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A STUDY OF PANE SPACING IN GLAZING SYSTEMS

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ABSTRACT

The selection of optimum pane spacing for glazing systems has been a topic of ongoing debate in the window manufacturing industry. Arguments are often based on speculation, intuition and results from tests not specifically designed to examine the effects of pane spacing. This study presents a set of measured centre-glass U-values taken from experiments where pane spacing was carefully varied while holding all remaining conditions unchanged. Heat flux measurements were made using a guarded heater plate apparatus. Glazing systems were all double glazed, air filled and tested in the vertical position.

Measured centre-glass U-values were compared to calculated U-values. These calculations were performed using a version of the VISION glazing system thermal analysis program which was modified in order to model the guarded heater plate test conditions. VISION runs were also carried out in order to predict the optimum pane spacing as a function of variations in glazing system design, fill gas type, weather condition, and the number of panes incorporated in the glazing system.

VISION results were combined with results of the window frame thermal analysis program, FRAME. FRAME was used to estimate the average edge-glass and frame U-values for several design options. The results of these calculations provide an estimate of the sensitivity of overall U-values to variations in pane spacing.

1. INTRODUCTION

In this study, experiments were conducted to measure centre-glass U-values where the pane spacing was carefully varied while all other variables were held constant. A set of calculated centre-glass U-values were compiled to compare directly to the measured data. An additional set of calculated centre-glass U-values were determined as a function of pane spacing, to investigate the effect on optimum pane spacing of glazing system design, fill gas type, weather condition, and the number of glazings incorporated in the glazing system. Finally, calculations were made to investigate the effect of edge-glass and frame heat transfer rates on optimum pane spacing.

Measurements of centre-glass heater transfer rates were made with a guarded heater plate apparatus. The heat transfer rates were used to calculate the centre-glass U-values. The measured centre-glass U-values for five pane spacings at two temperature differences are presented.

The VISION glazing thermal analysis program (1,2,3) was used to calculate centre-glass heat transfer rates, and centre-glass U-values. A modified version of the VISION program which models the guarded heater plate apparatus was used to calculate the centre-glass U-values that were compared to the measured data. A comparison of these calculated values and the measured data is presented.

The standard VISION program was used to calculate centre-glass U-values as a function of pane spacing for various glazing system configurations, fill gas types, weather conditions, and the number of glazings used. The results of these calculations and a discussion of the effect of the above parameters on optimum pane spacing are presented.

FRAME (4,5) is a finite-difference thermal analysis program which predicts edge-glass and frame heat transfer rates. FRAME was used to calculate the edge-glass and frame heat transfer rates as a function of pane spacing for three glazing system configurations, at two weather conditions and in two frame types. The frame heat transfer rates were used to calculate the edge-glass and frame U-values. The edge-glass and frame U-values were combined with the centre-glass U-values to get overall window U-values. The results of these calculations and a discussion of the effect of edge-glass and frame heat transfer on optimum pane spacing are presented.

2. MEASURED AND CALCULATED CENTRE-GLASS U-VALUES

Experiments were carried out to measure centre-glass U-values as a function of pane spacing, while holding all other parameters constant. Calculations to predict the measured centre-glass U-values were performed. The results of the measured and calculated U-values and a comparison of these data are presented.

2.1 MEASUREMENT OF CENTRE-GLASS U-VALUES

The measured centre-glass heat transfer rates were determined using a guarded heater plate apparatus. This apparatus consists of two flat copper plates that can each be maintained at a uniform temperature. The test samples were placed between these plates but separated from the plates by neoprene mats. The heat transfer through each sample (driven by the temperature difference between the plates) was measured over the face of a guarded heater-plate (8x8 inches (203x203 mm)) embedded in the warmer copper plate. The measured heat transfer rate, plate-to-plate temperature difference and the known thermal resistance of the neoprene mats was used to determine the glass-to-glass conductance. A detailed description of the test procedure has been published(6).

Heat transfer rates for five test samples were measured. The test samples had pane spacings of 10,13,16,19 and 25 mm. The test samples consisted of the following: two 6 mm sheets of clear glass 25x25 inches (635x635 mm) each, one with a low emissivity coating (measured emissivity of e=0.07), four polystyrene foam insulation spacers and four machined plexiglass spacers. All of the measured glazing systems were vented with air as the fill gas. The foam spacers were placed around the perimeter of the glass and the plexiglass spacers were placed at each corner, between the sheets of glass. When the copper plates were clamped together the pane spacing was equal to the length of the plexiglass spacers.

Each sample was tested at two temperature differences with the mean temperature being held constant. The mean temperature was -2 C and the two temperature differences were 15 C and 28 C. The larger temperature difference was used to model the American Society of Heating Refrigeration and Air-conditioning Engineers (ASHRAE) winter design condition (see Table 3). The lower temperature difference was chosen to represent a less severe weather condition.

The conductance value for each test sample was determined according to equation 1. The resulting U-value for each test sample was calculated by adding on the indoor and outdoor heat transfer coefficients according to equation 3. The indoor heat transfer coefficient assumes still air and the outdoor coefficient assumes a 6.7 m/s wind speed. The results of the measured U-values are presented in Table 1.

$$C = q / \Delta T_{gg} \quad [W/m^2C] \qquad [1]$$

where, C = glass-to-glass conductance
q = heat flux through glazing system
ΔT_{gg} = glass-to-glass temperature difference

$$q = U_{cg} \cdot \Delta T \quad [W/m^2] \qquad [2]$$

where, U_{cg} = centre-glass U-value
ΔT = indoor to outdoor air temperature difference

$$U_{cg} = ((1/h_{in})+(1/C)+(1/h_{out}))^{-1} \quad [W/m^2C] \qquad [3]$$

where, h_{in} = indoor heat transfer coefficient
h_{out} = outdoor heat transfer coefficient
$(1/h_{in})+(1/h_{out}) = 0.159 \quad [m^2C/W]$

2.2 CALCULATION OF CENTRE-GLASS U-VALUES TO PREDICT THE MEASURED DATA

Centre-glass U-values were calculated to compare with the U-values measured with the guarded heater plate apparatus. The calculated centre-glass U-values were found using a modified version of the VISION program. The modified program uses the conductive thermal resistance of the neoprene mats in place of the convective and radiative exchange between the glazing system and the environment. The program calculates the glass-to-glass conductance value given the measured pane spacing, the measured temperature difference and the known neoprene mat resistance. The calculated U-values were determined by taking the glass-to-glass conductance values from the modified VISION program and adding on the indoor and outdoor heat transfer coefficients according to equation 3. Results of these calculated U-values are presented in Table 1.

2.3 COMPARISON OF CENTRE GLASS U-VALUES MEASURED AND CALCULATED

Table 1 shows the U-values for the measured glazing systems, the calculated centre-glass U-values that were made to permit a direct comparison with the measured systems, and their percentage differences.

Table 1: Centre-Glass U-value for the Measured Glazing Systems

Pane Spacing [mm]	Measured U-value [W/m^{2}C]	Calculated U-value [W/m^{2}C]	Difference [%]
Temperature Difference = 15 C.			
10	1.86	1.87	0.7
13	1.60	1.62	1.5
16	1.50	1.60	6.2
19	1.49	1.59	6.2
25	1.56	1.65	5.6
Temperature Difference = 28 C.			
10	1.90	1.89	0.2
13	1.70	1.80	5.9
16	1.73	1.81	4.7
19	1.78	1.86	4.6
25	1.84	1.88	2.2

The results from the measured and calculated U-values show good agreement with the largest difference being 6%. The pane spacings that give the minimum U-value are 19 mm and 13 mm for the temperature differences of 15 C and 28 C respectively. Figure 1 shows that the U-value variation as a function of pane spacing is very small over the range of 13 to 19 mm. Therefore the optimum pane spacing range is of more interest than the actual value. The range of U-values within one percent of each other will establish the optimum U-value range. For a temperature difference of 15 C the optimum pane spacing range is 16 to 19 mm, for both the measured and the calculated values. For a 28 C temperature difference the optimum pane spacing range is 13 to 16 mm, both measured and calculated.

Two conclusions can be drawn with regards to the measured and calculated data. First the data show very good agreement on individual values of centre-glass U-value, and the data also agree on the optimum pane spacing range. Second, the optimum pane spacing for a glazing system is dependent on the temperature difference imposed on the system. As the temperature difference decreases, the optimum spacing increases. This agrees with the theory that the minimum U-value occurs at a critical Rayleigh number(7). Therefore, a decrease in ΔT for a system at the critical Rayleigh number would correspond to an increase in pane spacing to return to the optimum value.

3. CALCULATED CENTRE-GLASS U-VALUES

The standard VISION program was used to calculate centre-glass U-values as a function of pane spacing for various glazing system designs, fill gas types, weather conditions, and the number of panes incorporated in the glazing system. These calculations were made to investigate the effect of the above parameters on optimum pane spacing. The two glazing system designs studied were both double glazed systems with clear glass; one system had a low-e coating and the other had no coating. There were two types of fill gases examined, air and argon. The two weather conditions investigated were the ASHRAE winter design condition and the American Architectural Manufacturers Association (AAMA) test condition (see Table 3). Finally, to examine the effect of the number of glazings used in a system on the optimum pane spacing, a double, a triple, and a quadruple glazed system were compared.

3.1 EFFECT OF GLAZING SYSTEM DESIGN

The first glazing system design studied had two sheets of 6 mm clear glass, and is defined as a conventional double glazed system (CDG). The second system had two 6 mm sheets of clear glass, one sheet with a low-e (e=0.09) coating, defined as DG/LE. Both systems had air as the fill gas. The pane spacing for these glazing systems was varied from 7 to 25 mm in 3 mm steps.

The U-values, taken from the standard VISION runs for these systems are shown in the first two columns of Table 2. The optimum pane spacing range for the CDG system was 13 to 19 mm for the ASHRAE condition, and 13 to 22 mm for the AAMA condition. The optimum pane spacing range for the DG/LE system was 13 to 16 mm for the ASHRAE condition, and 13 to 19 mm for the AAMA condition.

The effect on optimum pane spacing as a result of the addition of a low-e coating to a glazing system, is a decrease in the optimum spacing range. This is the result of the increased temperature difference the fill gas cavity sees. An increase in ΔT reduces the optimum pane spacing, as discussed earlier.

3.2 EFFECT OF FILL GAS TYPE

The two glazing systems used for the fill gas study were both DG/LE. One system had an air fill gas and the other had an argon fill, which are defined as DG/LE and DG/LE/Ar respectively. The pane spacings used were the same as those outlined in section 3.1.

The U-values for the two fill gases are shown in the second and third columns of Table 2. The optimum pane spacing range for the DG/LE system was 13 to 16 mm for the ASHRAE condition, and 13 to 19 mm for the AAMA condition. The optimum pane spacing range for the DG/LE/Ar system was 10 to 13 mm for the ASHRAE condition, and 13 to 16 mm for the AAMA condition. The minimum U-value for both cases occurred at a pane spacing of 13 mm.

The effect of changing from a fill gas of air to argon for a given glazing system, is to decrease the optimum pane spacing. This result agrees with the convective theory that for a given ΔT and pane spacing, argon will have a larger Rayleigh number than air(7).

Table 2: Centre-Glass U-value - Calculated for Double Glazed System

Pane Spacing [mm]	CDG [W/m^{2}C]	DG/LE [W/m^{2}C]	DG/LE/Ar [W/m^{2}C]
ASHRAE winter design condition.			
7	3.13	2.33	1.88
10	2.89	1.94	1.57
13	2.82	1.87	1.56
16	2.82	1.89	1.59
19	2.84	1.93	1.62
22	2.85	1.94	1.62
25	2.86	1.95	1.62
AAMA test condition.			
7	3.21	2.37	1.91
10	2.97	1.95	1.56
13	2.84	1.76	1.46
16	2.82	1.76	1.46
19	2.82	1.78	1.50
22	2.84	1.81	1.52
25	2.85	1.83	1.53

3.3 EFFECT OF WEATHER CONDITIONS

The two weather conditions examined were the ASHRAE winter design condition and the AAMA test condition. Both of these are outlined in Table 3. Table 2 gives a summary of the U-values for all three glazing systems at both weather conditions.

For all of the glazings systems simulated, the optimum pane spacing range increased or shifted toward a wider pane spacing in changing from the ASHRAE to the AAMA condition. In all the cases the variation in the U-value beyond a spacing of 13 mm is very small as shown in Figure 2, less than four percent for the maximum variation.

This result is as expected, since the AAMA condition has a smaller ΔT than the ASHRAE condition, and decreasing ΔT will increase the pane spacing. Since the variation in U-value is small beyond 13 mm, any spacing greater than 13 mm will give a U-value within 4% of the optimum.

Table 3: Weather Conditions

	Inside Temp. [C]	Outside Temp. [C]	Wind Speed [m/s]	Temp. Diff. [C]
ASHRAE WINTER DESIGN CONDITION	21.0	-18.0	6.7	39.0
AAMA TEST CONDITION	20.0	-7.8	6.7	27.8

3.4 EFFECT OF THE NUMBER OF GLAZINGS INCORPORATED

Three glazing system configurations were simulated to examine the effect of the number of glazings incorporated in the system. The three were, double, triple and quadruple glazed systems. Each of the systems used clear 6 mm sheets of glass. There were one, two, and three low-e (e=0.09) coatings in the double, triple and quadruple systems respectively. The fill gas used in all three systems was air. The systems were simulated at pane spacings of 10, 13, 16, 19, 22, and 25 mm and at the ASHRAE winter condition.

The calculated U-values for the simulation of double, triple and quadruple glazed systems are shown in Table 4. The optimum pane spacing range for the double and triple systems was 13 to 19 mm. The optimum pane spacing range for the quadruple system was 16 to 19 mm. Figure 3 shows the variation in the U-value with pane spacing. Again, beyond a spacing of 13 mm the U-value variation was small in all three cases, less than six percent for the maximum variation.

Table 4: Centre-Glass U-value - Calculated for Double, Triple, and Quadruple Glazed System

Pane Spacing [mm]	Double [W/m^2C]	Triple [W/m^2C]	Quadruple [W/m^2C]
10	2.89	1.15	0.82
13	2.82	1.00	0.68
16	2.82	0.99	0.64
19	2.84	1.00	0.64
22	2.85	1.02	0.65
25	2.86	1.03	0.67

The effect of adding glazings to the system is to reduce the temperature difference across each of the fill gas cavities. This allows for an increase in the pane spacing. The addition of the third glazing does not indicate any change in the optimum spacing, but the addition of the fourth glazing does show an increase in the optimum spacing. The fact that the U-value variation is so small beyond 13 mm indicates that any spacing greater than 13 mm would yield a U-value within 6% of the optimum.

4. CALCULATED EDGE-GLASS AND FRAME U-VALUES

The calculated centre-glass U-values from the standard VISION results were combined with the window thermal analysis program, FRAME. FRAME was used to estimate the edge-glass and frame heat transfer rates for several design options. The edge-glass and frame heat transfer rates were used to calculate the edge-glass and frame U-values. These results were then combined with the centre-glass U-values to get an estimate of the overall U-value as a function of pane spacing.

4.1 CALCULATION OF FRAME AND EDGE-GLASS U-VALUES

The frame and edge-glass U-values were calculated for three glazing system configurations, in two frame types and at two different weather conditions. The glazing system designs were CDG, DG/LE, AND DG/LE/Ar. The two frame types were wood and a thermally broken aluminum. The weather conditions were the ASHRAE winter design condition and AAMA test condition. The results of the frame and edge-glass U-value calculations for all of the above configurations are summarized in Table 5.

Table 5: Frame and Edge-glass U-value For Double Glazed Systems

Pane Spacing mm	Wood Frame CDG W/m^2C	DG/LE W/m^2C	DG/LE/Ar W/m^2C	Aluminum Frame CDG W/m^2C	DG/LE W/m^2C	DG/LE/Ar W/m^2C
ASHRAE winter design condition.						
7	2.90	2.44	2.19	3.29	2.92	2.71
10	2.71	2.16	1.95	3.36	2.92	2.77
13	2.63	2.07	1.89	3.34	2.90	2.76
16	2.59	2.04	1.86	3.36	2.93	2.80
19	2.58	2.02	1.84	3.44	2.94	2.80
22	2.56	2.00	1.81	3.39	2.97	2.83
25	2.54	1.97	1.78	3.38	2.96	2.81
AAMA test condition.						
7	2.94	2.46	2.20	3.32	2.93	2.72
10	2.76	2.17	1.95	3.39	2.92	2.75
13	2.63	2.01	1.84	3.33	2.84	2.71
16	2.59	1.96	1.79	3.34	2.87	2.74
19	2.56	1.94	1.77	3.34	2.87	2.74
22	2.54	1.93	1.75	3.37	2.91	2.77
25	2.52	1.90	1.72	3.36	2.90	2.76

The wooden frames consistently showed a decrease in the edge-glass and frame U-values with increased pane spacing. This result is as expected, since the increase in pane spacing will increase the conduction path through the wood frame and reduce the heat transfer rate. The aluminum frame cases show a relatively constant U-value at all pane spacings, which is also as expected, since the width of the thermal break in the aluminum frame was held constant. The width of the thermal break has been established as the governing factor for the heat transfer in an aluminum frame(8).

4.2 CALCULATED OVERALL U-VALUE

The overall U-value was determined using a projected area weighted average of the edge-glass and frame U-value and the centre-glass U-value. The overall projected area for the window was assumed to be 1 m^2 similar to that of a residential window. The overall U-value for CDG, DG/LE, and DG/LE/Ar systems at the two weather conditions, and in the two frame types were calculated and the results are shown in Table 6.

Table 6: Overall Window U-value For Double Glazed Systems

Pane Spacing mm	Wood Frame CDG W/m^2C	DG/LE W/m^2C	DG/LE/Ar W/m^2C	Aluminum Frame CDG W/m^2C	DG/LE W/m^2C	DG/LE/Ar W/m^2C
ASHRAE winter design condition.						
7	3.01	2.39	2.03	3.21	2.62	2.29
10	2.81	2.05	1.75	3.12	2.42	2.15
13	2.73	1.97	1.72	3.07	2.38	2.15
16	2.71	1.96	1.72	3.08	2.40	2.18
19	2.71	1.97	1.73	3.14	2.42	2.20
22	2.71	1.97	1.71	3.12	2.44	2.21
25	2.70	1.96	1.70	3.12	2.44	2.20
AAMA test condition.						
7	3.08	2.41	2.05	3.26	2.64	2.30
10	2.87	2.06	1.75	3.18	2.43	2.14
13	2.74	1.88	1.65	3.08	2.29	2.08
16	2.71	1.86	1.63	3.08	2.30	2.09
19	2.69	1.86	1.63	3.07	2.31	2.11
22	2.70	1.87	1.63	3.10	2.35	2.13
25	2.69	1.87	1.62	3.10	2.35	2.13

Windows with wood frames at the ASHRAE condition show an optimum pane spacing range of 13 to 25 mm for both the CDG and the DG/LE systems, and 22 to 25 mm for the DG/LE/Ar system. Windows with wood frames at the AAMA condition show an optimum pane spacing range of 16 to 25 mm for all three systems. Figure 4 shows a plot of overall window U-value versus pane spacing for all of the wood frame systems. The figure indicates that, in all cases, the U-value variation beyond 13 mm is very small, less than two percent.

Windows with aluminum frames at both the ASHRAE and the AAMA conditions show the same optimum pane spacing ranges as those for the centre-glass U-values. Figure 5 plots overall window U-value against pane spacing for all of the aluminum frame configurations. Again, beyond 13 mm the variation in the U-value is less than two percent.

The increase in the optimum pane spacing for the overall U-values of the wood frame windows to that of the centre-glass U-values is as expected, since the heat transfer rates through the edge-glass and frame decrease as the pane spacing increases. The unchanged optimum pane spacing for the aluminum frame windows is also as expected, since the heat transfer rate through the aluminum frame is constant. Since the overall U-value variation is small beyond 13 mm for both frame types, any pane spacing greater than 13 mm will yield an overall U-value within 2% of the optimum value regardless of frame type.

5. CONCLUSIONS

The minimum U-value for any glazing system occurs at a critical Rayleigh (Ra) number.

$$Ra_L = \rho g \beta L^3 C_p \ \Delta T / \nu k \qquad [4]$$

ρ = mass density
β = coefficient of thermal expansion
L = pane spacing
C_p = specific heat at constant pressure
g = acceleration of gravity
ΔT = temperature difference
ν = kinematic viscosity
k = thermal conductivity

Therefore, according to equation 4 anything that increases ΔT will reduce the optimum pane spacing. The addition of a low-e coating increased ΔT, and reduced optimum pane spacing. Changing from the AAMA to the ASHRAE condition increased ΔT, and as expected the optimum pane spacing was reduced. Conversely, anything that decreases the ΔT across the pane spacing will increase the optimum pane spacing. The addition of glazings to a system reduced the ΔT across the pane spacings, and the optimum pane spacing was increased.

Changing the fill gas in a glazing system, such that the quantity $\rho C_p / \nu k$ is increased, will reduce the optimum pane spacing. This was the case in changing from air to argon.

For the parameters studied, the variation in U-value was very small. The variations were on the order of the experimental measurement accuracy and the variability in the manufacturing process. Thus, for all practical purposes any pane spacing greater than 13 mm will be within a few percent of the minimum U-value.

6. REFERENCES

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7. ACKNOWLEDGEMENTS

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Figure 1: Centre-glass U-value
Measured vs. Calculated

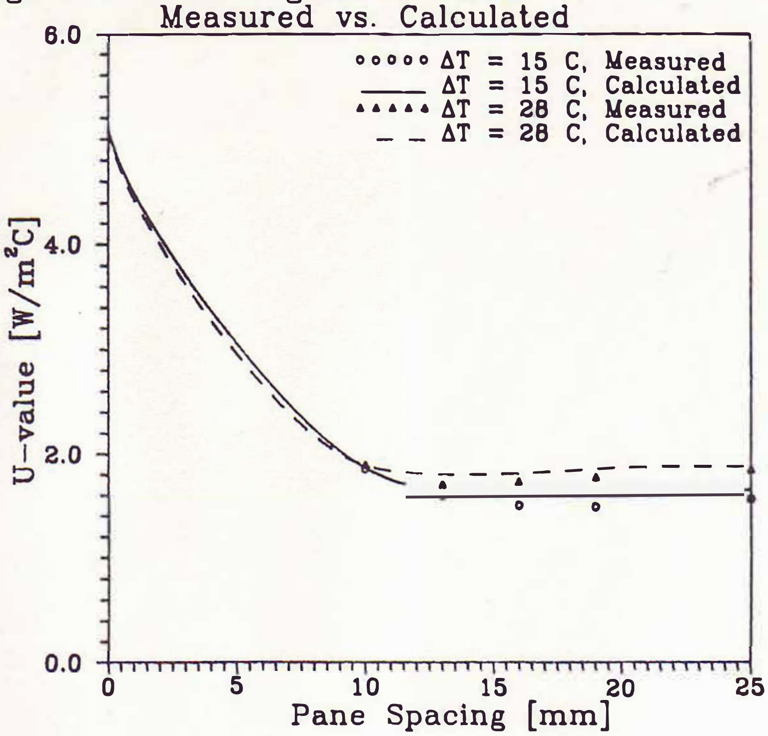


Figure 2: Calculated Centre-glass U-value
Double Glazed Systems

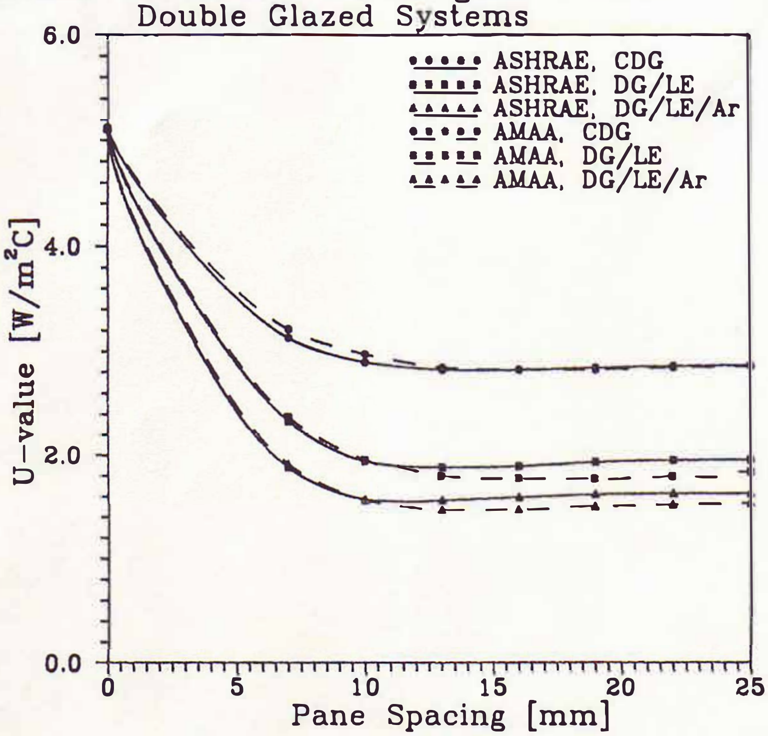


Figure 3: Calculated Centre-glass U-values Double, Triple and Quadruple Systems

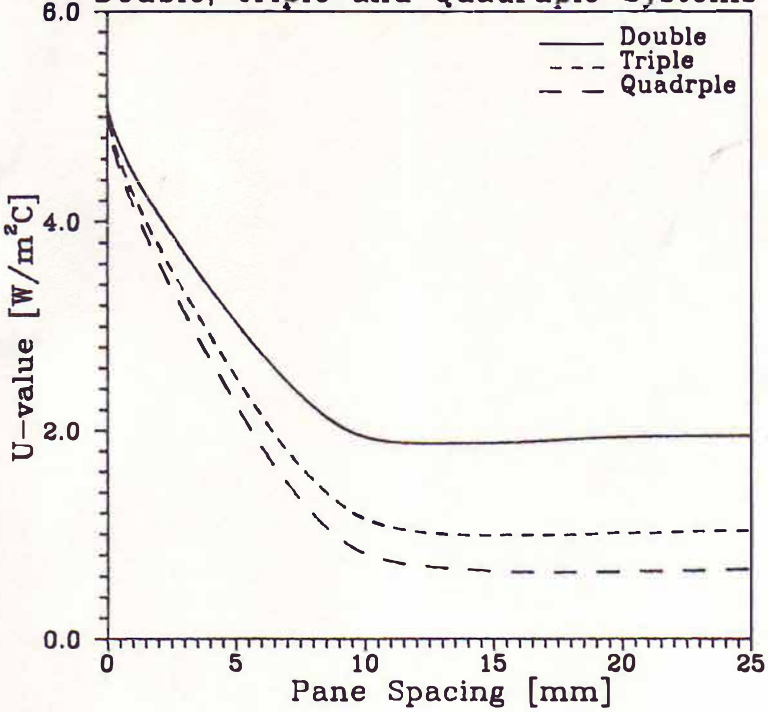


Figure 4: Calculated Overall U-value - Double Glazed Systems with Wood Frames

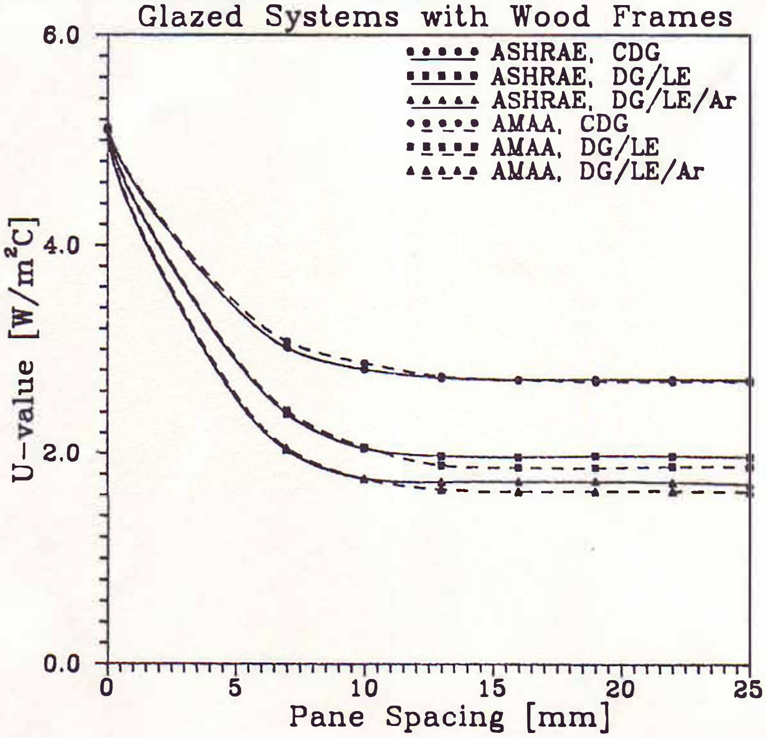
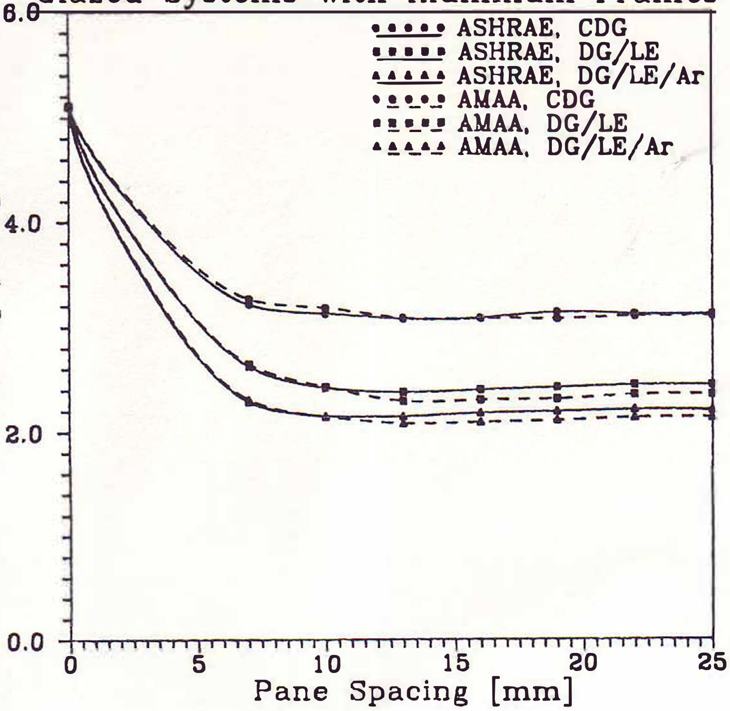


Figure 5: Calculated Overall U–value – Double Glazed Systems with Aluminum Frames



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