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The Reference Period for Predicting Long-Term Thermal Performance of Thermal Insulating Foams*

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INTRODUCTION

Replacement of traditional blowing agents, chlorofluorocarbons (CFC), with partially halogenated chlorofluorocarbons (HCFC) that have thermal insulating performance inherently lower than that of CFC brought to question their long-term thermal performance (LTTP). As a result of research activities, two predictive techniques, slicing and scaling [1,2] or slicing and modeling [3,4], are now considered for evaluating long-term thermal performance of different foam products: polyisocyanurate, polyurethane, extruded polystyrene, and phenolic (resole) foams. But without defining: What does the "long-term" period mean? much of these proposals remain unconvincing to the practitioners.

The knowledge of long-term thermal performance of the insulating material is used to select one of many thermal insulating products for the construction, as well as to assess the economics of the energy performance of the building envelope. Whether the building is situated in a cold or hot climate, the insulation reduces the cost of heating or

*This study is a part of a joint SPI-NRC Canada project on long term performance of thermal insulating foams.

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cooling energy and as such should be subjected to an economic evaluation. One must compare the cost of purchase and installation against the future saving of the energy costs.

To analyze future returns of the investment, one must select a financial analysis technique, for instance a life-cycle analysis. To perform the life-cycle cost analysis, however, an estimate of service life is needed. Making such an estimate may not be as simple as it appears to be. Accessibility and cost of replacement are different depending where the particular material was installed (roof deck, masonry cavity, curtain wall or insulating sheathing). Furthermore, according to the draft of the Canadian Standard Association (CSA) Guideline on Durability in Buildings, a design service life may be as short as ten years (e.g., temporary classroom) or as long as 100 years in monumental or heritage buildings.

Smith [5] in discussing the understanding of life-cycle (LCC) stated: "The estimated service life of a roof is the most difficult assessment to make of all of the LCC factors. And this estimation can have a dramatic impact on the analysis. For example, if you figure the life of the roof at forty years, but it fails in fifteen years, the owner's true roofing cost will be much higher than you figured." Except for exceptional cases, twenty years is recommended for comparative assessments [5].

Another cost-benefit analysis is based on the payback approach [6]. This approach was used, however, in a somewhat more complex scheme. First, an economic analysis was performed on several new and retrofitted wall constructions to establish an indicator called a "design *R*-value." This indicator would be used instead of the actual annual *R*-value, as the latter varies with the age of the foam. Since this indicator is sensitive to the length of the payback period for that insulation option, these calculations were performed for actual designs and prices of fuel and construction materials. Then, two other steps were taken, namely: (1) the actual measurements of foam aging were used to derive an analytical equation serving to establish the reference period; (2) the DIPAC computer model was applied for a case study, and its predictions were used to establish the reference period.

Evidently, one may expect different intervals of the reference period when applying these three techniques to foams with various aging characteristics, different thicknesses and constructions in diversified economic and service conditions. Bearing in mind that the objective of the design thermal resistance is to provide a comparative basis, the same reference time was selected for all foam products. The last part of this paper, therefore, applies the proposed definition of the design *R*-value to calculate payback for two selected foam products and ana-

lyze differences between an approximate and the precise calculation of the payback time.

THE SCOPE OF ECONOMIC ANALYSIS

The term "life-cycle costing" is broad in scope and relates to financial analysis techniques such as: cost-benefit analysis, savings-to-cost ratio, internal rate of return and the payback period. Depending on the type of investment under consideration, one technique may be better suited than the other [7,8]. Nevertheless, all these techniques essentially analyze initial and future costs with respect to future returns of the investment.

In this review, the cost of installing different cellular plastic insulation is compared with the potential saving in the energy cost. This implies a comparison between the sum of the initial investment (i.e., the purchase and installation costs) and the present worth of the heating costs (i.e., savings in energy) associated with the considered option. This approach is essentially the "payback period" and will be used as a basis for comparison of various long-term *R*-values. A more complete approach, a life-cycle cost (LCC) would go beyond the period in which the investment pays for itself and examine the total cost of the construction over the expected service life of twenty-five or fifty years.

The concern of an investor or designer weighing several insulation options is to analyze the payback period, i.e., to determine how many years of energy saving is necessary to pay for the initial cost of the selected insulation option. The payback analysis is more suitable for this purpose than other types of economic analysis, e.g., life-cycle cost analysis, and this analysis can be further simplified if it can be performed not with the actual thermal resistance as it changes with time, but with an indicator, called a design *R*-value. Therefore, the purpose of this paper is to select the reference period for the design *R*-value of the thermal insulating products.

To derive the reference time, we will establish a precise payback period based on the diminishing annual *R*-value and determine the foam age when the actual *R*-value of the foam gives the same payback period. Since this analysis relates to a comparative study "within a type" of cellular plastic insulation and not "between types" of insulation, costs related to maintenance, repair, replacement and disposal may be assumed as approximately equal and need not be quantified.

Five different cellular plastic insulations, polyisocyanurate, polyurethane, extruded and expanded polystyrene and phenolic (resole) foams, randomly denoted as A, B, C, D and E foams, were analyzed in three

Canadian climates, Nova Scotia, Ontario and Alberta. We have considered three heating fuels for comparison. All economic assumptions such as future interest rate, inflation rate and fuel escalation rate were the same as provided by the provincial authorities for development of the 1995 Canadian Energy Code. The cost of construction of the wall assemblies and cost of insulation alternatives were also provided by an independent consultant commissioned by the 1995 Energy Code Committee (in one case, the cost estimate was obtained from the industry).

The payback period was calculated in two steps: first, the annual heating cost per square meter of wall or roof was determined, then the present value (PV) of heating cost was calculated for each of the future years (now being year one). The sum of annual savings, expressed as the cumulative present value, is compared with the incremental cost of insulation. The investment is paid back when the cumulative present value is equal to the incremental cost of the insulation purchase and installation.

Since this is a comparative study of material alternatives, the heating degree-day estimation method is adequate to calculate the annual heating cost per unit of area:

$$HCU = 24 \times A \times HDD \times FC / (R \times E_{ff}) \quad (1)$$

where:

HCU = Heating cost per unit area, (\$/sq. m.)

A = Area of component, here 1 m^2

HDD = Sum of degree-days during the heating season ($^{\circ}\text{C day}$)

R = Thermal resistance of the component ($\text{m}^2\text{C}/\text{W}$)

FC = Cost of fuel: gas, oil or electricity (\$/GJ)

E_{ff} = Efficiency factor for appliance: 0.6 for gas or oil and 1.0 for electric

Then, the annual heating cost is calculated for several future years, each recalculated into the current dollars and expressed as the present value (PV). This is done by using escalating fuel costs and corrected cost of money, namely:

$$PV = HCU \times (1 + e)^{-1} / (1 + i)^{n-1} \quad (2)$$

where:

e = fuel escalation rate (%)

Table 1. Heating cost of the construction without (base case) and with insulation E.

Year	PV of Base Case (\$/sq. m.)	PV w/76 mm Insulation E (\$/sq. m.)	Cumulative PV Savings (\$/sq. m.)
1	3.729	0.517	3.212
2	3.639	0.506	6.342
3	3.545	0.494	9.392
4	3.370	0.483	12.366
5	3.266	0.471	15.264
13*	2.753	0.393	35.95

*At 13 years, the cumulative PV savings are equal to incremental cost.

i = nominal interest rate (%)

n = year number, starting from the present year

Thus, the payback period was established as a period when the cumulative energy savings was equal to the amount of incremental cost of installing the analyzed insulation material.

The following example illustrates the process, Table 1:

- precast concrete roof deck, uninsulated RSI 0.66 (Base Case)
- insulation E, 76 mm, RSI 4.4, installation costs (material and labor) = \$35.91/sq. m.
- heating fuel: Gas = 0.1492 \$/m³ (commercial rate, incl. taxes), fuel escalation rate = 5.2%
- Ontario, HDD = 4634 (Ottawa) (°C day)
- projected nominal interest rate (incl. projected inflation) = 8.1 %
- incremental cost of \$35.91/sq. m.

PAYBACK PERIODS

The following section gives a few examples to illustrate how the payback values may vary depending on construction and economic conditions. Figure 1 shows results of calculations performed for insulation E. The location was Ottawa and the fuel was natural gas. The R -value input for each thickness of insulation was the actual annual R -value obtained from the DIPAC model. This provided a payback period which takes into account the product's actual thermal performance as it decays over time. In the examined cases, the payback period ranged from ten to fourteen years. Figure 2 shows that, for Nova Scotia and heating with oil (i.e., using more expensive fuel than in Ottawa), the

Figure 1. Payback period for insulation E in the wall: Ontario, fuel-natural gas.

Figure 2. Payback period for insulation E in the wall: Nova Scotia, fuel-oil.

Figure 3. Payback period for insulation E in the wall: Nova Scotia, fuel-electricity.

same insulation results in a payback period between five and seven years.

Both figures show an increase in payback period with increased thickness of insulation, i.e., diminishing returns on investment with increase in thickness and/or R -value. Figure 3 shows the contrary, an increased insulation thickness (improved R -value) reduced the payback period. This could have been caused by one or both of the following factors:

- (1) An apparent cost advantage was associated with selecting the thicker insulation.
- (2) The thicker product maintained a higher thermal resistivity over the period due to a lower decay rate compared to the thinner product.

In the actual case, the increase in cost of material and installation was more than offset by the savings in heating costs.

COMPARISON OF PAYBACK PERIODS

Figure 4 shows errors caused by using a single thermal resistance value instead of the annual average value for calculation of the payback period. In case of insulation D, city of Ottawa with electricity as the fuel, the payback period was 19.9 years when using the annual aged R -value. When using the initial R -value payback was 12.8 years, with 180 day value (as recommended by the U.S. Federal Trade Commission) the payback period was 17.3 years. These methods misrepresented payback by thirty-five and thirteen percent respectively.

Requesting calculations to come within two percent of the reference value (allowing 2% error in calculations), one finds that for the con-

Figure 4. Effect of R -value selection. Insulation D, 19 mm thick, retrofit of wall, Ontario, fuel-electricity.

sidered set of parameters the reference period for R -value is between two and one-half to four years. In the considered case, using the four year reference time provides a correct estimate of the true payback period.

Insulations B and C, shown in Figures 5 and 6, show again that 180 day aged R -values do not represent the true payback period. Using four to six year (Figure 5) and three to five year (Figure 6) R -values represent the true payback period with 2% precision.

Aging rate is very slow for insulations A and E (not shown here). As a result, a close representation of the payback period obtained using the annual R -value may be obtained with any reference period.

Figure 5. Effect of R -value selection. Insulation B, 38 mm thick, retrofit of wall, Ontario, fuel-electricity.

Figure 6. Effect of R -value selection. Insulation C, 50 mm thick, retrofit of wall, Ontario, fuel—natural gas.

DISCUSSION ON PAYBACK APPROACH

The ASTM Standard E 1121, "Standard Practice for Measuring Payback for Investments in Buildings and Building Systems" [6] states: "Use the method to find if a project recovers its investment cost and other accrued costs within its service life or within a specified maximum acceptable payback period (MAPP) less than its service life. It is important to note that the decision to use the payback method should be made with care."

Indeed, care is used in this analysis which considers costs related to maintenance, repair, replacement and disposal as approximately equal for different types of cellular plastic insulation. The objective of this analysis is to establish the reference time for design R -value. The authors believe that with today's changing economy and marketplace a fifteen to twenty year payback period is likely to be all that the investors/owners are prepared to consider as a reasonable return. Thus the maximum acceptable payback period would be shorter than the service life of the building.

Selecting the payback period approach as the means of economic analysis of the selected construction option (indeed the average payback varied between ten and eighteen years Figures 1–3), one faces the question of what reference period should be selected to use a single R -value instead of the annual R -value. The five insulations examined may be suitably represented by a four year aged R -value. Thus, a four year reference period emerges as the benchmark for analyzing thermal performance.

The reference period for R -value is, however, sensitive to the length of the payback period for that insulation option. If a cavity filled with insulation is compared with "no" insulation in the cavity, the payback

period is usually less than ten years. When the payback period is less than ten years, the R -value input in the payback period calculation could be any R -value (e.g., 180 day, one or four years), and the result will be reasonably close to the true payback period.

In a retrofit situation, when adding an external insulating sheathing to a base wall with RSI 2.1 (R-12), the payback period often falls between ten to twenty years. In locations where the cost of fuel is low, the payback period will be closer to twenty years; higher fuel costs will result in lower payback period. A realistic prediction of long-term R -value (e.g., 4 year R -value) is important only in such a case. In essence, the four year aged R -value was found suitable to conduct an unbiased comparison of insulation alternatives.

THE RELATION BETWEEN THE REFERENCE TIME AND THE AGING PERIOD

Thermal resistivity (r -value or inverse of k -factor) may be related to the period of aging in different ways: an exponential dependence of r -value on time, r -value versus square root of time, or r -value versus logarithm of time. Independent of the manner in which this dependence is presented, one usually distinguishes between two stages of aging process. The primary aging stage shows a rapid reduction in thermal resistivity of the foam as a result of air components entering into the cells and changing the cell-gas composition. The secondary aging stage is often called a "plateau" stage, since the air ingress into the foam is nearly completed and the outward diffusion of blowing agent changes the cell-gas composition at a much slower rate.

Dillon [9] analyzed aging of twenty-five rigid foams with density ranging from 27 kg/m³ to 49 kg/m³ and thickness between 15 and 43 mm over the period up to ten years and described the data using two types of equations:

$$k = k_0 + A(1 - \exp(-\beta t)) \quad (3)$$

and

$$k = k_0 + (A + Bt)(1 - \exp(-\beta t)) \quad (4)$$

where k_0 is the initial thermal conductivity, k is the thermal conductivity at time t , A , B and β are constants obtained from the non-linear least square fitting of the data to Equations (3) or (4). At large values of time, Equation (3) approaches a horizontal asymptote of $(k_0 + A)$. As

it is not possible to define the end of aging process when describing it with Equation (3), normally one analyzes a period to reach 50% of the difference between the initial and final values of thermal conductivity, so called half-time, t^* , as defined by the relation $t^* = (\ln 2)/\beta$. The second curve has a rising asymptote defined by the equation $k = (k_0 + A) + Bt$, where the term (Bt) is usually small in comparison to the first term.

Equation (3) can be rewritten by introducing k_∞ as the value of the horizontal asymptote and k_0 being the initial thermal conductivity:

$$k = k_\infty + (k_0 - k_\infty) \exp(-\beta t) \quad (3a)$$

Introducing the time-averaged thermal conductivity, defined as follows:

$$k_{av} = \frac{1}{t} \int_0^t k \, dt \quad (5)$$

one obtains

$$k_{av} = k_\infty + (k_0 - k_\infty) / (\exp(-\beta t) - 1) \quad (6)$$

If time, τ , is defined in such a manner that after substituting to Equation (3a), thermal conductivity k becomes equal to the time-averaged thermal conductivity, $k_{av}(k(\tau) = k_{av})$, and denoting $\alpha = \beta t$ one obtains:

$$\ln(1/\alpha - \exp(-\alpha)/\alpha) = -\beta\tau \quad (7)$$

If searching for the relation between the total period of time, t , and the interim value of time, τ , one obtains¹:

$$\tau/t = -(1/\alpha) \ln(1/\alpha - \exp(-\alpha)/\alpha) \quad (8)$$

Using Equation (8) one may relate the time-averaged thermal conductivity to the total period of time, i.e., define the reference time for the thermal measurements used to determine long-term thermal performance of cellular plastics.

Yarbrough [10] fitted Equation (1) to the aging curve determined on

¹Private communication with professor David Yarbrough.

50 mm thick polyisocyanurate board manufactured with HCFC-22, obtaining $\beta = 0.0076$ 1/day (2.77 1/year). The half-time for this board was ninety-one days, i.e., a short half-time when comparing with CFC-11 blown polyurethane foams. Dillon [9], who analyzed twenty-five different types of PUR foams, found only six with the half-time shorter than 100 days and fifteen with the half-time in the range varying between 200 and 616. (Similar results can be deduced from the aging results published by Andrews [11]).

Using β factors corresponding to these two extreme values of half-time (91 and 616 days) and Equation (8), one obtains the reference time, τ , at which the measured value represents the thermal resistivity averaged over the specified service life (Table 2).

Table 2 indicates that varying service life between fifteen and twenty-five years does not have a large impact on the reference time. Furthermore, if Equation (6) was describing the aging process with sufficient accuracy, then the results shown in Table 2 indicate that the thermal resistance after five years would represent twenty-five year time-averaged thermal resistance for most of the PUR boards with thickness of 25–40 mm. Note that a similar opinion has already been expressed by a group of experts in the position paper of Canadian General Standards Board (Kabayama [12]).

As shown in Table 2, the reference time derived from Equation (6) depends on the β -factor, which depends on the foam thickness and type of the polymer. Furthermore, validity of Equation (6) has been established for four to ten years of aging [9,11] only, while we must also consider longer periods of aging. These issues are examined in the following case study where DIPAC (distributed parameter model) is

Table 2. Reference time calculated from Equation (8) for 25–50 mm thick PIR/PUR foams.

Aging Period, t , days	Factor (βt), with $\beta = 0.0076$ 1/day	Ratio τ/t from Equation (8)	Reference Time, τ , Days (Years)
5475	41.6	0.0896	490 (1.34)
7300	55.5	0.0724	528 (1.45)
9125	69.4	0.0611	557 (1.53)
$\beta = 0.00113$ 1/Day			
5475	6.19	0.2945	1612 (4.42)
7300	8.25	0.2558	1867 (5.11)
9125	10.31	0.2263	2065 (5.66)

first validated and then used to describe the aging during an extended period.

CASE STUDY: AGING OF A POLYISOCYANURATE BOARD

A PIR board produced in August 1986 was stored in laboratory until January 1987, when it was cut into the test specimens. An average thermal resistivity determined on eleven specimens was 52.1 (mK)/W, and the standard error of this measurement was 1.1% [3]. In addition to aging at 60°C, previously discussed [3], the dependence of thermal resistivity on time, diffusion and solubility coefficients were also measured.

Applying these properties to the DIPAC model, sufficient agreement with the measured data was obtained. Having validated the material characteristics, we may use them for calculating long-term thermal performance of the discussed PIR foam while varying the board thickness from 20 to 90 mm.

Results shown in Table 3 indicate that despite the thickness variation between 20 and 90 mm and associated change in time-averaged thermal resistivity, there is very small difference in the reference time. The reference time on thin board is about 8.3 years; it decreases with increase of thickness to about 6.3 years (for 30–40 mm thick product) and increases again to about 8.6 years on very thick board (90 mm).

Previous discussion implied that considering energy savings on the basis of life cycle cost is justified only for the period of fifteen to twenty years. The reference time is therefore calculated again, this time for the service period of twenty years (Table 4).

The results obtained in this calculation (Table 3) are similar to those shown in Table 3. The reference time is about 6.5 years for 20 mm board, becomes as low as 5.5 years for board with 40 mm thickness and increases to 6 years at 60 mm board thickness. These results are very consistent, and the differences between time-averaged values calculated for twenty and twenty-five years are small, in the range of 1 to 2 percent.

Four out of six reference periods shown in Table 4 (PIR product in the range between 30 to 60 mm thickness) indicate that taking six years (2200 days) would adequately describe long-term thermal performance of this product. It should also be mentioned that the actual 42 mm thick PIR board product was extensively tested by the manufacturer, who labeled the long-term thermal performance of this product within 1% of the estimated *R*-value at the reference period of six years.

Table 3. Time-averaged thermal resistance for twenty-five year aging of the PIR boards.

Thickness L , mm	Time-averaged r , (mK)/W	Period, τ , Days	Ratio τ/t
20	38.7	3028	0.33
30	39.9	2272	0.25
40	40.8	2305	0.25
50	41.7	2467	0.27
60	42.6	2632	0.29
90	45.0	3145	0.34

Table 4. Time-averaged thermal resistance for twenty year aging of the PIR boards.

Thickness L , mm	Time-averaged r , (mK)/W	Period, τ , Days	Ratio τ/t	Difference in r -value, for 20 and 25 Years, %
20	39.0	2355	0.32	0.8
30	40.2	1821	0.25	0.7
40	41.2	2005	0.27	1.0
50	42.2	2075	0.28	1.2
60	43.2	2207	0.30	1.4
90	46.0	2566	0.35	2.2

PROPOSED REFERENCE TIME FOR LONG-TERM THERMAL PERFORMANCE EVALUATION

Design life-time is normally defined as the time interval during which an installed material, product or system should substantially maintain its design performance, and the life-time may also depend on the serviceability of the installation.

This definition is frequently misunderstood by assuming that any product should maintain its initial performance through the service life. When a manufacturer claims a certain level of the product performance (accounting for weathering, aging or other time dependent processes), this manufacturer establishes the design performance level. It is therefore important for the SPL/NRC project to establish a reference time for which this "design performance level" should be related.

Economic analysis, discussed in the above section, indicated that using thermal resistance at four years of aging (i.e., four year became the reference time) provided a sufficient agreement with calculations based on yearly values of thermal resistance for ten to twenty year payback. Examining the relation between the integrated over twenty year and the average PIR board thermal performance, we have established six years reference period. The same analysis performed on thick phenolic or modified resole foams gives the reference period of seven years.

The "design thermal resistance" is, however, to provide a comparative basis which ensures that the materials would "substantially maintain declared performance" [13]. We have, therefore, selected five years as the reference time. The actual thermal performance of the foam board (as it varies depending on the foam thickness) at 1825 ± 25 days of aging is called the design thermal resistance of the foam board. Such a definition, as shown in Table 4, means that the actual design values of thermal resistivity (or thermal conductivity) will be different for thin and thick foam products.

The concept of design thermal resistance is then applied to calculate payback period in two extreme cases from the five compared materials. Figures 7 and 8 show such calculations performed for phenolic and polyisocyanurate forms where design r -value is compared with the actually calculated annual R -values and the average r -value over 20 year period. While the design R -value data predict the payback period within 1.0% for phenolic, they predict 2-4% longer payback period for polyisocyanurate roofing boards and up to 7% for unfaced sheathing boards. The proposed design R -value definition is therefore set on the conservative side.

(a)

(b)

(c)

Figure 7. Percentage comparison of payback with the actual, 5-year and 20-year average R-values for polyisocyanurate. Locations: (a) Ontario, (b) Nova Scotia, (c) Alberta, fuel-electricity.

(a)

(b)

(c)

Figure 8. Percentage comparison of payback with the actual, 5-year and 20-year average *R*-values of phenolic board. (a) Ontario-natural gas, (b) Nova Scotia-oil, (c) Alberta-natural gas.

CONCLUSION

The reference time of five years was previously postulated by a group of experts in the position paper of Canadian General Standards Board, Kabayama [12]. This analysis confirmed that their opinion was fully justified, and it may represent five typical thermal insulating materials with thickness between 20 mm and 90 mm and service life between fifteen and twenty-five years.

The actual thermal performance of the foam board at 1825 ± 25 days of aging (five years) is the proposed design thermal resistance of the foam board. As the aging process depends on the foam thickness, the actual design values of thermal resistivity (conductivity) will also vary with the thickness of the board.

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