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How Are U on Your R's?

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Introduction

Many HVAC engineers have cut their teeth on calculating R-Values (1), and for some situations the cornerstone of successful designs rests on good assessment of these values. In the past 20 years BRANZ has conducted hundreds of measurements of R-Values (2 - 6) for a wide range of materials and structures, and maintained close contact with corresponding overseas work in Australia, Canada, USA. This has taken the subject of R-Value estimation much further than used to be possible, and simple calculations can now deal quite well with many masonry (7) and metal framed structures (2, 3, 4, 6), as well as timber framed structures (3, 5).

At the same time, client demands for accuracy and for construction cost savings are becoming more stringent, as are demands for supporting evidence for use in contracts and building consents. This paper attempts to outline the kinds of calculations which can be done, discusses some problem areas and some techniques to apply to them, and a review of the accuracy which can be expected from them. It also looks at the effects of workmanship, and which factors to worry about.

Simple R-Values

The R-Value for a simple layered structure is easy to calculate, using the well known formulae (1) and (2):-

For any layer, $R_{layer} = l/k$ $m^2 \cdot {}^\circ C/W$ (1)

For a structure, $R_{tot} = \sum R_{layers}$ $m^2 \cdot {}^\circ C/W$ (2)

where: l = layer thickness, m
k = layer conductivity, W/m.°C

There isn't really a whole lot to add to this, except for some useful tricks like estimating temperatures partway through a structure by proportioning the R-Values. The neat simplicity of this begins to break down, however, when thermal bridges occur, as they do in many actual cases.

Thermal Bridging

Engineers are generally aware of thermal bridges. But perhaps it is thought that thermal bridges are minor reductions in the R-Value ratings which can be ignored by 'real' engineers. For low R-Values this is true and for building applications where the envelope conductance is a small part of the total loads, it is also a reasonable attitude for plant sizing purposes.

At higher R-Values thermal bridging becomes increasingly dominant. In high-R applications (eg. freezer stores) it is so important to avoid thermal bridging that whole new systems of preformed insulating panels have been developed, with very little thermal bridging. At higher R-Values, the effect of any bridging becomes progressively stronger, to the point that without attention to thermal breaks, the R-Value may turn out to be only a fraction of the 'ideal' value ('ideal' means with no losses from thermal bridging). As a rough rule, metal framed construction without a thermal break will need derating by about 50 %. And that is not the worst you can get.

Figure 1 shows a comparison of the measured with 'ideal' values, from Ref. (6), for a collection of published cases for 84 actual walls and roofs:

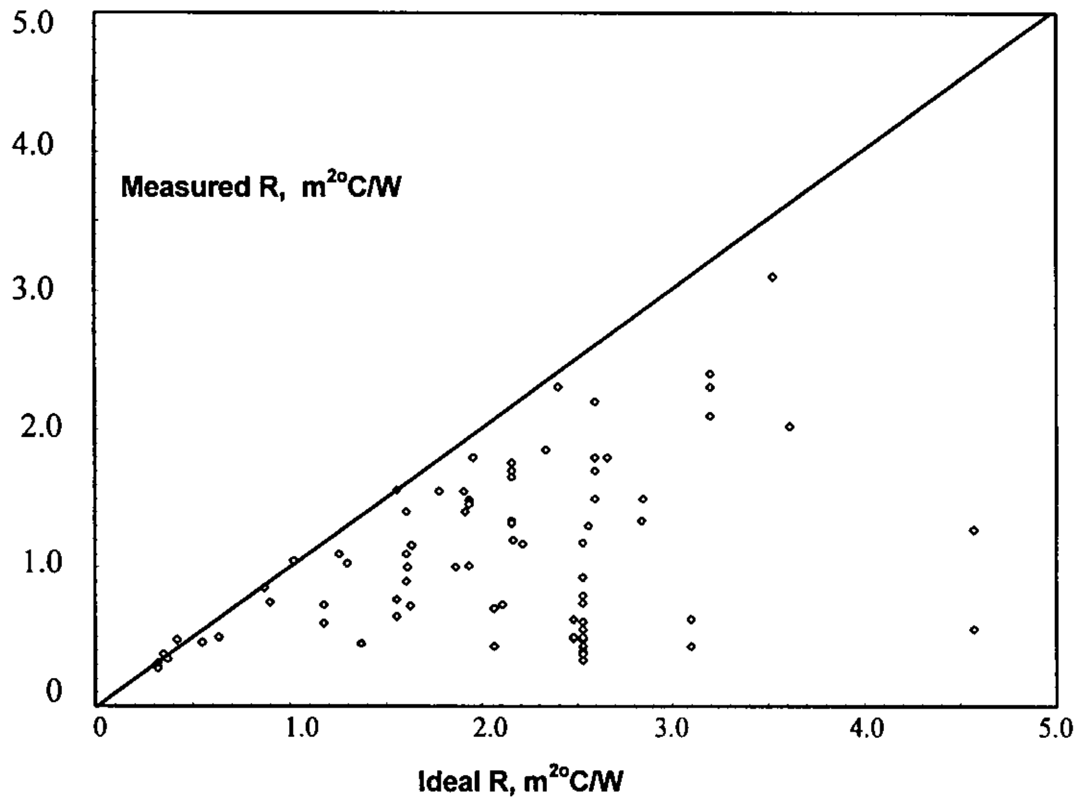

FIGURE 1: Measured v 'Ideal' R-Values for 84 published cases (6)

Better R Assessments

If you want better R-Value estimates, what do you do? Precision finite-difference computer analyses can be very useful, but in the end measurement is needed to show whether all the factors affecting heat losses have really been taken into account properly. For day-to-day practical work, there are two simple calculation methods - the "Isothermal Planes" method, and the "Parallel Flow" method. They both use the same formula, but it is applied in a slightly different way. Figure 2 illustrates the difference, using a masonry block wall as an example.

The Isothermal Planes method calculates the R-Value for the thermally bridged zone by area weighting, and then adds on the R-Values for the layers outside that. The Parallel Flow method calculates the whole wall R-Value for each zone, and then area-weights the result of that. Although these two sound very similar, they sometimes give similar answers and sometimes widely different answers. So which is right?

When the two methods give similar answers, they are probably both right. If they differ, the Isothermal planes method (which gives lower R-Values) is more likely to be right. It doesn't over-rate, and is seldom badly conservative. The bit of conservatism it has is often a useful margin for the things which may go wrong on site. In some cases the Parallel Flow method does give grossly over-optimistic results and is quite unable to handle things like metal framing. With good planning the Isothermal Planes method can be effectively used to forecast the effect of typical workmanship defects.

Both methods are based on area weighting. The Isothermal Planes Method applies the weighting across the bridged zone only, and the Parallel Flow Method applies it across the whole panel. If there are several zones, as in Figure 2, and the area fraction of the zones are f1, f2, f3..., and the thermal resistances in the zones are R1, R2, R3... then the effective R-Value R_b of the system is:

$$R_b = 1/\left[\frac{f_1}{R_1} + \frac{f_2}{R_2} + \frac{f_2}{R_2} + \ldots \right] \qquad (3)$$

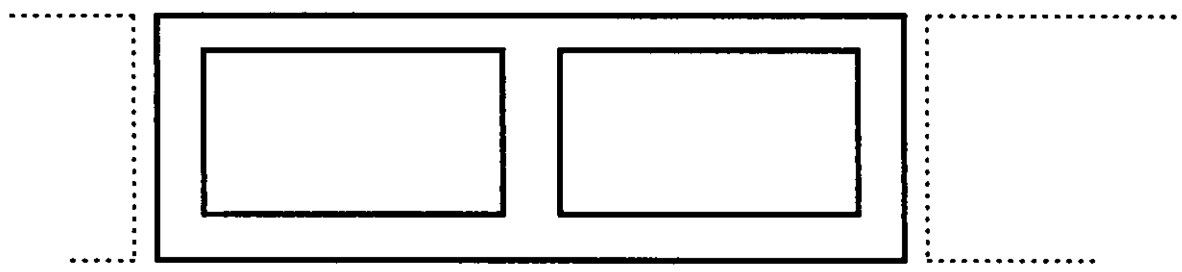

FIGURE 2a: A masonry wall outline

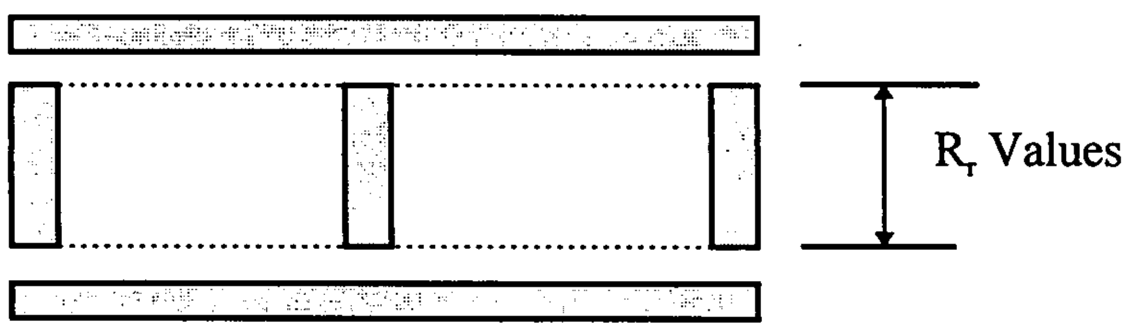

FIGURE 2b: Isothermal Planes method

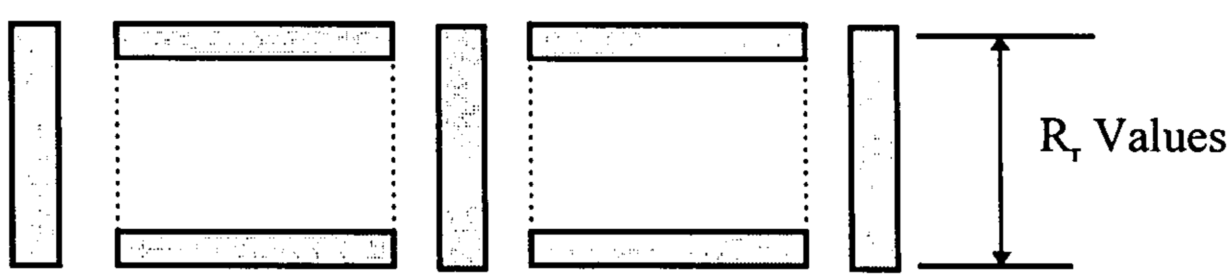

FIGURE 2c: Parallel Flow method

Several important aspects of heat transfer need consideration in applying equation (3). One is that each thermally bridged zone must finish on a complete surface. The surface may be only a membrane, but it must have no breaks or gaps.

Two issues concern metal frames. The first is the contact resistance between the frame and the facing. All materials in contact have some contact resistance, usually minute. A typical value for building materials in contact is 0.03 $m^{2}\cdot{}^{o}C/W$, but it can go down to 0.02 $m^{2}\cdot{}^{o}C/W$ or up to 0.06 - 0.08 $m^{2}\cdot{}^{o}C/W$. These values are so small that they have no significance, except when they occur in series with the even lower thermal resistance of the frame itself. The second issue concerns the shape of the frame section. Heat flows through the web portion of the metal, but it transfers to the facing via the flange, which might be 20 - 50 times larger. This creates a real difficulty, which can be solved by a transformation as in Figure 2 (d).

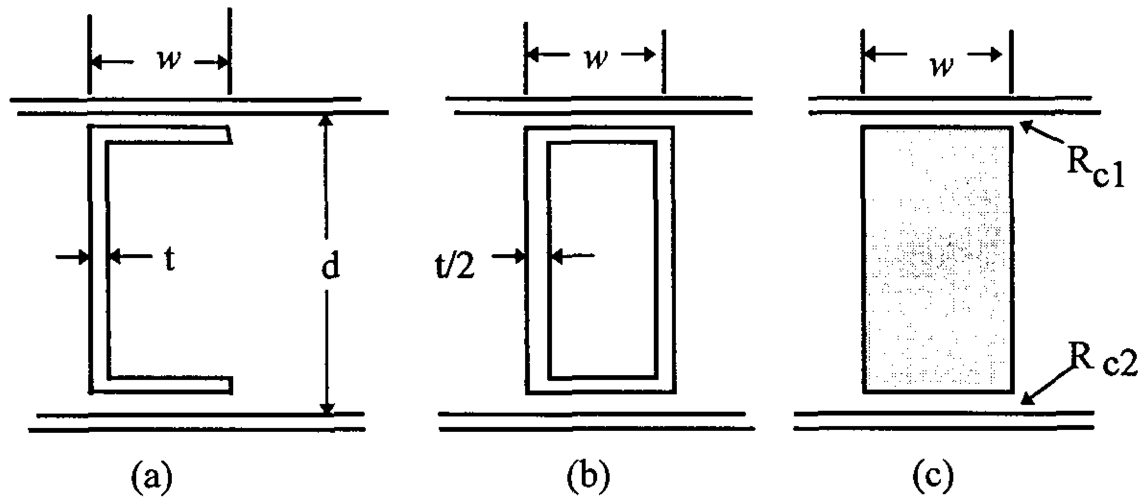

FIGURE 2(d): Transformation to a standard shape.

The series resistance of unit area of metal of conductivity k_m is d/k_m. The resistance of the equivalent shape is $(\frac{w}{t}).(\frac{d}{k_m})$. The "effective resistance" of the whole metal frame is:

$$Re = \frac{w.d}{t.k_m} + R_{c1} + R_{c2} \quad (4)$$

where R_{c1} and R_{c2} are the contact resistances between metal frame and facing.

Bright metal surfaces lose their reflectivity instantly on getting the first trace of condensation, even before the condensation becomes visible (1). This can happen any time when there is a bright metal finish on the cold side.

A further problem arises from convective bypassing of the insulation (5). This is possible wherever the insulant has an air cavity on both sides, and the results are shown in Figure 3. In a ceiling, insulant laid over battens can tolerate edge gaps of only about 3 or 4 mm before the R-Value suddenly drops catastrophically to about 50% of its original value. In walls this is even worse, and edge gaps too small to see (< 1 mm) will do the same thing - see Figure 3.

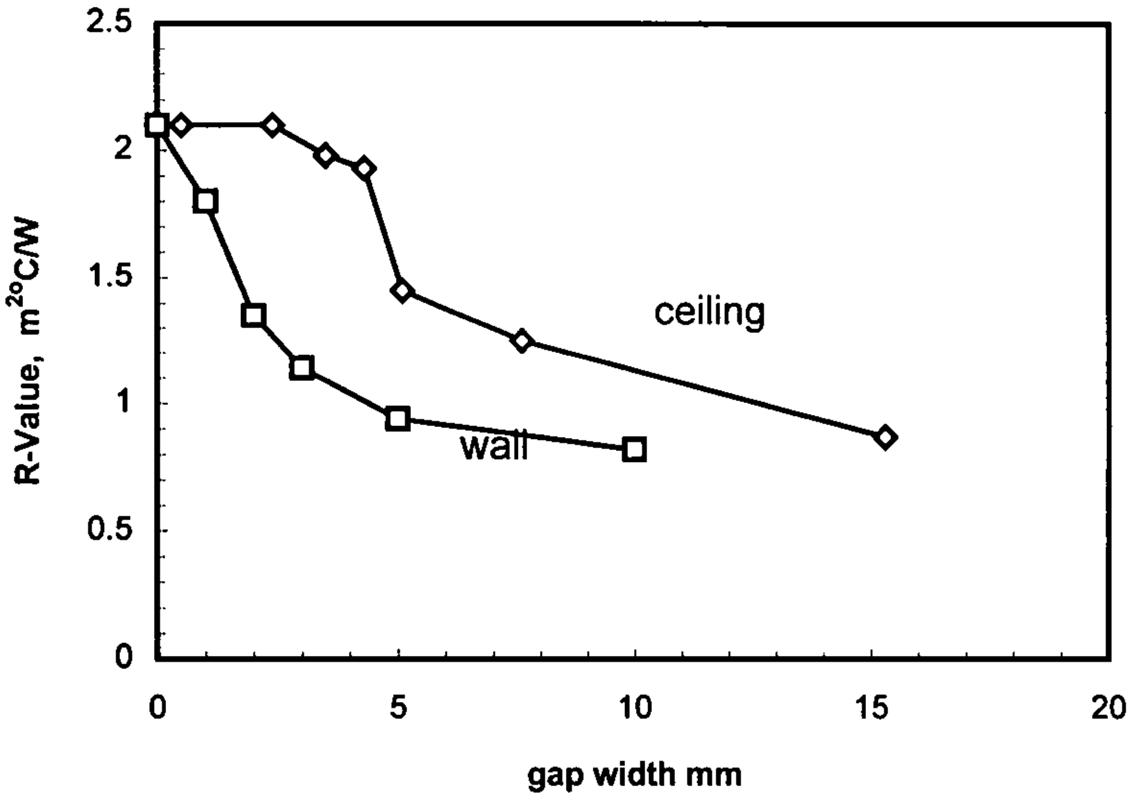

FIGURE 3: Effect of convective bridging v edge gaps on ceilings and walls

Thus there are a number of situations where there are important design decisions which greatly alter the influence workmanship factors may have on the R-Value achieved on site, with the same materials. Ref (6) lists a set of rules which BRANZ recommends for doing these calculations. The agreement that can be obtained with measured values is shown in Figure 4. Getting this quality of agreement needs particular care, but Figure 4 shows that forecasts within ~ 10% can be obtained over a wide range of R-Values, in timber framed, metal framed, and masonry constructions. However masonry is more difficult because the geometry is usually complicated.

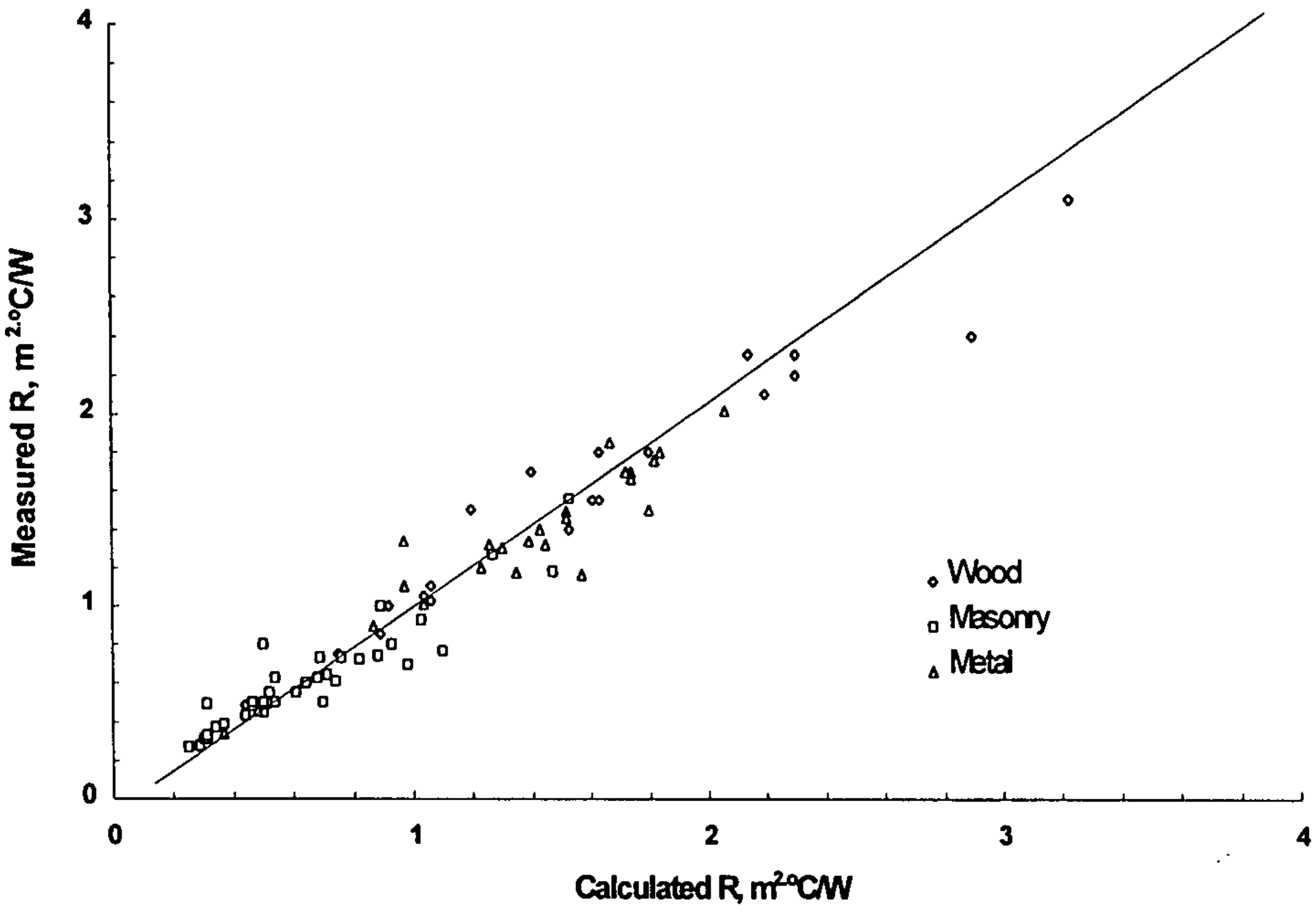

FIGURE 4. Measured v Calculated R-Values ($m^{2 \cdot o}C/W$), for 84 published cases (Isothermal Planes method).

Workmanship Errors

Some of the factors that undermine the achieved R-Value are now well known. Many are detailed in Ref (4, 6), and can be summarised as in Table 1. This uses a concept of "insulation efficiency", ie, the ratio of the actual R-Value to the 'ideal' R-Value with no thermal bridging or other losses.

Table 1 actually comes from published measurements (6), but it could be forecast reasonably well by the Isothermal Planes method. The insulation efficiencies in Table 1 vary with the insulation level, and should be treated as indicative only.

Feature	Details	Insul. Efficiency
Edge gaps	No edge gap	95 %
	10 mm around each frame cavity	73 %
Convection bridging	No edge gap	95 %
(these losses switch on	Ceilings, gap > 4 mm	50 %
quite suddenly)	Walls, gap > 0 mm	50 %
Omitting thermal break in steel	No thermal break	50 %
	With 10 mm thermal break	80 %
Effect of steel section	C-Section	53 %
	Z-Section	55 %
	S-Section	51 %
Contact resistance, steel section	gap ~ 1mm	77 %
	gap ~ 2 mm	61 %
Effect of steel thickness	1.2 mm steel	62 %
	0.8 mm steel	61 %
Effect of omitting insulation	insulated within stud	77 %
inside steel	not insulated within stud	75 %

TABLE 1: Some typical values of insulation efficiencies for various workmanship details.

Moisture Control

One of the main reasons for interest in the details of thermal insulation imperfections is that they can produce various moisture effects, including condensation, pattern staining, mildew growth or increased house dust mite activity. The reason for this is evident directly on the psychrometric chart. To a large extent, nearby surfaces will be at similar moisture contents (or absolute humidity). Therefore any point which is cooler must and usually does have higher local RH.

Pattern staining gives a very direct illustration of this. **Uninsulated** walls which show pattern staining are darker (mildewed) **between** the framing, on the cooler parts. **Insulated** walls which show pattern staining are darker **on** the framing, which is then the coolest part.

A useful concept here is that of the **Temperature Index** (8). This term is just a normalised temperature difference ratio, but it can also be converted into R-Value form:-

$$\text{Temperature Index,} \quad TI = \frac{(T_s - T_0)}{(T_i - T_0)} = \frac{R_l}{R_s} \qquad (4)$$

T_i = indoor temperature
T_0 = outdoor temperature
T_s = indoor surface temperature
R_s = standard rated R-Value, including surface resistance
R_l = local R-Value at a point, excluding surface resistance

A high TI value indicates that the winter indoor surface will be nearly as warm as the indoor space, but a low one indicates that the indoor surfaces will be cool. The risk of growing mildew on indoor surfaces is broadly linked to the TI, and values of 0.8 or more will rarely give trouble, but values below 0.6 are likely to.

Conclusions

The humble R-Value carries a lot of information about how buildings will behave, well beyond what many people expect of this simple parameter.

In cases where only moderate insulation levels are sought, thermal bridges do not much undermine the R-Values obtained. But as the insulation level increases, thermal bridging becomes a dominating influence, especially with metal-framed structures, where thermal breaks become essential. This arises both for performance and for economy reasons, since bridging effectively wastes half or more of the insulation value, and the cost of this can become quite high.

Metal-framed walls must have a thermal break if they are to perform properly.

Simple hand calculation methods can still give good indications of the likely achieved R-Values, but the Isothermal Planes method must be used. The use of the Isothermal Planes method also allows many workmanship defects to be assessed.

Avoiding thermal weaknesses is necessary to properly protect against mildew and condensation problems on building linings.

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