ABSTRACT
This paper reviews the basis and methods for the evaluation of the thermal resistance (R-values) of enclosed reflective air spaces. Four methods of calculating R-values for enclosed reflective air spaces are discussed. Comparisons are made of results obtained with the methods. Examples are given for the calculation of R-values for typical building applications. The difficulties and shortcomings of the different methods are discussed.

INTRODUCTION
The use of reflective materials (low-emittance surfaces) to reduce radiation across enclosed air spaces has been discussed in the literature for about 100 years. A comprehensive review in 1989 by Goss and Miller (1995) cited 105 references published from 1900 to 1989. A very early paper by Dickenson and Van Dusen (1916) at the U.S. National Bureau of Standards observed that a “bright” metal inserted in an air space could result in an insulation superior to any on the market at that time. Numerous research papers that explored measurement techniques, heat transfer calculations, and development of commercial products followed the 1916 paper. Reflective air spaces (reflective insulation assemblies) were prominent in a 1955 reference by Nash et al. dealing with building thermal insulation. The 1955 publication discussed the heat transfer aspects of reflective insulation, presented a number of typical assemblies that are much like the assemblies currently used, and listed typical thermal resistance values.

At about the same time as the publication of the 1955 reference from the UK, two major reports were issued by the U.S. National Bureau of Standards (Robinson et al. 1954, Robinson et al. 1957). The 1954 report contained results for a series of hot box measurements for reflective insulation assemblies. These data formed the basis for handbook values for the thermal resistances of plane air spaces contained in the 1972 ASHRAE Handbook of Fundamentals and all subsequent editions of the Handbook as well as the AIRAH Handbook. The collection of data for reflective air spaces assemblies was extended in 1991 and reported by Desjarlais and Yarbrough. The 1991 measurements and analysis confirmed the earlier NBS measurements and extended the range of air space aspect ratios represented in the data base. The 1991 paper contained dimensionless correlations for the Nusselt number (Nu) for the five major heat flow directions (up, 45° up, horizontal, 45° down, and down). The Nusselt number introduces the convective contribution to the total heat flow across an air space with thickness “L”. A series of computer programs (“Reflect” with various added symbols) for calculating the thermal resistance of air spaces have been written to calculate R-values for a wide range of input variables such as effective emittance, heat-flow direction, air-gap dimensions, and bounding temperatures. These programs are widely used to evaluate building envelope assemblies that include enclosed air spaces. The correlations are a necessary step for introducing reflective insulation assemblies into building simulation programs since hot box data seldom exist for the assembly as it occurs in the building envelope.

THERMAL EVALUATION OF ENCLOSED REFLECTIVE AIR SPACES
R-values for enclosed reflective air spaces are measured using a test facility such as that shown in Figure 1. ASTM C 1363 (2010), the test method used for reflective insulation assembly measurements, provides for the measurement of steady-state heat flux, q, across a test specimen due to a temperature difference between air spaces bounding the test specimen. Typically, the test specimen is instrumented to provide the temperature difference, “ΔT”, between the solid surfaces of the test specimen. In the case of reflective air spaces, positioning of thermocouples on the surfaces directly in contact with the enclosed air space provides a measurement of the temperature difference across the enclosed air space. Additional measurements are required to determine the heat flux across the enclosed air space from which the R-value for the air space is calculated. ASTM C 1224 (2010) contains the procedure for determining the heat flux across the reflective air space.

The procedure is summarized by Eqs. 1, 2, and 3 with $R_{ed}$ in Eq. 3 being for the enclosed reflective air space.
\[
R_{\text{frame}} = \frac{(A_{\text{frame}} \Delta T_{\text{frame}})}{(Q_{\text{total}} - A_{\text{ins}} \Delta T_{\text{ins}} / R_{\text{ins}})} \tag{1}
\]
\[
Q_{\text{ref}} = Q_{\text{total}} - (A_{\text{frame}} \Delta T_{\text{frame}} / R_{\text{frame}}) \tag{2}
\]
\[
R_{\text{ref}} = \frac{A_{\text{ref}} \Delta T_{\text{ref}}}{Q_{\text{ref}}} \tag{3}
\]

A procedure based on Eqs. 4-7 for calculating R-values for assemblies not directly measured has been developed to utilize the available hot box data for practical applications. This is important since actual building systems seldom coincide exactly with any hot box test result. The simulation of heat flows across the building envelope requires a way to calculate the thermal resistance of enclosed air spaces both reflected and non-reflective. This has been done by using hot box data to obtain correlations for the convective component of heat transfer coefficient, \( h \). The correlations provide a way to use actual air space bounding temperature and dimensions to obtain the convective contribution to the heat transfer.

**Figure 1. Rotatable Hot Box for Building Assembly Measurements** (Courtesy: Building Technology Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA)

### CALCULATION OF THE THERMAL RESISTANCE OF AIR SPACES

The calculation of the thermal resistance (R-value) of reflective air spaces with infinite parallel isothermal bounding surfaces has been discussed (Robinson & Powell 1954, Desjarlais & Yarborough 1991). This type of analysis is contained in Annex A of ISO 6946 and the Australian/New Zealand Standard AS/NZS 4859. The one-dimension calculation is described by the following four equations (Yarborough 2010).

\[
R\text{-value} = \frac{\Delta T}{(Q/A)} = 1/(E h_i + h_r) \tag{4}
\]
\[
E = \frac{1}{(1/\varepsilon_1 + 1/\varepsilon_2 - 1)} \tag{5}
\]
\[
h_i = 4 \cdot (5.67 \times 10^{-8} \cdot T_i^3) \tag{6}
\]
\[
h_r = \text{Nu} \cdot k_{air} / d \tag{7}
\]

The input material properties are the bounding thermal emittances, \( \varepsilon_1 \) and \( \varepsilon_2 \), and the thermal conductivity of air, \( k_{air} \), at the average temperature of the enclosed air space, \( T_m \). The radiation term, \( h_r \), follows from the Stefan-Boltzmann expression (Robinson et al. 1954) with \( T_m \) (K) being the average absolute air space temperature. The Nusselt number is expressed as a function of the Grashof Number \( (Gr) \) by a set of equations derived from the hot box data (ASTM 2010). The \( h_i \) contribution can also be obtained by numerical interpolation in the data sets given by Robinson and Powell (1957). Given access to the Nu correlations or the hot box data, the evaluation of R-value is a mathematical exercise that requires input of the temperatures of the bounding surfaces of the enclosed air space. Since the enclosed air space is part of a building envelope component with bounding temperatures defined by inside and outside surface or air temperatures, the evaluation of the reflective air space is an iterative process that involves an initial estimate of the air space bounding temperatures followed by calculation of component R-values and a corrected pair of temperatures for the enclosed air space.

The computational procedure described above has been used to calculate R-values for uniform thickness air spaces for input to building simulation programs for many years. Results have been published for wedge-shaped air spaces formed by reflective partitions that are not parallel to the bounding surfaces of the air space (Robinson et al. 1957). These results show air space resistances ranging from 50 to 90% of the uniform tandem air spaces of the same dimension. The percentage reduction are greatest for downward heat flow because the non-uniform air space results in non-uniform surface temperatures. This effect has yet to be introduced in code-related calculations.

In 1983, the HRP32 data sets were analysed by Yarborough to obtain polynomial curve fit algorithms. Allen and Aynsley incorporated these in the now popular software, Reflect3, published in 2002. (This software was endorsed by AFIA as recommended for reflective insulation calculations to AS/NZS 4859, 2006). Yarborough re-examined the raw data of HRP32 and developed spline fits of \( \log_{10} \text{Nu} \) vs. \( \log_{10} \text{Gr} \). This provides a justification for modest extrapolation of the hot box data to greater thicknesses than actually measured (Desjarlais et al. 1991). The input data for the R-value calculations are surface emittances, the distance between the parallel surfaces, and the bounding temperatures. When there are several air spaces in series between bounding temperatures it is necessary to determine the temperature difference across each air space. This is an iterative procedure since the thermal resistance of an air space depends on \( \Delta T \). The iteration proceeds by partitioning the total temperature difference into temperature differences across each air space, calculating the individual air space resistances, and then recalculating the temperature profile. This procedure converges quickly to a final temperature and set of air space thermal resistance values.
In 1997 Fricker developed software (Res2) based on the data in HRP32 for calculating air space thermal resistances. Res2 uses multiple line segments to interpolate in the experimental data set for \( h_c \).

All of the above softwares have the same limitations of use based on the original HRP32 physical research: \( \Delta T \cdot L^3 < 5000 \) (T in °F and L in inches), e.g. If \( \Delta T \) is 3.6°F , then the limit would be \( L^3 = 1389 \) or \( L = 11.16 \) inches, i.e. \( \Delta T = 2^\circ C \), then the limit would be \( L = 283 \) mm. Use of the correlations for \( \Delta T \cdot L^3 > 5000 \) represents an extrapolation.

In 2002, AS/NZS 4859.1:2002 - "Materials for the thermal insulation of buildings - Part 1: General criteria and technical provisions" allowed the data published in HRP32 for calculation of R-values for unventilated reflective air spaces. The standard did not identify any particular software. AFIA felt that Reflect3 should be the standard, and most calculations have been done using this software. In 2002, ISO 6946:2007 became a reference for reflective insulation calculations, introducing new (and simplified) algorithms. To date, it has rarely been used in Australia except for air spaces greater than 100 mm which is considered the maximum air gap that can be handled by Reflect3.

### 2011 APPLICATIONS

The BCA2011 sets energy efficiency requirements in all new buildings by mandating high total thermal resistances for roof, wall and floor for building types in each climate zone. As a consequence, building engineers need accurate correlations to ensure that every component of thermal resistance in a building section is fairly considered. Thus, it is now necessary to have properly calculated reflective insulation R-values.

Interestingly, with the higher R-value requirements of BCA2011, reflective insulation performance is often enhanced by conventional bulk insulation. The bulk insulation takes a large fraction of the total temperature drop between outside and room interior, leaving a smaller \( \Delta T \) across the air space, and a smaller \( \Delta T \) reduces (perhaps eliminates) convection (air circulation within the cavity) resulting in a high air space R. If convection is eliminated by decreased \( \Delta T \) and radiation is decreased by low emittance surfaces, then the R-value is based on the thermal resistance of air, about 5.6 \( \text{ft}^2\cdot\text{°F}/\text{Btu} \) at 75°F for one inch (0.99 \( \text{m}^2\cdot\text{K}/\text{W} \) at 24°C for 25.4 mm). The high R from small \( \Delta T \) is also exploited by some reflective insulation systems that utilise multiple reflective insulating cavities. For example, two air gaps each with half the \( \Delta T \) provide more R than the equivalent single air gap with the greater single \( \Delta T \).

### SOFTWARE COMPARISONS

This section compares the different calculation methods by referring to the Figures in Appendix 1.

Figures A1 to A6 are for typical building reflective foil insulations (including reflective bubble foils and similar materials), each with a high \( \Delta T = 6K \). In practice, the \( \Delta T \) per air space is usually less, resulting in less convection and higher R (especially in mild weather). In the case of reflective insulations with significant product thickness, 6mm (0.25 inch), for example, there is a material R-value that adds to the R-value for the reflective air space. The reflective insulation material becomes an element in the sequence of materials in the building envelope.

It is notable that results from the different methods match closely for air gaps less than 10mm because heat transfer by convection is absent. Heat flow by conduction and radiation can be calculated with good precision. With increasing gap, the dominant heat transfer mechanism is natural convection (transfer of heat by movement of air molecules due to buoyancy). For 40mm to 80mm air gap (in these examples), the different methods calculate R-values with some differences due to convective contribution estimation differences (\( h_c \)). In most cases, the difference between methods is small. The ISO method predicts a higher R than the other methods for 10 to 30mm in Figure A3 and then sets the R as constant despite increasing air gap, unlike the other methods. In Figure A4, Reflect3 gives a lower R for 20mm to 90mm than the other methods.

All figures shown are for cavities with one reflective foil (\( \varepsilon = 0.03 \)). R-values are less when the foil is semireflective (so-called antiglare foil) as radiant heat transfer becomes significant, hiding model differences for convection loss.

In all cases, there was good agreement between Fricker’s Res2 and Yarbrough’s Reflect2 curves (replicating the original HRP32 data). They seem less erratic than ISO 6946 and Reflect3 curves. Reflect3 curves tend to be unrepresentative for gaps greater than 90mm. Yarbrough’s Reflect2 curves seem to have the smoothest curve fits. JFRRes2 is not subject to the polynomial limitations of applicability as it very closely follows the original HRP32 graphs, but its curves are not mathematically smooth having slight discontinuity in the slopes of the line segments. For air gaps up to 100mm, reflective air space R-values by the different calculation methods vary by -3% to +6%. Excluding Reflect3, for 5mm to 200mm air gaps, reflective air space R-values from Fricker’s Res2 and Yarbrough’s Reflect2 differ by less than 4%.

### AUSTRALIAN REQUIREMENTS

Typically, Total R and reflective air gap R values are iteratively calculated per AS/NZS 4859.1:2002/Amdt 1 2006 for the required system air conditions 12°C outside/18°C inside (winter) and 36°C outside/24°C inside (summer). The total \( \Delta T \) is thus 6K for our mild winter and 12K for our severe summer rating conditions. Any air cavity present typically has a \( \Delta T \) much less than these values as other components...
share the temperature profile. (Note: For air-conditioning peak load estimation, ambient air temperatures would be more severe than 12°C winter and 36°C summer). AS/NZS 4859 also requires adjustment of bulk insulation R based upon its average temperature. A typical wall calculation with a reflective air cavity combined with glasswool insulation is shown in Figure 2.

**FUTURE TRENDS**

The computational methods that have been described involve an assumption of one-dimensional heat transfer between large parallel surfaces (infinite parallel planes). This is evident in Equation (4) which is derived for infinite parallel planes. In an actual building enclosure there are surfaces connecting the parallel planes (framing). These surfaces absorb, emit and reflect radiation. The framing members do not exhibit one dimensional behavior because there is heat input along the surfaces. Glicksman (1991) has published an analysis of the heat transfer process that includes radiation interaction between the parallel surfaces and the framing. The result is increased heat transfer through the framing, a thus a decrease in the overall performance. The magnitude of the effect depends on the aspect ratio (depth/width) of the air space. If the aspect ratio is large, then the 2D correction is large.

CFD programs are being used to calculate the velocity profiles and resulting convection in enclosed cavities (Han et al. 1986). These advanced methods provide improved correlations for the convective component characterized by Nu.

**CONCLUSIONS**

The four methods available for estimating the thermal resistance of enclosed reflective air spaces provide results that generally agree to within 10%, and 4% when the ISO 6946 is not included.

The computational methods discussed in this paper provide a way to reliably introduce reflective insulation systems into building simulation programs that typically require R-values for the building envelope.

**REFERENCES**

AFIA, Aluminium Foil Insulation Association (Australia) www.afia.com.au


Allen, R. Glenn and Aynsley, Richard (2002) Reflect3, Version 1.05, Southern Polytechnic State University, Marietta, GA, USA

AS/NZS 4859.1:2002/Amdt 1 2006 - "Materials for the thermal insulation of buildings - Part 1: General criteria and technical provisions".

ASHRAE Handbook of Fundamentals, "Design Heat Transmission Coefficients", Table 1 in Chapter 20 (1972). The American Society of Heating, Refrigerating, and Air-Conditioning Engineers is now located in Atlanta, Georgia, USA.


Res2 was developed by J. Fricker of James M Fricker Pty Ltd from 1997 to 2006. (The work has not been published previously.)


APPENDIX 1  All figures include +/-5% error bars on its DYReflect2 graph.

Figure A1. R-value Calculations for Horizontal Heat Flow with 12 and 18°C Surfaces with Emittances 0.03 and 0.87.

Figure A2. R-value Calculations for Horizontal Heat Flow with 30 and 36°C Surfaces with Emittances 0.03 and 0.87
Figure A3. R-value Calculations for Upward Heat Flow with 12 and 18 °C Surfaces with Emittances 0.03 and 0.87

Figure A4. R-value Calculations for Downward Heat Flow with 30 and 36°C Surfaces with Emittances 0.03 and 0.87
Figure A5. R-value Calculations for 45° Upward Heat Flow with 12 and 18 °C Surfaces having Emittances 0.03 and 0.87

Figure A6. R-value Calculations for 45° Downward Heat Flow with 30 and 36°C Surfaces having Emittances 0.03 and 0.87