summer U-value for the film VEP70 was given to be 2.498 W/m^{2}K and the emissivity given for VEP70 by the manufacturer was 0.09 (This data can be found in the Appendix). Figure 23 demonstrates if 0.09 was used instead of 0.34 with measurements from the 12th:

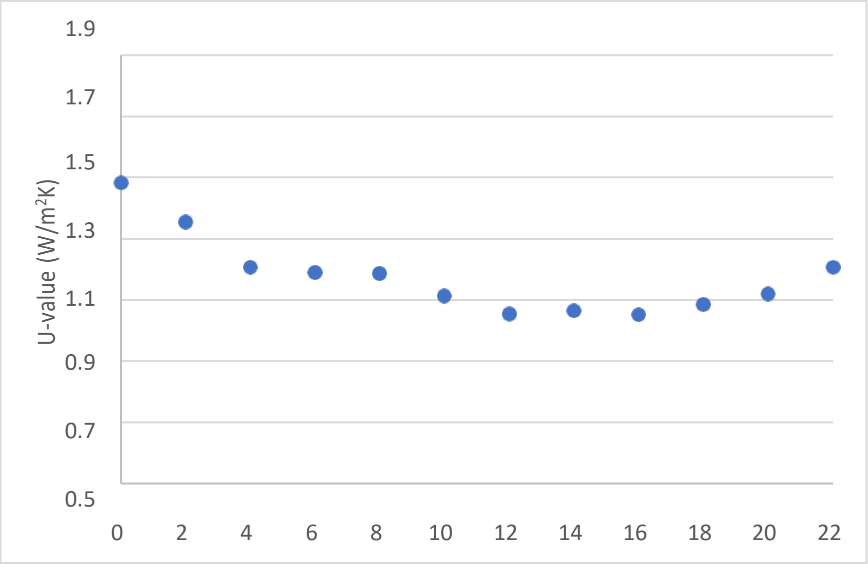


Figure 23, The U-value results if an emissivity of 0.09 was used.

6 Discussion

6.1 ICM-1307 film

The ICM-1307 located in lab 1.N10 has a winter U-value of 4.76 W/m^{2}K (see Appendix for further data), however, a summer U-value was not provided for this film. The calculated U-values from these results therefore cannot be compared to the provided U-value. It has been stated that U-values calculated in the summer U-value are lower then those calculated in the winter due to a lower temperaturedifference and wind speed.[xv] Through further research, there has been very little to no academic explanation regarding the main difference between the summer and winter U-values. One reference found discussed the correction of the U-value in the heating session due to thermal delay,[xvi] this perhaps indicates that the summer U-value may not be the most accurate when compared to the winter U-value.

In section 5.4.2 of the results, for the most part window 1 and 3 have lower U-values when compared to their control window. In Figures 14 and 15, the first three U-values calculated for windows 1 and 2show the opposite, however, this is a trend for most of the recorded data from the windows that were measured first in the night (see Excel, Lab 1.N10). This could be due to the IR camera's calibration; in future measurements the camera might need 10 minutes to allow it to 'warm up' before takingmeasurements.

In Figures 18 and 19 the data looks to be conflicting as there appears to be two grouping for both the low-e films and the no low-e films. Using Figure 19, it can be broken down to show that the U-values for the low-e film are still lower than the control values and follow a general trend, it just depends onthe dates that the recordings were made for some unknown reason.

This is shown below in Figure 23 below, where Figure 23a shows the measurements from the 7th, 8th and 15th. Figure 23b shows the 9th and the 13th .

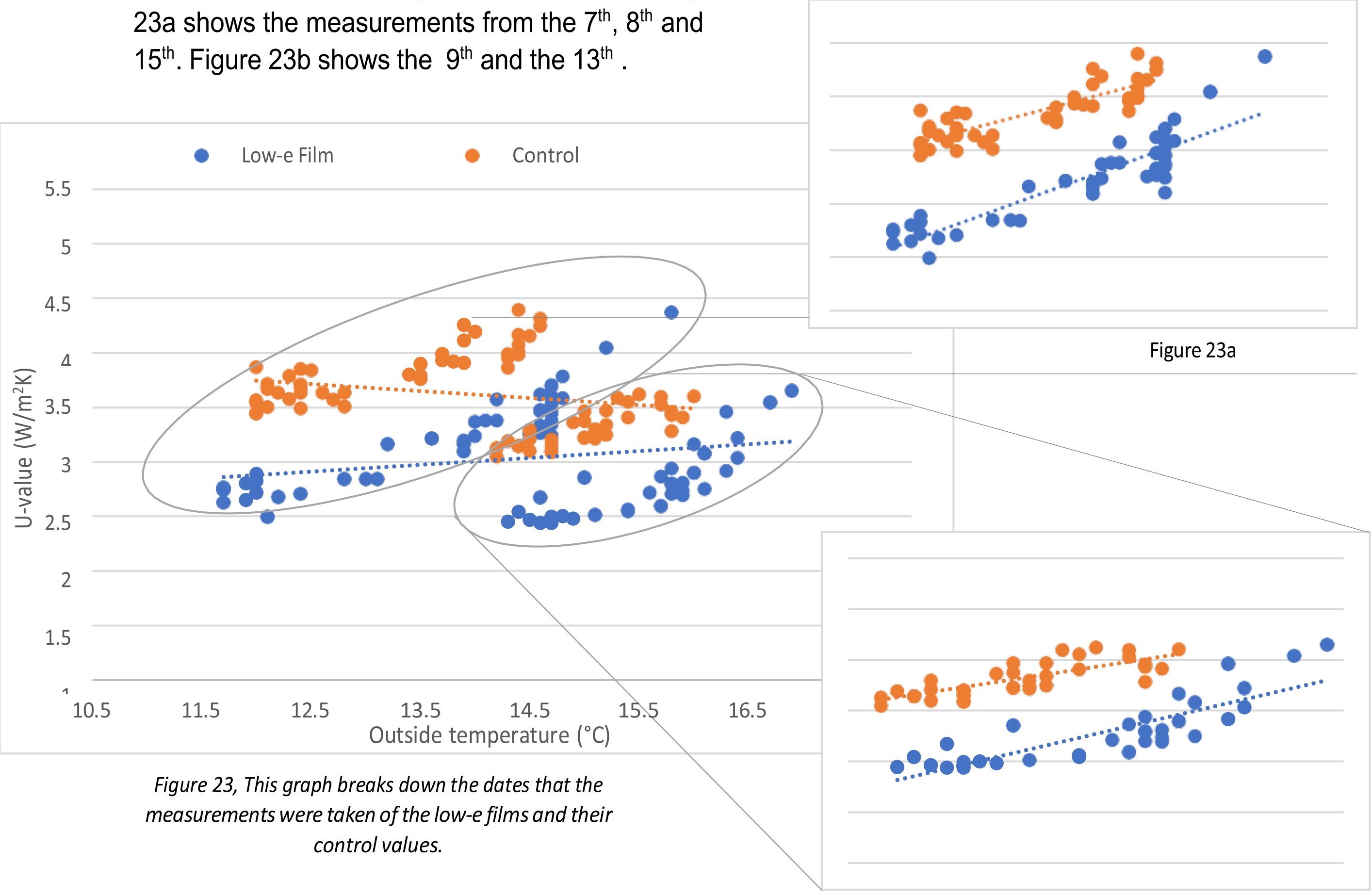


Figure 23a

Figure 23, This graph breaks down the dates that the measurements were taken of the low-e films and their control values.

Figure 23b

By focusing on Figures 23a and 23b, there appears to be a general trend of the U-value increasing as the outside temperature increases. This is inconsistent with what is known with the summer and winter U-values, because as the outside temperature increases the U-value should decrease.

When analysing the graph in Figure 19 of how the emissivity effects the U-value, it is observed that the conditions with the highest and the lowest temperatures have the steepest gradient and are therefore more sensitive to the emissivity. This is beneficial for when a location is either too hot or too cool, the low-e films will greatly affect the U-value of the window and therefore the energy performance of the room.

The manufacturing emissivity value that was provided for this film is 0.49, however the ε value that was found on three different occasions for this film was 0.56.

Two possible explanations for this could be that the calibration on the IR camera is off or that the ε value of the film could degrade over time. An Raytek IR camera was trialed at the start of this study and found to record lower than the actual temperature (see Excel, Raytek vs Flir). It was also compared to the Flir IR camera that was used during a measurement, again it was found to record lower temperatures and therefore produced higher U-values.

Figure 24, This shows window 1 with the low-e film on the left and the control window on the right

A disadvantage that has been stated about the low-e films is that they can reduce the amount of visible light into a room which can therefore cause an increase of artificial light. This problem will vary with the type of low-e film that is being utilized. The ICM-1307 in lab 1.N10 only showed a slight tint as seen in Figure 24, so this does not appear to be a problem with the chosen low-e film at the university.

When some of the low-e film is inspected in lab 1.N10, there appeared to be a few small bubbles in the film, this probably occurred during installation. This is a small problem as these could cause a small change in the heat transfer, it also makes the film look more noticeable. One more remark about the ICM-1307, is that in lab 1.N10 a small portion of it has already started to peel off and it was only applied in 2018.

6.2 VEP70 film

No accurate emissivity value for the VEP70 at Abbey College was found from the measurements taken. During the first set of measurements the emissivity was found to be 0.34, however on the second attempt no value was able to be recorded due to the fluctuations in the IR camera as seen in Table 8. Whenever the emissivity on the camera was set to 0.4 or below, there was an increase of temperature fluctuations.

The given emissivity value for VEP70 was 0.09, it is therefore believed that the true ε value for this film is in between 0.09 – 0.34. When 0.09 was used to calculate the U-values for this film all values werefound to be under 1.5 W/m^{2}K (Figure 22). The provided summer U-value for this film was 2.498 W/m^{2}K,so when this is compared to the U-values calculated from the ε values of 0.09 and 0.34, neither are accurate to this value.

However, the U-values from the 0.34 results are not too far off as they are centered mainly around the 2.0 W/m^{2}K mark.

However, this calls to question just how accurate the equation used in this study is for calculating U-values for a window. The equation from Tejedor et al. was chosen as it incorporated the core components for calculating a U-value while including the Ra, Pr and Nu numbers to approximate for the convective coefficient. These values were used in the research paper by Kou et al. where they specifically evaluated the U-value of a window. In comparison, the other equations from papers such as Fokaides and Kalogirou, Albatici et al. along with Albatici and Tonelli mainly used their equations to calculate the U-value of a wall. Hence, the equation used from Tejedor et al. appear to be best suited for calculating the U-value of a window in situ.

The equation from Albatici and Tonelli was used for comparison with the Tejedor et al. equation, however this showed a range of U-values and did not appear reliable (see excel, Abbey College).

6.3 R and U values

The R value is known as the thermal resistance for a material, this is another known value that shows a materials' degree of insulation. The R and the U value are related and be converted into each other by Equation 9 below.

$$R = \frac{1}{U}$$ Equation 9

Therefore, the lower the U value the higher the R value and the greater the insulation. For example, an R value of 3 m^{2}K/W corresponds to a U value of 0.33 W/m^{2}K which would be an ideal value for insulation.

6.4 Alternative options/Next steps

Thermal comfort was previously assessed on these low-e films by Mark Mason, thermal comfort assesses the worker's thermal comfort in their environment.[xvii] By using the method from ASHRAE 55 that includes the Predicted Percentage of Dissatisfied (PPD), where the aim is to have less than 10 % of people dissatisfied in their working thermal environment. This work was left unfinished. However, it does not give an accurate value on how well the low-e films have reduced the energy required for space heating or cooling.

When operating the Raytek IR camera, it did not fluctuate in temperature as frequency as the Flir IR camera did. Therefore, the Raytek camera may be able to record a more accurate emissivity value for low-e films with extremely low emissivity values such as the VEP70. In future, a better method might arise from using the Raytek camera in combination with the Flir camera when finding the ε value of a low emissivity film and recording the temperatures. To ensure that both camera function properly, it might be beneficial to use a temperature surface probe on the glass and compare with the values onboth IR cameras before taking measurements. When comparing the Raytek and Flir cameras earlier in the study, a mercury thermometer was used to conclude the true temperature of the glass surface (see excel, Raytek vs Flir). This took time to come to temperature and does not give a temperature to a decimal place.

In future, it would be helpful to model the equation on software such as MATLAB and show which temperatures have the most influence on the outcome of the U-value or if it is a combination. This might help explain why there is such a difference in U-values on different nights such as the 9th of December and the 13th of January as seen in Figure 23; or why when the outside temperature increases so does the U-value. Different equations could also be modelled and compared. It could also be beneficial to evaluate the T1316 film and even a double-glazed window and compare it to the VEP70 and ICM-1307 films. Another option could be to redo these measurements of the low-e film in winter and compared them to the results in this study.

7 Conclusion

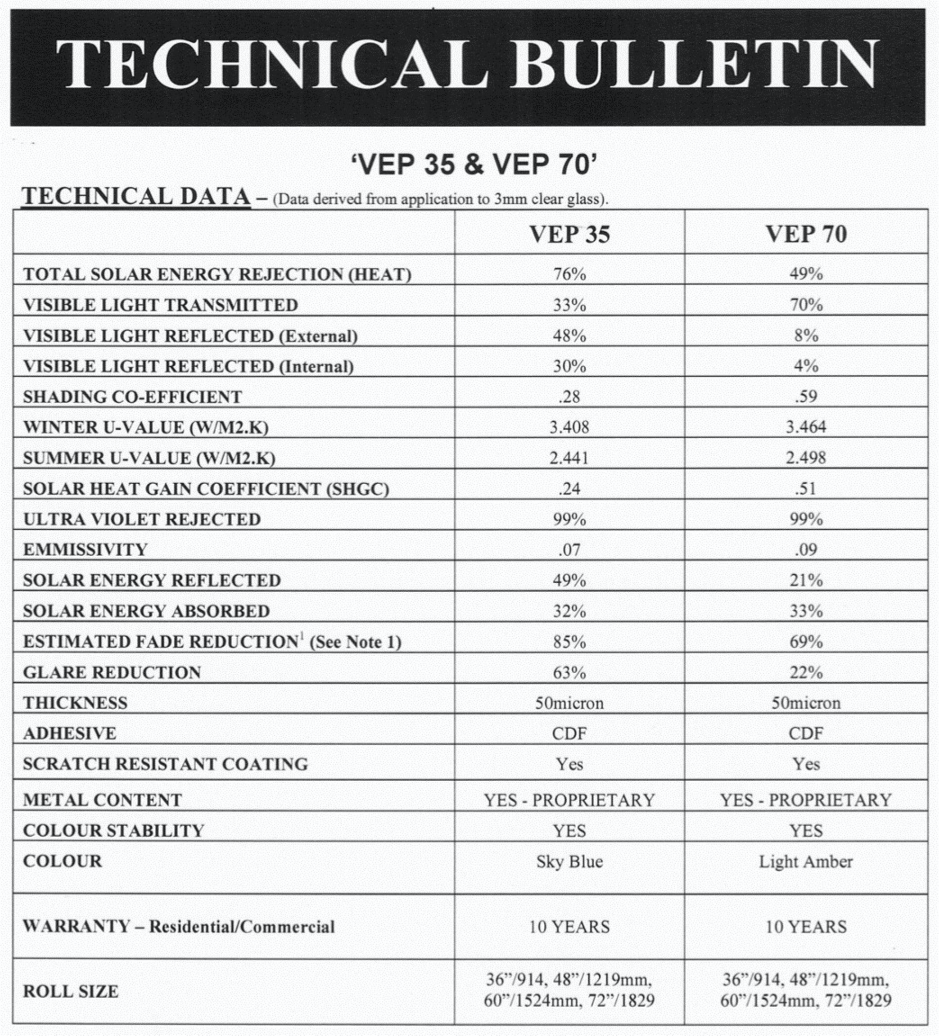
From these results, an exact U-value for low-e films ICM-1307 and VEP70 could not be found using an IR camera. The method used in this experiment was not able to produce reliable results as they were too inconsistent. The equation used from Tejedor et al.'s paper it showed that the outside temperature had a large influence on the U-value calculated. Therefore, in future studies it would be recommended to repeat the measurements in winter, the results could then be compared to those in this report. The Raytek IR camera could be reconsidered for measurements as well as the titanium T1316 film present at Te Pa.

The use of an IR camera in this study worked well for finding the emissivity of the ICM-1307 film, however, another method might be needed when finding the emissivity value of a low-e film that has an emissivity under 0.4 such as the VEP70 film. The expected ε value for the ICM-1307 was given to be 0.49, however, the found ε value was 0.56. These ε values are reasonably close, however a conclusive ε value for the VEP70 film was never found. The first ε value of VEP70 was found to be 0.34, but this is not to be relied upon due to inconsistency. It would be anticipated that the true ε value is under 0.34, it may not be the expected value of 0.09. The VEP70 film was the only low-e film to have a summer U value of 2.498 W/m^{2}K provided, unlike the ICM-1307 film, the calculated U values for VEP70 could be compared.

In conclusion, these low-e films do appear to have an impact on the U-value of the window when compared to a single glass pane control window. However, no specific results can be relied upon from this study due to their inconsistency. For example, when the low-e films VEP70 and ICM-1307 are compared, it is seen that most of the U- values from the ICM-1307 are around 3.0 W/m^{2}K whereas the U-values from VEP70 are around 2.0 W/m^{2}K. Hence, the lower the emissivity value of a window the lower the U-value and therefore the more efficient it is at reflecting the heat back into a room. Further measurements and an alternate method in future would provide more specific results.

8 Appendix

Manufacture data on VEP70 film:



TECHNICAL BULLETIN

'VEP 35 & VEP 70'

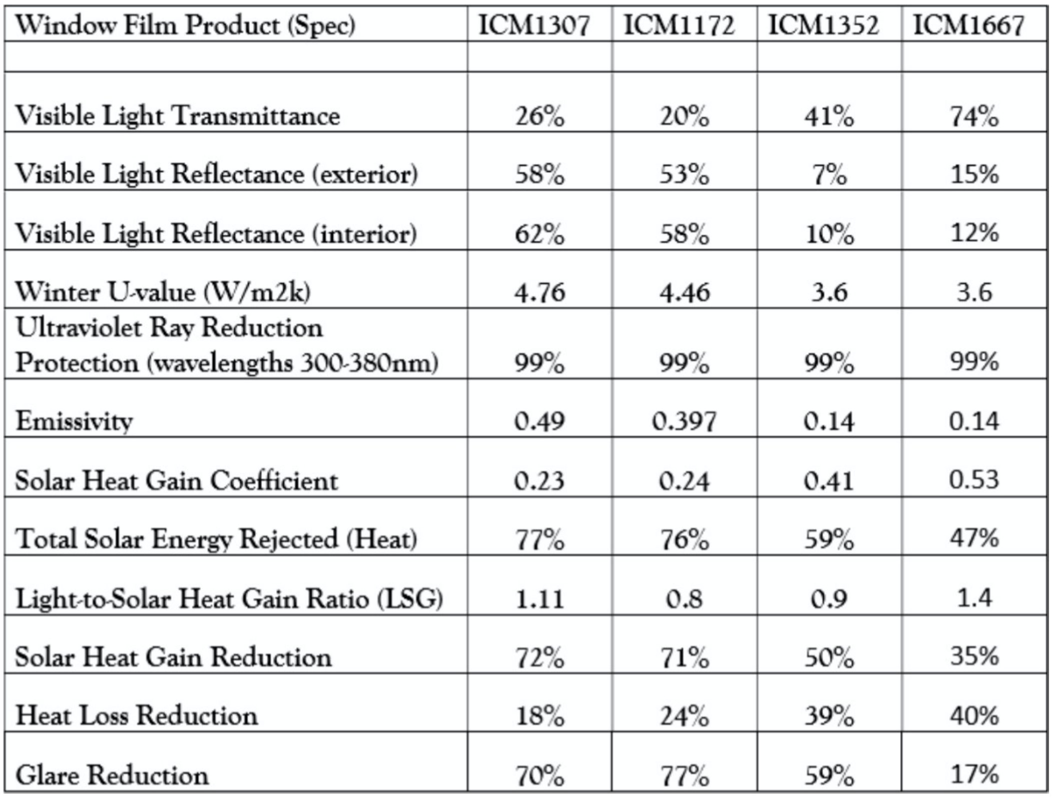
TECHNICAL DATA – (Data derived from application to 3mm clear glass).

	VEP 35	VEP 70
TOTAL SOLAR ENERGY REJECTION (HEAT)	76%	49%
VISIBLE LIGHT TRANSMITTED	33%	70%
VISIBLE LIGHT REFLECTED (External)	48%	8%
VISIBLE LIGHT REFLECTED (Internal)	30%	4%
SHADING CO-EFFICIENT	.28	.59
WINTER U-VALUE (W/M2.K)	3.408	3.464
SUMMER U-VALUE (W/M2.K)	2.441	2.498
SOLAR HEAT GAIN COEFFICIENT (SHGC)	.24	.51
ULTRA VIOLET REJECTED	99%	99%
EMMISSIVITY	.07	.09
SOLAR ENERGY REFLECTED	49%	21%
SOLAR ENERGY ABSORBED	32%	33%
ESTIMATED FADE REDUCTION[1] (See Note 1)	85%	69%
GLARE REDUCTION	63%	22%
THICKNESS	50micron	50micron
ADHESIVE	CDF	CDF
SCRATCH RESISTANT COATING	Yes	Yes
METAL CONTENT	YES - PROPRIETARY	YES - PROPRIETARY
COLOUR STABILITY	YES	YES
COLOUR	Sky Blue	Light Amber
WARRANTY – Residential/Commercial	10 YEARS	10 YEARS
ROLL SIZE	36"/914, 48"/1219mm, 60"/1524mm, 72"/1829	36"/914, 48"/1219mm, 60"/1524mm, 72"/1829

Manufacture data on Titanium T1316:

Titanium Series	Glass	T1182	T1154	T1190	T1244	T1316
Light Transmitted	88%	6%	16%	22%	27%	36%
Visible Light Reflected						
- Exterior %	8%	13%	12%	27%	13%	19%
- Interior %	8%	13%	12%	13%	11%	13%
UV Stopped	38	99%	99%	99%	99%	99%
Glare Reduction	12%	93%	82%	78%	69%	59%
Colour Stability	N/A	Life	Life	Life	Life	Life
Solar Energy Rejected	19%	73%	62%	65%	56%	56%
Residential Warranty	N/A	Life	Life	Life	Life	Life
Commercial Warranty	N/A	12 Years	12 Years	12 Years	12 Years	12 Years

Manufacture data on ICM-1307:



Window Film Product (Spec)	ICM1307	ICM1172	ICM1352	ICM1667
Visible Light Transmittance	26%	20%	41%	74%
Visible Light Reflectance (exterior)	58%	53%	7%	15%
Visible Light Reflectance (interior)	62%	58%	10%	12%
Winter U-value (W/m2k)	4.76	4.46	3.6	3.6
Ultraviolet Ray Reduction Protection (wavelengths 300-380nm)	99%	99%	99%	99%
Emissivity	0.49	0.397	0.14	0.14
Solar Heat Gain Coefficient	0.23	0.24	0.41	0.53
Total Solar Energy Rejected (Heat)	77%	76%	59%	47%
Light-to-Solar Heat Gain Ratio (LSG)	1.11	0.8	0.9	1.4
Solar Heat Gain Reduction	72%	71%	50%	35%
Heat Loss Reduction	18%	24%	39%	40%
Glare Reduction	70%	77%	59%	17%

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