Annex 1

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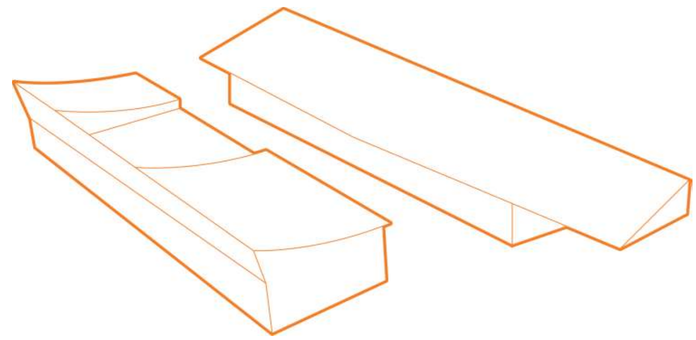

REVIEW OF GBI GUIDEBOOK ON ROOF U-VALUE CALCULATIONS

FINAL REPORT

SEPTEMBER 2023

ABOUT THIS REPORT

Title: Review of GBI Guidebook on Roof U-Value Calculations

Version: 3

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Revision Record:

Version 1 – Original version

Version 2 – Added explanation of how dust cover is modelled in AS/NZS 4859.2

Version 3 – Clarified Conclusion F regarding (i) the inclusion of insulation on top of the ceiling lining in most Australian roof systems, and (ii) the suitability of each suggested option to different types of practitioner.

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Executive Summary

This report contains a review of the *GBI Guidebook on How to Calculate Roof U-Values for Lightweight Roofs* (rev. 1, April 2020), undertaken by the Sustainable Buildings Research Centre (SBRC) at the University of Wollongong, Australia, for FMM-Malaysian Insulation Manufacturers Group (FMM-MIMG).

The review found that Tables A1 to A5 in the GBI Guidebook appear to be applicable in the Malaysian context, except that they only apply to unventilated cavities. On the other hand, Table B in the Guidebook does not appear to be applicable to the Malaysian context, at least not for the case-study roofs considered.

A more detailed summary of the key findings is presented below.

Tables A1 to A5 (Parallel-sided cavities)

A. The ASTM STP 1116 method used to calculate the nominal R-values of enclosed, parallel-sided cavities in Tables A1 to A5 produces very similar results to other standard calculation methods used for this purpose, including the method specified in AS/NZS 4859.2. The combination of this method with elements of AS/NZS 4859.2 in the GBI Guidebook is unlikely to have introduced significant error.

B. The most important limitation in the validity of values in Tables A1 to A5 is that they are based on measurements from completely enclosed (i.e. unventilated) cavities, whereas it is very uncommon for cavities in real roofs to be completely sealed. We recommend that users of the GBI Guidebook be mindful of this limitation.

C. While the GBI Guidebook does not contain any guidance for the treatment of ventilated, parallel-sided cavities, it is worth noting that the simplistic treatment of cavity ventilation in standards such as AS/NZS 4859.2 and ISO 6946 has been shown to not match reality in many situations, because it neglects any potential mitigation of solar gains and long-wave radiant cooling by cavity ventilation. Therefore, users of the Guidebook wishing to extend its use to parallel-sided cavities with ventilation should consider alternative methods, such as the thermal network model used in this study.

D. The footnote below Tables A1 to A5 (which suggests that the effective emittance of a cavity is approximately equal to the surface emittance of the lower emittance surface) does not appear to have been employed when producing the values in those tables. However, in this report we have demonstrated that this approximation can underestimate the R-value of high-emittance cavities by up to 8.70%. The error caused by this approximation is less significant for cavities with at least one low-emittance surface.

Table B (Roof spaces)

E. Tables of nominal roof space R-values such as Table B from the GBI Guidebook (which is a partial copy of Table 14 from AS/NZS 4859.2:2018) can only provide approximate estimates of the average effective R-value of a roof space. In reality, the effective R-value of such cavities changes over time, especially in the case of ventilated roof spaces.

F. Moreover, such tables of nominal R-values are likely to only be accurate for construction details and climatic conditions similar to those of the experiments from which the values were derived. This has been demonstrated in Section 3 of this report, where it was shown that while Table B suggests that ventilation *increases* the R-value of roof spaces (as it typically does in Australian roofs, with bulk insulation installed on top of the ceiling lining), a more sophisticated model predicts that ventilation would actually *decrease* the R-value of the GBI Guidebook example roofs under climatic conditions typical of Kuala Lumpur. Publications such as ASHRAE Fundamentals have moved away from the use of tables of nominal R-values for roof spaces for this reason. Possible solutions for the GBI Guidebook could be to develop a new table of roof space R-values tailored for typical Malaysian construction practices and conditions, or to specify that more sophisticated modelling is required—the former option is likely to be most suitable for adoption by building design practitioners, whereas the latter option is suitable for scientists with expertise in building physics.

G. The footnotes below Table B that define non-ventilated and ventilated roof spaces based on a threshold 'opening ratio' of 1:600 are, in our view, misleading. The IRC, on which the definition was based, specifies a threshold opening ratio of 1:300, where certain proportions of the total opening area must be located towards the top and bottom of the roof space.

H. Furthermore, to the best of our knowledge the combination of the IRC definitions of ventilated and non-ventilated roof spaces with the AS 4859.2 table of nominal roof space R-values has not been validated. In principle, we would support the use of the IRC definitions, since they are quantitative and clearly defined, whereas the definitions in AS 4859.2 are not. However, it should be noted that by combining elements from IRC and AS/NZS 4859.2 in this way, the GBI Guidebook is deviating from an exact adoption of the AS/NZS 4859.2 method.

I. The footnotes below Table B of the GBI Guidebook specify that "Non reflective surface has an emittance of greater than 0.05", whereas Table 14 from AS/NZS 4859.2 defines this threshold as 0.15. This may be a typographical error, or an intentional modification to align the GBI Guidebook with definitions in MS 2095. Either way, it represents another deviation from the AS 4859.2 method, which will impact roof spaces with surface emittances between 0.05 and 0.15.

Example Calculations in the GBI Guidebook

J. Comparison of R-values published in the GBI Guidebook example calculations with R-values generated using a more sophisticated thermal model demonstrated the magnitude of uncertainty in R-values produced using simple calculation methods such as those in the Guidebook (see Figure 1):
   - The Guidebook R-values for ventilated roofs with horizontal ceilings were within the range of R-values modelled for the same roofs, but were 8–39 % higher than the median modelled values;
   - The Guidebook R-values for unventilated roofs with horizontal ceilings were 21–34 % lower than the median modelled values; and
   - The Guidebook R-values for unventilated roofs with cathedral ceilings were 3–11 % lower than the median modelled values.

K. Modelling also demonstrated that the effects of ventilation are nonlinear. Even very small openings (e.g. 1 mm-wide slot openings along the high and low edges of a roof) can significantly impact the R-value of a roof, as compared to a completely sealed assembly. Such openings can be formed unintentionally, e.g. due to construction tolerances.

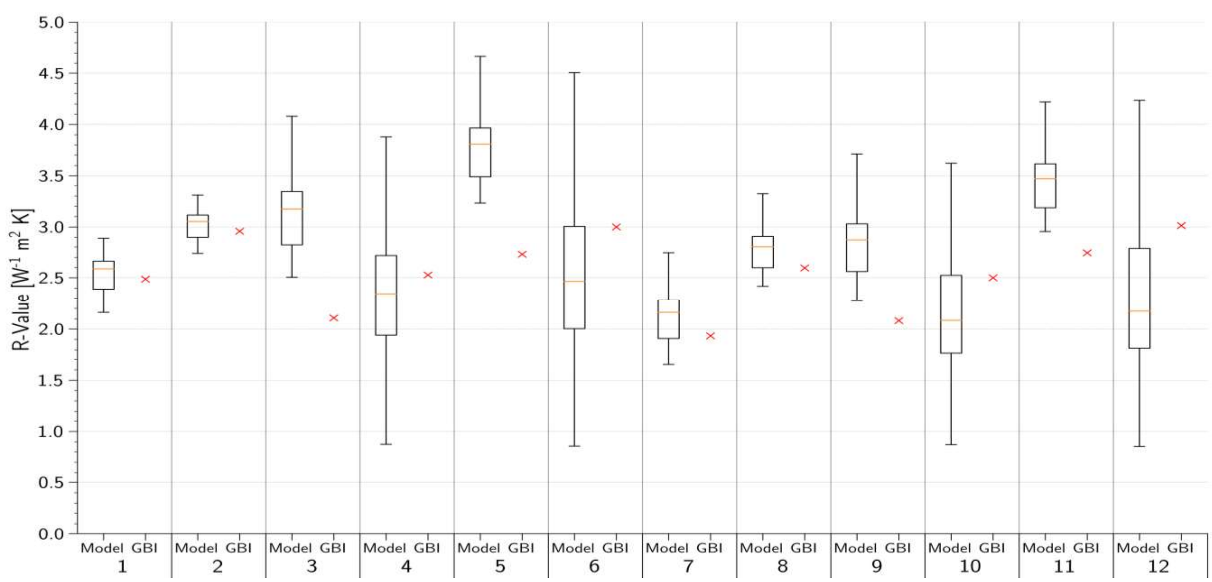

Figure 1 – R-values of the roof assemblies determined using the physics-based model compared with those in the GBI Guidebook for the 12 example roofs. Note that outliers have been removed for clarity.

List of Abbreviations

AS	Australian Standard
ASHRAE	The American Society of Heating, Refrigerating and Air-Conditioning Engineers
ASTM	American Society for Testing and Materials
ISO	International Organization for Standardization
NZS	New Zealand Standard
R-value	Thermal resistance, expressed in SI units [m^2 K W^{-1}]
SBRC	Sustainable Buildings Research Centre, at the University of Wollongong
SI	Système International
TMY	Typical meteorological year
U-value	Thermal transmittance, expressed in SI units [W m^{-2} K^{-1}]

Table of contents

1 Introduction

This report details the outcomes of the review of the "GBI Guidebook on How to Calculate Roof U-Values for Lightweight Roof" carried out by the Sustainable Buildings Research Centre (SBRC) at the University of Wollongong for FMM-Malaysian Insulation Manufacturers Group (FMM-MIMG). The review focussed on evaluating the validity and compatibility of the combination of calculation methods presented and applied to the example roofs in the guidebook.

This report also presents a comparison of roof R-values presented in the GBI Guidebook with values calculated using a physics-based model developed at the SBRC. This comparison covers each of the example roofs presented in the guidebook under climatic conditions typical of Kuala Lumpur.

1.1 BACKGROUND

Heat and mass transfer in roofs is highly complex, transient, and three-dimensional. The primary source of complexity comes from air-filled cavities in the roof assembly, where convection, radiation, and air exchange with the outdoor environment (i.e. ventilation) occur. When calculating the thermal resistance (R-value) or transmittance (U-value) of roofs, these processes within cavities are typically modelled in simplified ways, to facilitate more straightforward calculation. Such simplified methods can result in the unrealistic treatment of heat transfer processes (especially ventilation), may fail to capture the dynamic nature of the heat transfer process in reality, may be misapplied to situations for which they were not intended, and may be used in combination with other simplification methods that are incompatible.

This report examines the validity of the methods specified in the GBI Guidebook to calculate the R-values of roof spaces, evaluates the impacts of any simplifications made within those methods, and evaluates the applicability of the methods in the Malaysian context.

1.2 AIMS AND OBJECTIVES

The aim of this project was to review of the methods specified in the GBI Guidebook for the calculation of the R-values and U-values of roof assemblies.

In order to accomplish this aim, the following objectives were established:

1. Assess the overall approach for calculating the R-values of roof assemblies specified in the guidebook including the use and combination of different methods used.
2. Compare the R-values determined using the calculation methods in the GBI Guidebook with R-values calculated using a more realistic physics-based model.
3. Evaluate whether the calculation methods specified in the GBI Guidebook are applicable in the Malaysian context.

This report documents the work undertaken to achieve these aims and objectives.

2 Review of GBI Guidebook

The GBI Guidebook is composed of Tables A1 to A5, Table B, and a set of example R-value calculations for twelve roofs.

2.1 REVIEW OF TABLES A1 TO A5

Tables A1 to A5 contain tabulated data on the R-value of enclosed (i.e. unventilated), parallel-sided cavities under conditions typical of the Malaysian climate. Each of the five tables contains R-value data for cavities with internal surfaces that have a specific thermal emittance value (0.03, 0.05, 0.1, 0.5 or 0.9); data are presented for a range of cavity depths and orientations relative to horizontal. According to correspondence between GBI and FMM-MIMG (FMM-MIMG, 2021), these tabulated values were calculated using the calculation method in *ASTM STP 1116 Prediction of the Thermal Performance of Single and Multi-Airspace Reflective Insulation Materials*, developed by Desjarlais and Yarbrough (1991).

2.1.1 Validity of ASTM STP 1116 method used to calculate R-values of enclosed cavities in the GBI Guidebook

The ASTM STP 1116 method was developed based on experimental data reported by Robinson and Powell (1956). The method demonstrated close agreement with experimental data for cavities up to 3.5 inches (approximately 90 mm) deep. These data have been widely used in calculating R-values for airspaces with reflective boundaries, most notably the ASHRAE Fundamentals Handbook (ASHRAE, 2017; Yarbrough, 1983).

Several other standard methods have been developed to estimate the effective R-value of parallel-sided cavities, including those published in the Australian and New Zealand standard AS/NZS 4859.2 *Thermal insulation materials for buildings, Part 2: Design* (AS/NZS, 2018), and the international standard ISO 6946 *Building components and building elements – Thermal resistance and thermal transmittance – Calculation methods* (ISO, 2017). A comparison of R-values calculated using ASTM STP 1116, AS/NZS 4859.2, and ISO 6946 is presented for downward heat flow in horizontal and inclined ($\alpha = 20°$) cavities in Figure 2 and Figure 3, respectively. Values taken directly from the GBI Guidebook are also presented.

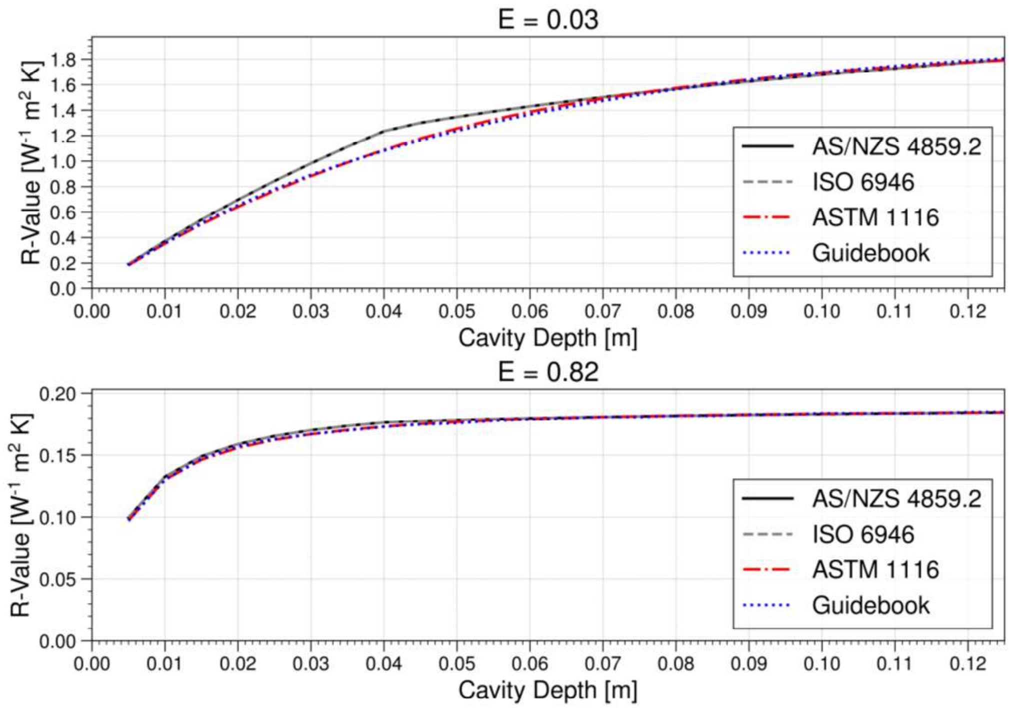

Figure 2 – Comparison of the R-value of enclosed, parallel-sided cavities as a function of cavity depth for downward heat flow in a horizontal cavity (α = 0°) for effective emittances of 0.03 (top), and 0.82 (bottom), calculated using several standard methods. Values from the GBI Guidebook have also been included for comparison.

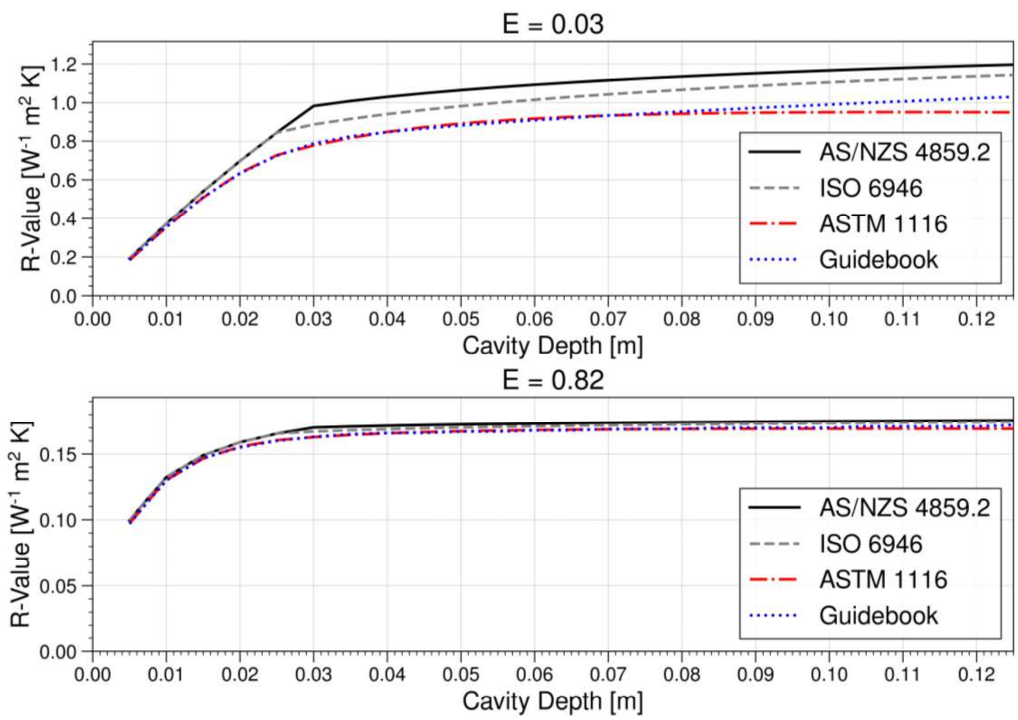

Figure 3 – Comparison of the R-value of enclosed, parallel-sided cavities as a function of cavity depth for downward heat flow in an inclined cavity (α = 20°) for effective emittances of 0.03 (top), and 0.82 (bottom), calculated using several standard methods. The values from the Guidebook have also been included for comparison.

For downward heat flows in horizontal cavities, each of the standard calculation methods predicts very similar R-values. For inclined cavities, the ASTM STP 1116 method predicts R-values approximately 10 % and 20 % lower than the ISO 6946 and AS/NZS 4859.2 methods, respectively. This can be partially explained by the different interpolation methods, but is also due to differences in the convection correlations used. There is a minor discrepancy between the ASTM STP 1116 method and the GBI Guidebook values above cavity depths of 0.09 m. The cause of this discrepancy is unclear.

Overall, the ASTM STP 1116 method for calculating R-values of parallel-sided cavities appears to be based on sound evidence, and produce very similar results to alternative methods in common use. However, there are limitations that should be borne in mind when using any of these simplified methods.

The primary limitation of such simplified calculation methods is that the values produced are only valid for completely enclosed (i.e. unventilated) cavities. Following typical construction practices, it is extremely unlikely that cavities in roofs would be completely unventilated, unless purposefully made airtight (e.g. using sealant, etc.). Even inadvertent gaps (such as 0.25 mm gaps at the edges of cladding sheets or under flashings) can provide significant levels of ventilation (Green & Cooper, 2020). Cavity ventilation can transport significant quantities of heat into and out of roofs, thereby impacting their thermal performance. This is explained further in Section 0.

In undertaking our review, we also noted that the ASTM STP 1116 method only enables calculations for three cavity orientations (0°, i.e. horizontal; 45°; and 90°, i.e. vertical) and for five heat flow directions: upward across a horizontal cavity, downward across a horizontal cavity, 45° upward, 45° downward, and horizontal across a 90° cavity. However, the values in Tables A1 to A5 are provided over a range of downward heat flow directions in 5° increments from 0° (vertically downward) to 90° (horizontal). It is suspected that these intermediate values were generated through linear interpolation, as suggested by Yam *et al*. (2020). This is similar to the interpolation methods specified in comparable standards. Whilst changes in the effective R-values of cavities caused by different inclination angles are likely to be non-linear, it is our view that linear interpolation between R-values for 0°, 45° and 90° is a reasonable approach for such simplified R-value calculations.

2.1.2 Error in approximating the effective emittance

In ASTM STP 1116, and AS/NZS 4859.2:2018, the effective emittance, E, of an airspace is calculated using Equation (1):

$$E = \frac{1}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1} \qquad \text{Equation (1)}$$

Where:

- E is the effective emittance of the two interacting surfaces (also known as intersurface emittance).
- ε_1 and ε_2 are the hemispherical emittances of the surfaces bounding the airspace, normal to the primary direction of heat flow.

Tables A1 to A5 of the GBI Guidebook are accompanied by the following note (Note that Equation 6.2(3) in AS/NZS 4859.2:2018 is identical to Equation (1).):

"ε is surface emittance. Effective emittance, E, is approximated as E=ε in most practical cases (see Equation 6.2(3) in AS/NZS 4859.2:2018)".

This note appears to imply that the tabulated data were calculated using the stated approximation, where ε is taken to be that of the low emittance surface, if present. However, review of the tabulated data indicates that this approximation was not used to generate the values in these tables. Therefore, we suspect that purpose of the footnote is to aid users of the guidebook in determining the appropriate table for their particular situation more easily.

Use of this approximation would introduce some degree of error. Figure 4 presents the relationship between surface emittance of one surface bounding the airspace, ε, and effective emittance, E, based on Equation (1), assuming that the other surface bounding the airspace has an emittance of 0.9. The error associated with using ε to approximate E is also presented.

For low-emittance surfaces ($\varepsilon < 0.15$), the maximum error is less than 0.0025 (2 %). However, the error increases significantly for high-emittance surfaces, where the error is 0.08 (10 %) at $\varepsilon = 0.9$. As the error is positive, the approximation overestimates the amount of radiative heat exchanged between the surfaces bounding the airspace, and therefore slightly underestimates the effective R-value of the cavity. Table 1 quantifies the impact of this approximation on the R-values of an unventilated cavity with various surface emittances. The values in Table 1 indicate that use of the approximation $E = \varepsilon$ can underestimate the R-value by up to 8.70 % for cavities with two high-emittance surfaces. The degree of underestimation is less significant for cavities with at least one low emittance surface.

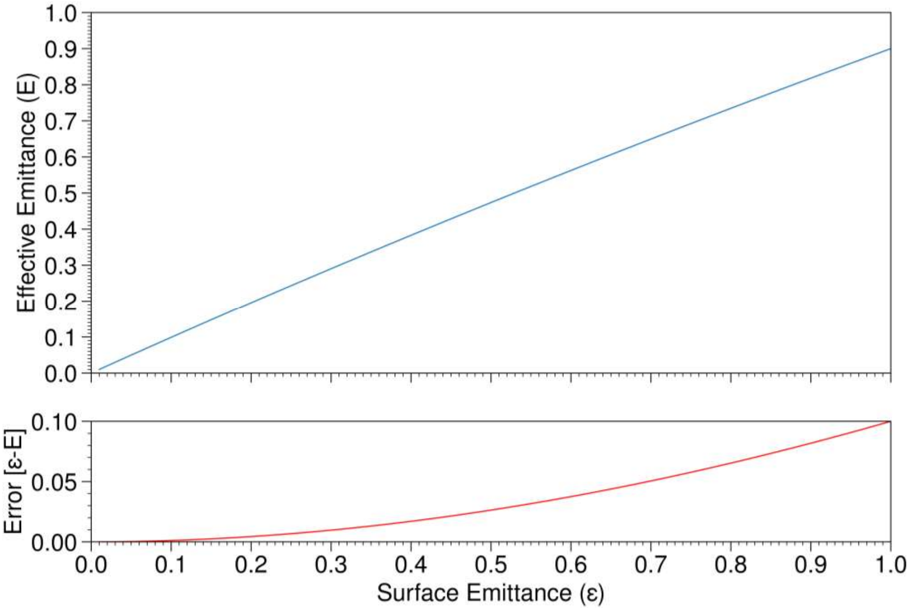

Figure 4 - Effective emittance (E) of an enclosed airspace as a function of the surface emittance (ε) of one side of the cavity, given the surface emittance of the second side is 0.9. The lower graph illustrates the error associated with using ε to approximate E.

Table 1 – R-values of an unventilated air cavity calculated using ASTM STP 1116, comparing values generated by the use of Equation (1) to calculate the effective emittance versus the approximation E= ε. When calculating E using Equation (1), it was assumed that ε_2=0.9. All values were calculated for downward heat flow with a cavity thickness of 0.10 m, a mean temperature of 27.5 °C, and a temperature difference of 15 °C.

Surface Emittance (ε_1)	**R-Value [m_2 K^{-1} W^{-1}] (E from Equation (1))**	**R-Value [m_2 K^{-1} W^{-1}] (E=ε_1)**	**Error [%]**
0.03	1.686	1.685	-0.06
0.05	1.398	1.395	-0.21
0.10	0.982	0.976	-0.61
0.50	0.301	0.287	-4.65
0.90	0.184	0.168	-8.70

2.1.3 Emittance value adjustments to account for dust cover

Dust cover on IR-reflective (low emittance) surfaces can increase the effective surface emittance and thereby increase rates of radiant heat transfer between that surface and its surroundings. AS 4859.2 models these effects by applying the following emittance adjustments to upward-facing horizontal and upward-facing inclined reflective surfaces:

- No dust cover – 0.00 to be added to the tested surface emittance;
- Slight dust cover – 0.05 to be added to the tested surface emittance; and
- Moderate dust cover – 0.25 to be added to the tested surface emittance.

The assumed level of dust cover (i.e. none, slight or moderate) is determined by the surface orientation and degree of cavity ventilation, as follows:

- Upward-facing surfaces (either horizontal or inclined) in unventilated airspaces (where the cavity is assumed to be fully sealed) are modelled with no dust cover.
- Upward-facing surfaces (either horizontal or inclined) in unventilated airspaces where no special precautions for the prevention of air ingress have been included are modelled with slight dust cover.
- Upward-facing surfaces of horizontal or inclined IR-reflective surfaces in well-ventilated airspaces are modelled with moderate dust cover.
- Vertical and downward-facing surfaces in unventilated, slightly ventilated, and well-ventilated airspaces are modelled with no dust cover.

The classification cavities as 'unventilated', 'slightly ventilated', or 'well-ventilated' in AS 4859.2 is described and discussed in Section 2.1.4, below.

2.1.4 Treatment of ventilated parallel-sided cavities in AS/NZS 4859.2

While the GBI Guidebook does not currently include instructions for calculating the R-values of ventilated parallel-sided cavities, a limitation in the method used to model such cavities in AS/NZS 4859.2 is worth noting, as explained below.

The calculation procedure for the R-value of ventilated cavities in AS 4859.2 was adapted from ISO 6946, and involves the classification of horizontal parallel-sided cavities with a length and width more than ten times the depth of the cavity as either 'unventilated', 'slightly ventilated', or 'well-ventilated', based on the total area of openings per square metre of the assembly (e.g. per square metre of roof).

- Unventilated' cavities are those with a maximum total opening area of 500 mm^2 per metre squared.
- 'Slightly ventilated' cavities are those with a total opening area between 500 mm^2 and 1500 mm^2 per metre squared.
- 'Well-ventilated' cavities are those with an opening area greater than 1500 mm^2 per metre squared.

The R-value of 'unventilated' cavities is calculated using a similar approach to ASTM STP 1116. The R-value of building assemblies with 'well ventilated' cavities is calculated by neglecting the R-value of the cavity and any material layers on the external side of the cavity, and the R-value of assemblies with 'slightly ventilated' cavities is calculated by linear interpolation between the 'unventilated' and 'well-ventilated' values.

Such treatment of ventilation in parallel-sided cavities has been shown to be inaccurate for many realistic scenarios (Green & Cooper, 2020). The assumption that cavity ventilation always reduces the effective R-value of the assembly does not take into account the ability of ventilation to mitigate solar gains during the daytime and longwave night-sky cooling during the nighttime. When these effects are included in a calculation, cavity ventilation has been demonstrated to increase the effective R-value of the building assembly in Australian case studies (Green & Cooper, 2020).

Moreover, cavity ventilation is a dynamic process so its effects on the thermal performance are not constant (as is the case for bulk insulation). Ventilation rates in the cases considered by Green & Cooper (2020) were typically higher during the day, when solar heat gains caused buoyancy-driven flow through the cavity. Ventilation rates can also be significantly affected by wind speed and direction depending on the location of openings.

2.1.5 Applicability of Tables A1 to A5 to the Malaysian context

The values in Tables A1 to A5 have been calculated for downward heat flow with a mean temperature of 27.5 °C and a temperature difference of 15 °C across the cavity. While such temperatures are likely to vary in reality in response to local indoor and outdoor conditions, for the purposes of defining a single set of boundary conditions to rate the R-value of the cavity, these values appear to be suitable for Malaysia. The difference between using temperature-dependent boundary conditions versus a single-set of parameters is discussed further in Section 3.3.

2.2 REVIEW OF TABLE B

Table B of the GBI Guidebook provides R-values for cavities formed between horizontal ceilings and pitched roofs (i.e. 'attic spaces' or 'roof spaces'). Table B is an adapted version of Table 14 from AS/NZS 4859.2:2018, with the only difference between the tables being that Table B only includes the values for downward heat flow (typical of summer conditions in Australia, or year-round conditions in Malaysia).

Table 14 in AS/NZS 4859.2 originates from the AIRAH Technical Handbook (AIRAH, 2013). While the source of the data is not specified in the AIRAH Handbook, the handbook states the following:

"*The insulation rating [of airspaces] cannot be easily calculated except for parallel-faced still air cavities, and this value depends on the mean airspace temperature, infrared emittance, and surface temperatures. Historical values (as listed) are often used for calculations, but research is needed to update these values for modern construction.*"

Therefore, the data in the table are likely to be based on historical experimental measurements (e.g. those by Joy (1598)). However, the details of those experiments could not be located.

2.2.1 Validity of R-values specified for roof spaces

Heat transfer through a roof space is much more complex than heat transfer through solid building elements and enclosed, parallel-sided air cavities. Convection and radiation heat transfer processes interact to produce a net heat transfer rate across the roof space, and air exchange between the roof space and the outdoor environment (i.e. ventilation) can transfer significant quantities of heat to or from the space. Importantly, these processes are also transient. The result of such complex heat and mass transfer processes in the roof space is that the effective R-value of the roof space can vary significantly, depending on the boundary conditions and roof construction details. Therefore, tables of nominal R-values such as Table B in the GBI Guidebook provide an approximate single-value estimate of roof space R-value do not capture the complex and dynamic nature of heat transfer in the roof space that would occur in reality.

The limitations of single-value R-values for roof spaces are acknowledged in documents such as ASHRAE Fundamentals (ASHRAE, 2017), where previous editions had included tables of nominal R-values for roof spaces, a note is now published stating the following:

"During sunny periods, unconditioned attics may be hotter than outdoor air. Peak attic temperatures on a hot, sunny day may be 10 to 45 K above outdoor air temperature, depending on factors such as shingle color, roof framing type, air exchange rate through vents, and use of radiant barriers. Therefore, simple one-dimensional solutions cannot be offered for attics."

The R-values for “irregular airspaces” presented in Table 14 of AS/NZS 4859.2 and Table B of the GBI Guidebook correspond closely to R-values published in similar sources, such as previous editions of the ASHRAE Fundamentals Handbook (ASHRAE, 2001). The values are likely to be accurate for the specific roof configurations and conditions matching the experiments on which the R-values were originally based. However, users of such R-values should understand that they are unlikely to be accurate for all roof constructions, or conditions.

2.2.2 Comparison of footnotes in Table B with AS/NZS 4859.2

The footnotes published with Table B in the GBI Guidebook do not match those published with Table 14 of AS/NZS 4859.2:2018. In both tables, the footnotes provide clarification on how to classify roof spaces based on the degree of ventilation and thermal emittance of surfaces bounding the roof space. Differences between the two sets of footnotes can be summarised as follows:

1. In categorising roof spaces as either “IR reflective” or “IR non-reflective”, both sources specify that surfaces with emittance less than 0.05 are reflective, and surfaces with emittance greater than 0.15 are non-reflective. However, AS/NZS 4859.2 specifies that linear interpolation should be used between these two values, whereas the GBI guidebook specifies that surfaces with emittance between 0.05 and 0.15 should be treated as non-reflective. This difference could have been caused by a typographic error when transcribing the table notes into the GBI Guidebook.
2. In categorising roof spaces as either “ventilated” or “non-ventilated”, AS/NZS 4859.2:2018 states that roof spaces with continuous cover (such as metal or sarked tile roofing) and no specified provision for ventilation should be treated as “non-ventilated”, whereas the GBI Guidebook specifies that “non-ventilated” refers to roof spaces with an “opening ratio” (typically defined as the ratio of total opening area to total ceiling area) less than 1:600. This raises two issues:
    a. The GBI Guidebook cites the 2015 International Residential Code (IRC) for this provision. However, the 2015 IRC actually specifies that a roof space requires a minimum opening ratio of 1:300 to be considered ventilated in warm climates, with between 40% to 50% of the opening area positioned near the upper portion of the roof space and the balance of ventilation air provided from openings located in the lower third of the space (IRC, 2021). Based on correspondence between GBI and FMM-MIMG (FMM-MIMG, 2021), we are of the understanding that that the minimum opening ratio of 1:600 provided in the footnotes of Table B is intended to refer to the

separate opening ratios of inlets and outlets. However, this is not stated clearly in the GBI Guidebook.

b. The combination of a ventilation categories from the IRC and roof space R-values from AS 4859.2 does not appear to have been validated.

2.2.3 Applicability of Table B to the Malaysian context

The modelling presented in Section 3 investigates the thermal performance of the example roof assemblies from the GBI Guidebook under climatic conditions typical of Malaysia. This analysis provides further insights into the effective R-values of Malaysian roof spaces, and the applicability of values in Table B to that context.

3 Comparison with Physics-Based Model

3.1 INTRODUCTION

To assess the accuracy of the combination of calculation methods specified in the GBI Guidebook under Malaysian conditions, including the accuracy of the example calculations of twelve roofs, a thermal network model was developed to calculate steady-state heat transfer and ventilation air flow through a roof.

3.2 METHODOLOGY

3.2.1 Model description

The thermal network model was developed to calculate the quasi-steady heat and mass flow through a roof system exposed to realistic outdoor boundary conditions. It combines a thermal network that includes separate convection, conduction, solar heat gains, and long-wave radiant heat transfer where appropriate, with a flow network model that calculates ventilation flow rates by finding equilibrium between the driving pressures created by buoyancy and wind, and the aerodynamic resistance posed by ventilation openings and other constrictions in the flow path. Figure 5 illustrates the model heat and mass transfer paths.

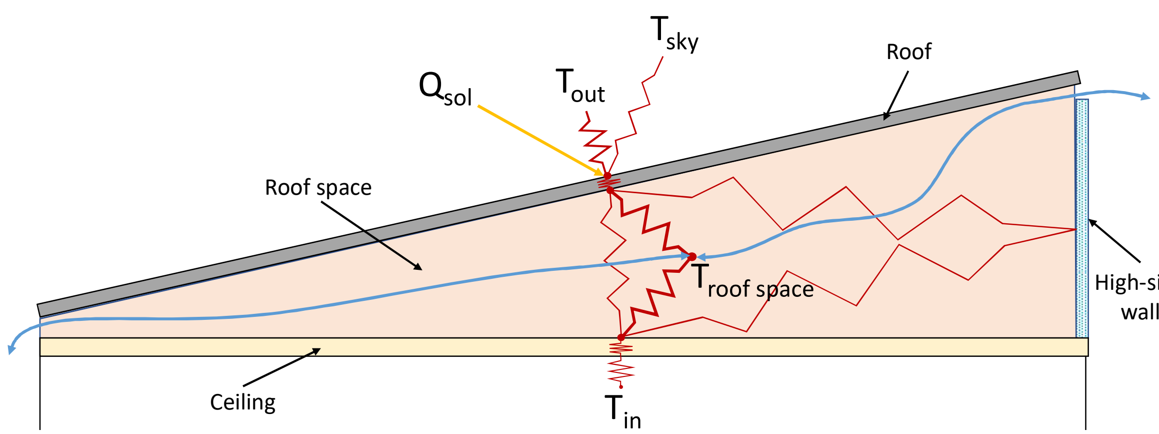

Figure 5 – Schematic diagram of the thermal network model, as it was applied to a skillion roof with a horizontal ceiling. Conduction and convection heat flow paths are shown in bold, red lines. Radiation heat transfer paths are shown in narrow, red lines. Solar radiation incident on the rooftop is shown in yellow. Ventilation air paths through openings into the roof space are shown in blue.

The advantages of this type of model over the more simplistic calculations specified in standards such as AS/NZS 4859.2, and the GBI Guidebook, are as follows:

1. Interaction with the outdoor environment includes separate solar gains, convective heat transfer, and long-wave radiant heat transfer, so the model is able to calculate the impacts of cavity ventilation on the overall roof effective R-value more accurately.
2. Cavity ventilation rates are modelled based on established fluid mechanics theory (which is often used to model natural ventilation of indoor spaces, for example), and are therefore sensitive to the modelled construction details (e.g. opening sizes) and boundary conditions (e.g. outdoor weather).
3. Heat transfer within roof spaces formed between pitched roofs and horizontal ceilings (as drawn in Figure 5) does not rely on tables of nominal R-values such as those in Table B of the GBI Guidebook; instead, radiation, convection and ventilation processes are modelled separately within such cavities.

Other than these differences, the thermal network model is essentially the same as the simplified calculation methods specified in AS/NZS 4859.2 and the GBI Guidebook. Heat transfer through solid components (e.g. a plasterboard ceiling lining, or bulk insulation) was modelled as one-dimensional conduction, based on the thickness and thermal conductivity of the component. Heat transfer between the ceiling and indoor air was modelled with a constant combined convection-radiation heat transfer coefficient of 6.25 W m^{-2} K^{-1}, taken from the GBI Guidebook. Heat transfer between the roof top surface and outdoor air was modelled with a constant convection heat transfer coefficient of 22.7 W m^{-2} K^{-1}, also taken from the GBI Guidebook. The thermal resistance of unventilated, parallel-sided cavities was calculated using the ASTM STP 1116 method, but importantly it was recalculated for each set of conditions investigated (i.e. for each example roof at each timestep) and therefore could vary in response to changing surface temperatures.

Quasi-steady ventilation was modelled in roof spaces that included openings. Air in the roof space was assumed to be ‘well-mixed’ (i.e. effectively isothermal). Wind and buoyancy pressures were calculated at each opening to determine the ventilation rates in the roof space. The flow through each opening was given by Equation (2):

$$V = C_d A \sqrt{\frac{2(\Delta P_w + \Delta P_b)}{\rho}} \qquad \text{Equation (2)}$$

Where:

- V is the volumetric flow rate (m^3 s^{-1})
- C_d is the discharge coefficient of the opening
- A is the opening area (m^2)

- ΔP_w is the pressure difference exerted across the opening by wind
- ΔP_b is the pressure difference exerted across the opening by buoyancy
- ρ is air density (kg m^{-3})

The driving pressure due to wind (ΔP_w) was calculated at each opening using the expression:

$$\Delta P_w = \frac{\rho {U_h}^2}{2} C_p \qquad \text{Equation (3)}$$

Where:

- U_h is wind speed at the height of the low side of the roof (m s^{-1})
- C_p is the wind pressure coefficient at the opening.

U_h was determined from the reference wind speed measured 10 m above the ground in open terrain (U_{ref} in the climate file) using the power-law representation of the atmospheric boundary layer velocity profile given by Equation (4) (Pinon et al., 2004), with the assumption that the building under investigation was single-storey and in an urban setting.

$$U_h = 1.6\, U_{ref} \left(\frac{h}{370}\right)^{0.22} \qquad \text{Equation (4)}$$

The wind pressure coefficient, C_p, at each opening was determined from the wind direction (in the climate file), wall orientation, and spatial distributions of wind pressure coefficients proposed by Pinon *et al.* based on a low-rise cube-shaped building.

The buoyancy pressure (ΔP_b) at each opening was calculated using Equation (5):

$$\Delta P_b = \rho g \beta (T_o - T_a)(h - NPL) \qquad \text{Equation (5)}$$

Where:

- g is acceleration due to gravity (m s^{-2})
- β is the thermal expansion coefficient of air
- T_o is the outdoor air temperature (°C)
- T_a is the roof space air temperature (°C)
- h is the height of the opening (m)
- NPL is the height of the neutral pressure level (NPL) (m).

The height of the neutral pressure level was calculated iteratively, by solving for the mass balance of air entering and exiting the roof space (i.e. the sum of flows into the roof space equals the sum of flows out of the roof space).

Coupling of the flow network and thermal network models also required an iterative solution process, since ventilation rates impact temperatures within the network, and temperatures impact the ventilation rate.

3.2.2 Cases Investigated

The 12 roofs used in the example calculations provided in the GBI Guidebook were modelled using the physics-based thermal model. The parameters provided in the GBI Guidebook for each of these cases are provided in Table 2.

All roofs were modelled as skillion roofs oriented to face south on a single-storey building. It was assumed that the roof spanned 8 metres and did not have eave. The solar absorptance of the roof top surface was assumed to be 0.6, and the thermal emittance of the rooftop surface was assumed to be 0.9.

Table 2 – Roof parameters of the 12 examples cases provided in the GBI Guidebook.

Name	Thermal resistance [W^{-1} m^2 K^1]			Cavity depth [m]		Effective emittance		Roof pitch [°]	Ceiling type	Ventilated
	Cladding	Radiant Layer	Ceiling	Cavity 1[1]	Cavity 2[2]	Cavity 1[1]	Cavity 2[2]			
Example 1	2.10×10^{-5}	0.15	0.048	0.025	0.075	0.03	0.03	5	cathedral	FALSE
Example 2	1.39	0	0.048	-	0.075	-	0.03	5	cathedral	FALSE
Example 3	2.10×10^{-5}	0	0.048	0.025	roof space	0.03	0.03	5	horizontal	FALSE
Example 4	2.10×10^{-5}	0.15	0.048	0.025	roof space	0.03	0.03	5	horizontal	TRUE
Example 5	1.39	0	0.048	-	roof space	-	0.03	5	horizontal	FALSE
Example 6	1.38	0	0.048	-	roof space	-	0.03	5	horizontal	TRUE
Example 7	0.0144	0	0.048	0.025	0.075	0.03	0.03	20	cathedral	FALSE
Example 8	1.40	0	0.048	-	0.075	-	0.03	20	cathedral	FALSE
Example 9	0.0144	0	0.048	0.025	roof space	0.03	0.03	20	horizontal	FALSE
Example 10	0.0144	0.15	0.048	0.025	roof space	0.03	0.03	20	horizontal	TRUE
Example 11	1.40	0	0.048	-	roof space	-	0.03	20	horizontal	FALSE
Example 12	1.40	0	0.048	-	roof space	-	0.03	20	horizontal	TRUE

1 Cavity 1 refers to the cavity present between the cladding and the radiant layer in several of the example cases.

2 Cavity 2 refers to the cavity formed by the 75 mm rafters in the cases with cathedral ceilings and refers to the roof spaces in cases with horizontal ceilings.

Roofs with ventilation openings were modelled with the following construction details.

- Roofs were modelled with two openings.
- Openings were located at each end of the roof; one opening on the low end and one on the high end, as illustrated in Figure 5 (not-to-scale).

- The area of each opening was sized to achieve a 1:600 opening ratio with the ceiling. Therefore, the sum of the opening areas provided a total opening ratio of 1:300, in accordance with the International Residential Code for naturally ventilated roofs (IRC, 2021).
- The discharge coefficients of the openings were assumed to be 0.6 in all cases, based on experimental characterisation of typical Australian roof openings (Fricker, 2020).

3.2.3 Boundary conditions

Each roof case was simulated for one year using hourly weather data for Kuala Lumpur (a total of 8760 steady-state calculations for each case). The simulations used TMY (typical meteorological year) weather data for Kuala Lumpur based on weather observations between 2006 and 2021 obtained from the OneBuilding online repository (Lawrie & Crawley, 2022).

Meteorological data used in the model included:

- Solar radiation (global, direct, and diffuse)
- Dry bulb temperature
- Horizontal infrared radiation intensity
- Wind speed
- Wind direction

The horizontal infrared radiation intensity was used to determine the effective sky temperature. The solar radiation data was used in combination with knowledge of the sun position to calculate the total solar radiation intensity incident on the roof top surface. The contribution of reflected solar radiation onto the roof from surrounding surfaces was also included, assuming an albedo of 0.18, which corresponds to an ‘urban’ environment (Loutzenhiser et al., 2007).

The indoor space was assumed to be controlled to a constant 22 °C throughout the year.

3.2.4 Performance assessment

For cases without ventilation, the R-value of the roof assembly could be directly calculated at each timestep. For cases with ventilation, an effective R-value of the roof assembly was calculated. The effective R-value was defined as the R-value of an unventilated roof assembly that would result in the same heat flux transmitted through the ceiling as the ventilated roof assembly.

3.3 RESULTS

The distribution of modelled R-values for the 12 cases are presented in Figure 6. Each distribution represents the annual performance of the roof systems and is made up of 8760 hourly R-values. The reason why R-values change on an hourly basis in reality is that ventilation rates, surface temperatures (for radiative heat transfer) and convection coefficients change with boundary conditions, which affect heat flow through the roof space. R-values from the GBI Handbook are also presented for each example case (represented by red crosses).

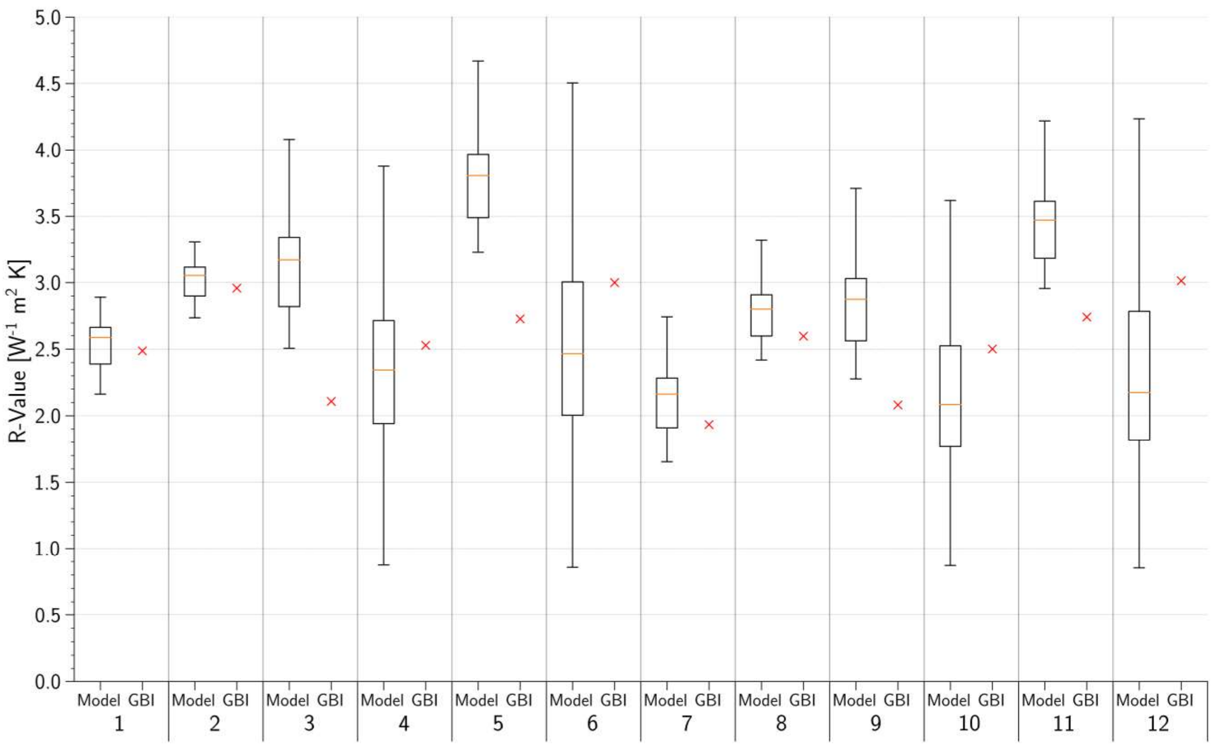

Figure 6 – R-values of the example roof assemblies determined using the physics-based model compared with R-values in the GBI Guidebook. Note that outliers have been removed for clarity.

For the purposes of explaining these results, the roofs can be grouped into the following three categories.

- Ventilated roofs with horizontal ceilings (Cases 4, 6, 10, and 12).
- Unventilated roofs with horizontal ceilings (Cases 3, 5, 9 and 11).
- Unventilated roofs with 'cathedral' ceilings (Cases 1,2, 7 and 8).

Ventilated roofs with horizontal ceilings

Modelling of the ventilated roofs with roof spaces formed between pitched roofs and horizontal ceilings produced R-values that spanned a relatively wide range of values throughout the year (typically varying between values of approximately 1 and 4 m^2 K W^{-1}). The corresponding R-values in the GBI Guidebook were within the range of modelled R-values, but were higher than the median modelled value by 8–39 %.

These results demonstrate that the R-values for ventilated roof spaces in Table B of the Guidebook are within the range of values that are likely to occur in the investigated roofs under Malaysian conditions, but they are somewhat higher than ‘typical’ R-values occurring in such cases. These results also highlight the high variability in effective R-value of ventilated roof spaces.

An important finding that emerged from this study was that roof space ventilation reduced the effective R-value of the roof assembly in all cases investigated. This is directly visible in Figure 6 by comparing ventilated cases with their unventilated equivalent (i.e. comparing roofs 5 and 6, or roofs 11 and 12). This finding conflicts with the values in Table B of the GBI Guidebook, where ventilation is predicted to increase the effective R-value of the roof space. As explained in Section 2.2, the values in Table B are likely to be valid under conditions and for roof construction details similar to those for which the values were developed, but such simple sets of nominal R-values cannot be accurate for all roofs and under all boundary conditions.

The primary reason why ventilation can negatively impact the thermal performance of the roof in these cases is explained below:

- The primary thermal benefit of roof space ventilation in hot climates is to exhaust excess heat caused by solar gains transmitted into the roof space through the roof assembly.
- In the example cases, the roof assembly above the attic space is highly insulated and the ceiling is uninsulated. This is significantly different to typical Australian construction practice, where the majority of insulation is installed on top of the ceiling.
- The Malaysian climate also differs from most Australian climates in that the outdoor air temperature remains higher than comfortable indoor temperatures for the majority of the year, even at night.
- Therefore, in the examined roof cases, roof space temperatures were frequently cooler than the outdoor air, but still warmer than the indoor space. Under these circumstances, ventilation of warm outdoor air into the roof space increases heat gains through the uninsulated ceiling lining. This differs from typical ventilated roofs in Australia (for which AS 4859.2 is primarily intended), where roof space temperatures are frequently significantly warmer than the outdoor air during the day and the majority of insulation is installed on the ceiling. Under these conditions, roof space ventilation can remove solar heat gains, thereby reducing heat flow through the ceiling.

Therefore, the negative impact of ventilation in the example cases can be explained by the roof construction typology, and the high outdoor temperatures of Kuala Lumpur.

Unventilated roofs with horizontal ceilings

In cases with horizontal ceilings and without ventilation, the R-values calculated using the model were significantly higher than those included in the GBI Guidebook; R-values from the Guidebook were 21–34 % lower than the median modelled R-values in these cases. This indicates that the R-values of unventilated roof spaces supplied in Table B underestimate the effective R-value of roof spaces for these types of roofs under Malaysian climate conditions. Again, this highlights that the values in Table B may not be applicable in Malaysia.

Unventilated roofs with 'cathedral' ceilings

There was relatively close agreement between the modelled R-values and the GBI Guidebook R-values for unventilated roofs with 'cathedral' ceilings; values from the Guidebook were 3–11 % lower than the median modelled values. The model applied to these roofs was relatively similar to the calculation method specified in the GBI Guidebook, with the primary difference being that the R-values of cavities in the model varied depending on the modelled temperature of surfaces bounding the cavity (as explained in Section 3.2.1).

R-value versus Ventilation Opening Size

The example roofs with ventilated roof spaces discussed above had an overall opening ratio of 1/300. However, ventilation effects can be significant even in cases with very small openings, and it is very difficult (and uncommon) to completely seal cavities in buildings. To explore the impact of ventilation as function of opening size, example roof number 5 was modelled with a range of different opening ratios. Figure 7 presents the annual distribution of R-values modelled using each opening ratio.

The annual mean R-value of the roof assembly was highest in the unventilated case and decreases with increasing opening ratio, and increasing hence ventilation rates. Even at a very low opening area ratio of 1/4000 the mean R-value of the roof assembly is 0.25 $W^{-1}m^2K$ lower than the unventilated case. Such small openings could be, for example, 1 mm-wide slot openings at the high and low edges of the modelled skillion roof. This difference increases to 0.72 $W^{-1}m^2K$ at an opening ratio of 1/1000. Therefore, the thermal resistances calculated for the example cases without ventilation should be used with caution, unless it is assured that the air cavities in these cases are sufficiently well-sealed to completely prevent ventilation.

The R-value of the roof assembly in cases with very high ventilation rates (e.g. with an opening ratio of 1/100) is still significantly higher than the R-value of the ceiling alone (0.048 $W^{-1}m^2K$). This is because, in spite of negative thermal impact of outdoor air ventilating into the roof space, the roof space and roof layer are still effective at "shielding" the top of the ceiling from solar irradiance.

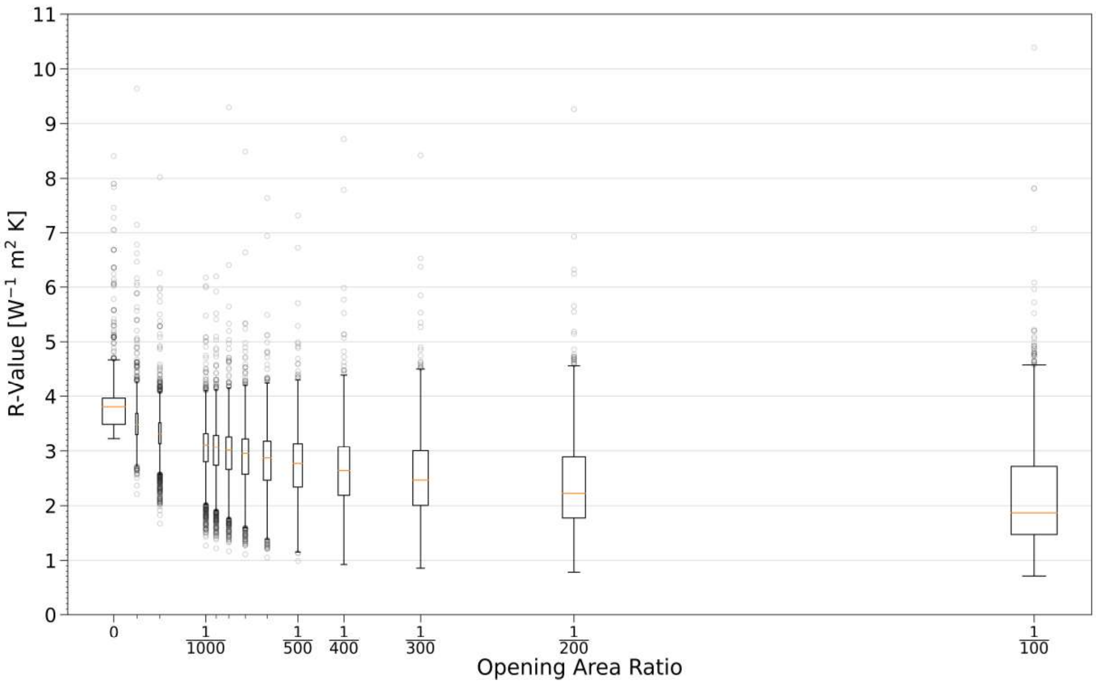

Figure 7 – R-value of the roof assembly as a function of opening area (expressed as a ratio of opening area to ceiling area) for a roof with a horizontal ceiling, based on 'Example 5'. Instances where the absolute value of heat flux through the ceiling was less than 0.1 Wm^{-2} have been excluded from the plot (80 of 113880 data points).

It should be noted that a similar correlation between opening ratio and roof R-value is likely to apply to roofs with 'cathedral' ceilings and ventilated cavities, which were not included in the GBI Guidebook example cases, and therefore have not been modelled here.

4 Conclusion

The key findings from the review of the GBI Guidebook and the simulation study are summarised below.

Tables A1 to A5 (Parallel-sided cavities)

A. The ASTM STP 1116 method used to calculate the nominal R-values of enclosed, parallel-sided cavities in Tables A1 to A5 produces very similar results to other standard calculation methods used for this purpose, including the method specified in AS/NZS 4859.2. The combination of this method with elements of AS/NZS 4859.2 in the GBI Guidebook is unlikely to have introduced significant error.

B. The most important limitation in the validity of values in Tables A1 to A5 is that they are based on measurements from completely enclosed (i.e. unventilated) cavities, whereas it is very uncommon for cavities in real roofs to be completely sealed. We recommend that users of the GBI Guidebook be mindful of this limitation.

C. While the GBI Guidebook does not contain any guidance for the treatment of ventilated, parallel-sided cavities, it is worth noting that the simplistic treatment of cavity ventilation in standards such as AS/NZS 4859.2 and ISO 6946 has been shown to not match reality in many situations, because it neglects any potential mitigation of solar gains and long-wave radiant cooling by cavity ventilation. Therefore, users of the Guidebook wishing to extend its use to parallel-sided cavities with ventilation should consider alternative methods, such as the thermal network model used in this study.

D. The footnote below Tables A1 to A5 (which suggests that the effective emittance of a cavity is approximately equal to the surface emittance of the lower emittance surface) does not appear to have been employed when producing the values in those tables. However, in this report we have demonstrated that this approximation can underestimate the R-value of high-emittance cavities by up to 8.70%. The error caused by this approximation is less significant for cavities with at least one low-emittance surface.

Table B (Roof spaces)

E. Tables of nominal roof space R-values such as Table B from the GBI Guidebook (which is a partial copy of Table 14 from AS/NZS 4859.2:2018) can only provide approximate estimates of the average effective R-value of a roof space. In reality, the effective R-value of such cavities changes over time, especially in the case of ventilated roof spaces.

F. Moreover, such tables of nominal R-values are likely to only be accurate for construction details and climatic conditions similar to those of the experiments from which the values were derived. This has been demonstrated in Section 3 of this report, where it was shown that while Table B suggests that ventilation *increases* the R-value of roof spaces (as it typically does in Australian roofs, with bulk insulation installed on top of the ceiling lining), a more sophisticated model predicts that ventilation would actually *decrease* the R-value of the GBI Guidebook example roofs under climatic conditions typical of Kuala Lumpur. Publications such as ASHRAE Fundamentals have moved away from the use of tables of nominal R-values for roof spaces for this reason. Possible solutions for the GBI Guidebook could be to develop a new table of roof space R-values tailored for typical Malaysian construction practices and conditions, or to specify that more sophisticated modelling is required—the former option is likely to be most suitable for adoption by building design practitioners, whereas the latter option is suitable for scientists with expertise in building physics.

G. The footnotes below Table B that define non-ventilated and ventilated roof spaces based on a threshold ‘opening ratio’ of 1:600 are, in our view, misleading. The IRC, on which the definition was based, specifies a threshold opening ratio of 1:300, where certain proportions of the total opening area must be located towards the top and bottom of the roof space.

H. Furthermore, to the best of our knowledge the combination of the IRC definitions of ventilated and non-ventilated roof spaces with the AS 4859.2 table of nominal roof space R-values has not been validated. In principle, we would support the use of the IRC definitions, since they are quantitative and clearly defined, whereas the definitions in AS 4859.2 are not. However, it should be noted that by combining elements from IRC and AS/NZS 4859.2 in this way, the GBI Guidebook is deviating from an exact adoption of the AS/NZS 4859.2 method.

I. The footnotes below Table B of the GBI Guidebook specify that “Non reflective surface has an emittance of greater than 0.05”, whereas Table 14 from AS/NZS 4859.2 defines this threshold as 0.15. This may be a typographical error, or an intentional modification to align the GBI Guidebook with definitions in MS 2095. Either way, it represents another deviation from the AS 4859.2 method, which will impact roof spaces with surface emittances between 0.05 and 0.15.

Example Calculations in the GBI Guidebook

J. Comparison of R-values published in the GBI Guidebook example calculations with R-values generated using a more sophisticated thermal model demonstrated the magnitude of uncertainty in R-values produced using simple calculation methods such as those in the Guidebook:

- The Guidebook R-values for ventilated roofs with horizontal ceilings were within the range of R-values modelled for the same roofs, but were 8–39 % higher than the median modelled values;
- The Guidebook R-values for unventilated roofs with horizontal ceilings were 21–34 % lower than the median modelled values; and
- The Guidebook R-values for unventilated roofs with cathedral ceilings were 3–11 % lower than the median modelled values.

K. Modelling also demonstrated that the effects of ventilation are nonlinear. Even very small openings (e.g. 1 mm-wide slot openings along the high and low edges of a roof) can significantly impact the R-value of a roof, as compared to a completely sealed assembly. Such openings can be formed unintentionally, e.g. due to construction tolerances.

4.1 RECOMMENDATIONS

A summary of our suggestions for improvements to, and usage of, the GBI Guidebook is provided below.

- Tables A1–A5 should include a reference to the method used to create the tables (i.e. ASTM STP 1116).
- The footnotes to Tables A1–A5 should include an explanation that the simplified approach to determine the effective emittance of cavities was not used in producing the tables.
- Users of Tables A1–A5 should be mindful that they do not necessarily provide accurate data for ventilated cavities, even in cases where no intentional ventilation openings are included in a roof design (i.e. when ventilation occurs through unintentional openings formed between components). Users wishing to extend the use of the guidebook to cover ventilated cavities should consider methods such as the thermal network model presented in this report, rather than the simplistic methods prescribed for parallel-sided ventilated cavities in AS 4859.2 and ISO 6946.
- Users of Table B should be mindful that the increase in R-value indicated by that table for ventilated roof spaces is not accurate for all Malaysian roof systems and climates; the opposite effect (i.e. a reduction in R-value) was found in the cases investigated in this report.
- Table B could be improved by developing new R-values based on Malaysian construction practices and climates; these new values could be based on experiments and/or mathematical models such as the model presented in this report.
- The inconsistency between the thermal resistance, thickness and thermal conductivity of plasterboard in the example calculations should be corrected.

- Text should be included to explain that the 1/600 opening ratio specified in the example cases refers to half of the openings to the roof space (i.e. the total opening ratio would be 1/300).
- An additional footnote should ideally be included with Table B explaining that the combination of nominal R-values from AS 4859.2 Table 14 with the definitions of 'ventilated' and 'unventilated' roof spaces from the IRC has not been previously validated.
- The existing footnote below Table B should be corrected to match that in AS 4859.2 (i.e. to allow interpolation of R-values when the roof space surface emittance is between 0.05 and 0.15).

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