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Closed Cell Foam Insulation: A Review of Long Term Thermal Performance Research

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1. Introduction

Research related to closed-cell foam insulation dates back to the 1960s [Cuddihy and Moacanin, 1967; Norton, 1967]. This form of insulation is often more costly than other products, but offers relatively high thermal resistance and intrinsic strength properties. This report will focus on the thermal performance of the products. The specific goals of this project are to:

- Summarize the existing literature on thermal performance of closed cell plastics over the last thirty years.
- Review the science of closed cell plastic foam aging and how test methods have been developed to attempt to address this reality.
- Review the models that are available to predict the long-term performance of closed cell plastic foams.

As with other insulation products, closed-cell foam is designed to retard heat transfer. Convective heat transport is essentially eliminated by the small cell size. In a few specialty products, the cell size is small enough to inhibit gaseous conduction as well, but more often gases with low thermal conductivity are selected to reduce gaseous conduction within the closed cells. These gases are also used to produce the fine cellular structure of closed-cell foam and are called blowing agents. In closed-cell foam insulation, these gases remain within the cells for a long period of time and are of particular interest for two reasons. First, the gases initially selected were found to have an adverse effect on the global environment. This led to the development of multiple generations of products as those gases were transitioned to more benign blowing agents. Second, the gaseous content within the insulation changes over time, which causes the thermal performance of the product to also vary over time, or 'age'.

This paper will review the research that has improved our understanding of the long-term thermal performance of closed cell foam insulation, summarize the science of foam aging, and describe some models that have been developed over the years to investigate the phenomena. An annotated bibliography is included in Appendix A. Standards pertinent to foam insulation performance and aging are summarized in Appendix B.

2. The Physics of Heat Transport Through Closed-Cell Foam Insulation

[Glicksman 1994]

The most comprehensive resource for an in-depth description of foam insulation thermal performance, and the source for the discussion in this section, is Glicksman, 1994. Total heat transport through foam insulation is typically represented as the superposition of the heat transported via solid conduction, gas conduction, and radiation, as shown in Eq. 1. This approximation is valid for low-density materials with modest temperature differences.

$$q_{\text{total}} = \left(q_{\text{gas}} + q_{\text{solid}}\right)_{\text{conduction}} + q_{\text{radiation}} \qquad \text{Eq. 1}$$

where:

q = heat transfer, W/m^2.

The solid conductive portion is approximately linear with foam density, ranging from less than 5% to more than 40% as foam ranges from 10 to 80 kg/m^3. The gas conductivity depends upon the gas mixture within the cells. In new foam, the gas contributes from ~ 40% for foams filled with low-conductivity blowing agents; up to ~70% for foams filled with air. The radiation portion of the heat transfer decreases rapidly as density increases from 5 to 20 kg/m^{3}and more slowly for further increases in density. The foam density is therefore an optimized trade-off between radiation and solid conduction heat transport mechanisms. For CFC-11-filled polyurethane foam, the decreasing radiation heat transfer equals the increasing solid conduction at a density of ~40 kg/m^3.

The solid conduction and radiation performance are determined by the foam morphology, which does not change appreciably over the lifetime of the product. The magnitude of the solid conduction in low density foam is [Glicksman, 1994, page 121] shown in Eq. 2.

$$q_{\text{solid conduction}} = -k_p \frac{(1-\text{Void fraction})}{3}\left[f_s\left(\frac{a}{b}\right)^{0.5} + 2(1-f_s)\left(\frac{a}{b}\right)^{0.25}\right]\frac{dT}{dx} \qquad \text{Eq. 2}$$

where:

k_p	=	cell wall and strut (polymer) thermal conductivity,
f_s	=	fraction of solid in strut,
a/b	=	cell aspect ratio, and
dT/dx	=	temperature gradient.

The major factor in the net radiation flux is the emission from the solid portions of the foam. The radiation heat transfer is usually modeled using the Rosseland equation, which is valid where the radiation mean free path is much less than the foam thickness and the foam is isotropic (that is, the cell aspect ratio is one). The extinction coefficient is the reciprocal of the photon mean free path. Reducing the mean free path of the photons, by reducing the cell size, is therefore an effective way to reduce this portion of the total heat transport, as shown in Eqs. 3 and 4. The radiation transmission from one side of the foam to the other is very small, so that using reflective layers on the exterior foam surfaces has little impact on the radiation heat transport.

$$q_{\text{radiation}} = -\left[\frac{16}{3(\mathrm{K_e})}\right]\sigma T^3 \frac{dT}{dx} \qquad \text{Eq. 3}$$

$$K_e = \frac{4.10}{d}\left(f_s\frac{\rho_f}{\rho_s}\right)^{0.5} + (1-f_s)\left(\frac{\rho_f}{\rho_s}\right)K_{\text{e, cell walls}} \qquad \text{Eq. 4}$$

where:

K_e	=	Extinction coefficient,
σ	=	Stefan-Boltzman constant,
T	=	absolute temperature,
d	=	cell diameter,
ρ_f/ρ_s	=	ratio of foam density to solid polymer density, and
d	=	cell diameter.

The remainder of the total conduction is due to gaseous conduction. As gases diffuse in and out of the foam, that mixture changes, and therefore the total thermal conductivity changes. The thermal conductivity of a gas mixture has been characterized by Wassiljewa and Lindsay and

Bromley as function of mole fraction, thermal conductivity, viscosity, and absolute boiling temperature at one atmosphere pressure, as shown in Eq. 5 [Wassiljewa, 1904; Lindsay and Bromley, 1950]. This form reflects the interactions between gas molecules as explained by Glicksman, 1994, "*The conductivity is a function of the mean free path; the mean free path of a gas component will be altered when a second component is present. For example, nitrogen in the presence of a high molecular weight blowing agent will have reduced contribution to the conductivity because the larger molecules will inhibit the motion of the smaller nitrogen molecules.*"

$$q_{\text{gas conduction}} = -\sum_{i=1}^{N} \frac{y_i k_{gi}}{\sum_{j=1}^{N} \frac{y_i}{4} \left(\left\{ 1 + \left(\frac{\mu_i}{\mu_k} \left(\frac{M_j}{M_i} \right)^{0.75} \frac{\left(1 + 1.5 C_0 \frac{\sqrt{T_{bi} T_{bj}}}{T} \right)}{\left(1 + 1.5 \frac{T_{bj}}{T} \right)} \right)^{0.5} \right\}^2 \left\{ \frac{\left(1 + 1.5 C_0 \frac{\sqrt{T_{bi} T_{bj}}}{T} \right)}{\left(1 + 1.5 \frac{T_{bi}}{T} \right)} \right\} \right)} \frac{dT}{dx} \qquad \text{Eq. 5}$$

where:

N	=	Number of gas species,
y_i	=	Mole fraction of i^{th} component,
k_{gi}	=	Thermal conductivity of pure i^{th} component,
μ	=	Viscosity of pure i^{th} component,
M	=	Molecular weight,
C_0	=	1.0 unless one of the i or j gases is polar (such as water), and
T_{bi}	=	Absolute boiling temperature at one atmosphere pressure of pure i^{th}

component.

The radiation and gas conduction are both dependent upon the local temperature and will therefore vary throughout the thickness of the foam. Even more important, the gas mixture will vary throughout the thickness of the foam during the diffusion, or aging, process, causing variations in the gas conduction per Eq. 5.

As with any air-filled insulation, the thermal conductivity is temperature dependent, decreasing with temperature. Depending on the selected blowing agent, condensation may occur within the cell volume at lower temperatures. Most research has shown that the addition of this small amount of liquid to the cell walls has a negligible effect on the solid conduction portion of the heat transfer [Bogdan, Hoerter, and Moore. 2005, Kumaran et al. 1989]. However, if any portion of the cell gas contents condenses, the partial pressure (and mole fraction) for that gas will decrease, impacting the thermal conductivity of the gas mixture. The reduced pressure of the low thermal conductivity gas in the mixture causes an increase in the gas conductivity, which continues as the temperature drops until all the blowing agent throughout the foam thickness has condensed. At that point, the thermal conductivity will again decrease with decreasing temperatures.

In closed-cell foam, the radiation and conduction heat transfer mechanisms are coupled, with cell walls largely transparent to radiation and cell struts largely opaque to radiation. This is a second order effect, so that for most purposes they can be treated as independent mechanisms. However, this coupled mode of heat transfer makes the measured effective thermal conductivity sensitive to the total thickness of the foam and the emissivity of the testing apparatus surfaces. Below a certain threshold, the foam is 'optically thin', interacting with the surfaces of the thermal conductivity measurement device. In that regime, the measured effective thermal conductivity will vary with foam thickness. Outside that regime, the foam is 'optically thick', and the measured effective thermal conductivity no longer varies with thickness. This characteristic is an important consideration in the thin-slicing accelerated aging method described below. The optically thick regime where radiation can be modeled as a diffusion process should start ~10 mm for most polyurethane foams [Glicksman, 1994].

3. The Science of Foam Aging [Hoogendoorn 1994]

The most comprehensive resource for an in-depth description of foam insulation aging, and the source for the discussion in this section, is Hoogendoorn, 1994. The foam aging is caused by the diffusion of atmospheric gases into the foam and the diffusion of blowing agent gases out of the foam. The process can be broken down into several stages. First, the gas within a cell dissolves into the cell wall or strut material. Second, the gas is transported across the thickness of the cell wall or strut. Third, the gas is released into the bounding space, either an adjacent cell or the open surrounding environment. Thicker cell walls and struts retard the diffusion process, but increase the solid conduction heat transfer; so again, the foam design is based on an optimal compromise between these factors.

Research has generally agreed that this three-step process within homogenous foam can be described with an effective diffusion resistance, as described by Fick's Law and shown in Eq. 2. Within any given foam, the diffusion resistance for each gas is a unique function of the material and the temperature. That is, while elevated temperatures will reduce the diffusion resistance for all gases, the amount of reduction will be different for each gas. Also, for both modeling and accelerated aging purposes, modifications are often made to consider differences in diffusion parameters at regions at or near the surface vs. within the core of the foam.

$$\frac{\partial c}{\partial t} = D_{eff} \frac{\partial^2 c}{\partial x^2} \qquad \text{Eq. 6}$$

Where:

c	=	gas concentration as a function of time,
t	=	time, and
D_{eff}	=	effective diffusion coefficient.

Note the diffusion process is driven by the gradient in the partial pressure for each gas, independent of other gases present. The blowing agent gases are selected based upon their characteristics of low thermal conductivity and slow diffusion rates through the foam polymers. The atmospheric gases have a greater thermal conductivity and are typically much smaller molecules with much faster diffusion rates through the foam. The impact of this inward atmospheric gas diffusion is the early steeper portion of the aging curve shown in Fig. 1. Over a longer period of time, the blowing agent diffuses out of the foam, increasing the mixed gas thermal conductivity still further but at a much slower rate.

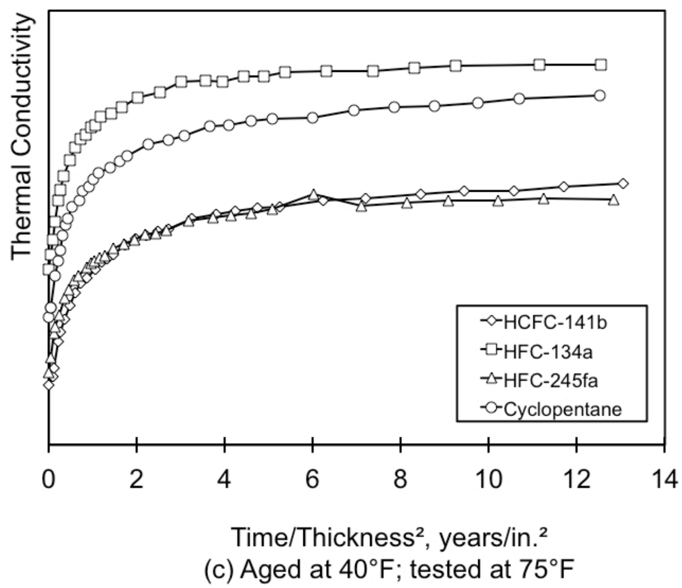

Figure 1 Typical aging curves, data from prototype specimens in [Wilkes et al. 2003]

In addition to work on accelerated aging, much research has focused on full product thickness aging[Desjarlais, 1984; Mukhopadhyaya, et al. 2010; Wilkes, et al., 2003; Bomberg and Alumbaugh, 1993; Desjarlais, Christian, and Graves, 1993; Kabayama, 1987; Yarbrough, Graves, and Christian, 1991]. One of the more important results of this work is that non-permeable facers, such as foil, are often less effective than expected. The bonding between these facers and the foam body is often flawed, providing an open pathway for gas exchanges[Glicksman 1994b].

4. Accelerating Foam Aging

As discussed, foam aging takes place over a long time frame. For thick foams with large molecule blowing agents, the aging could take more than 50 years! Accelerating the aging process is desirable, then, for several reasons. First, rated values are used to make product comparisons; it is useful if the rated values therefore reflect the long term performance of each product. Second, designers need to have long term performance information when balancing out expected heat transfer for buildings or appliances against the size of the equipment needed to heat or cool those spaces over their lifetime. Third, evaluating possible product improvements, such as the transition from CFC blowing agents to less harmful gases, needs to be made based on the product's long term performance. Overall, the accelerated aging research has focused on (1) elevated temperature to increase diffusion rates, (2) thin slicing to reduce diffusion lengths, and (3) evaluating diffusion parameters to facilitate models.

4.1 Elevated temperature age acceleration

The elevated temperature work is interesting because the same experimental results led to two starkly different conclusions, depending upon which side of the Atlantic Ocean the researcher called home. The experimental work clearly showed, for CFC blowing agents used in the 1980's, that a limited time at elevated temperature would effectively complete the inward diffusion of atmospheric gases while having a minimal impact upon the outward diffusion of the blowing agents. (In fact, the diffusion rates for the CFCs were more than an order of magnitude less than those for atmospheric gases.) For example, Bomberg and Gilbo exposed foam insulation specimens to varying temperatures for varying periods of time. They found that after two years, the foam thermal performance was not affected by this treatment because for all cases the inward diffusion of atmospheric gases was complete but the outward diffusion of blowing agent was relatively unchanged [Bomberg and Gilbo 1989]. Hoogendoorn notes that elevated temperature aging provides a better representation of long term performance for those foams with the slowest-diffusing blowing agents [Hoogendoorn 1994].

On the European side of the Atlantic, this elevated temperature age acceleration was considered adequate to characterize the long-term thermal performance, based on the observation that a large part of the blowing agent would remain trapped within the foam cells throughout the service life for that product. On the North American side of the Atlantic, elevated temperature age acceleration was considered inadequate because it failed to quantify the amount of blowing agent that would diffuse out of the foam during the service life. This dichotomy led to the inclusion of elevated temperature procedures for foam ratings in Europe and the development of thin-slicing test methods in Canada and the U.S. The European standards have been based on a number of studies, some of which included 15 years of full thickness foam aging. [BING, 2006; Isberg, 1988] In most of these European standards, correction factors are applied to account for the long term blowing agent gas diffusion not captured in the elevated temperature measurement.[ACERMI; Annex C in multiple EN standards as shown in Appendix B]. Pending the completion of the thin-slicing research, Canada and the U.S. also allowed ratings based upon specified times at elevated temperatures or six months of room temperature aging, producing values similar to those used in Europe. In North America, correction factors were not used, but the process was seen to provide consistent ratings, even though it was a poor representation of long-term performance.

The differences between elevated temperature and thin-slicing acceleration methods are greater with modern blowing agents than with the CFC generation of gases, because the diffusion rates for air and blowing agent gases are not as far apart as they once were. The correction factors in European standards include several qualifying options based on the observed rate of aging.

4.2 Thin slicing age acceleration

As shown in Eq. 2, the rate of gas diffusion is inversely proportional to the square of the foam thickness. Thin slicing therefore accelerates the gas diffusion for all species proportional to the square of the ratio of the product thickness to the slice thickness, as shown in Eq. 7. For example, if the slice is one fourth as thick as the foam product, then one year of slice aging will result in the same total gas diffusion as 16 years for the full thickness product [ASTM C1303, CAN/ULC S770].

$$Time_{\text{thin slice aging}} = Time_{\text{full product thickness aging}} \left(\frac{thickness_{\text{thin slice}}}{thickness_{\text{product}}} \right)^2 \qquad \text{Eq. 7}$$

As with any test method, the devil is in the details. The important factors for thin slicing acceleration are:

- Thickness of the destroyed surface layers (TDSL)
- Homogeneity and therefore the slice extraction location from the foam thickness profile

- Slicing mechanism – slice flatness – slice uniformity
- Accuracy of thermal conductivity measurement device

Jan Isberg and Per Sandberg led early European research in this area [Isberg 1988, Sandberg and Isberg 1989, and Sandberg 1990]. This research covered all the major factors addressed during research that would continue to be of interest to researchers from 1988 to 2012, except for the influence of blowing agents not in use at that time. They recognized the importance of including surface slices for XPS products and the need for an adequate number of slices in the thermal conductivity measurement. Their research concluded with a practical proposal to use a single set of measurements taken at 90 days for a set of 10 mm slices representing the whole profile, or cross section, of the insulation product. Using empirical data as well as theoretical analysis, they concluded that this would provide 25-year aged thermal conductivity values accurate to +-5% for PUR ($CFCl_3$) of 20-200 mm thickness and for XPS (CF_2Cl_2) of 50-200 mm thickness (30 mm if the surface skin is retained).

Bomberg and Kumaran led most of the Canadian research, and have provided most of the research relevant to spray foam products [multiple references from Bomberg and Kumaran, with varying coauthors, from 1988 to 1994. Also see Yuan, 2010 re spray foam] In the U.S., the early research was largely led by Glicksman at the Massachusetts Institute of Technology (MIT) and Booth at Dow Chemical, with supporting work at Oak Ridge National Laboratory[see references from Glicksman, Booth, McElroy, Graves, and Wilkes]. The early work on foam thin-slicing coincided with great improvements in the accuracy and convenience of thermal conductivity measurement devices, and much of the research on foam performance was intertwined with this development [McElroy et al., 1991; Graves et al., 1991].

The work on thin slicing during the development of the ASTM C1303 standard test method focused on the integrated lifetime performance, usually over a period of 15 years. However, multiple researchers have noted that the instantaneous value after 5 years is approximately equal to that average[Stovall, 2009; Singh and Coleman, 2007]. The latest prescriptive version of C1303 therefore uses this equivalence, as does the ULC/CAN-S770 test method.

In any closed-cell product there will be some finite, albeit small, fraction of open cell walls. However, when foam is sliced, all the cells at the cut line are immediately open to the environment. This portion of the foam thickness is therefore immediately full of atmospheric gases and devoid of low-conductivity blowing agents. This introduces errors in the calculated time for the thermal conductivity measurement as well as in that thermal conductivity itself. Much research has shown that this error source will be less than 5% if the total slice thickness is on the order of 10 mm or more[Fabian, et al., 1997; Stovall, 2006; Schwartz, Bomberg, and Kumaran, 1990; Booth and Grimes, 1993]. A recent ruggedness test for ASTM test method C1303 quantified the combined magnitude of the TDSL errors in the ~1-3% range [Stovall 2012; ASTM 2012].

Many of the references listed in Appendix A include direct comparisons between field- and laboratory-aged full thickness specimens and thin slice aging predictions, lending a high degree of confidence in this test method [Christian et al, 1993; Stovall, Vanderlan, and Atchley, 2012; Mukhopadhyaya, et al., 2010; Bomberg, 1993; Booth, 1993].

4.3 Measuring diffusion rates to facilitate models

Early researchers noted that the diffusion rates for gases entering the cells are much faster than the rates for the blowing agent gases leaving the cells, and divided the aging curve into two distinct regions [Booth 1991; Graves et al., 1995; McElroy et al., 1991]. However, the diffusion phenomena for all gases are continuous over the entire time period, frustrating their efforts to use the slopes of the two regions to accurately measure diffusion rates. Diffusion rates can be more successfully measured using gravimetric and gas analysis equipment [Glicksman, Ostrogorsky and Chiapetta, 1984; Bhattacharjee et al., 1994; Singh, Ntiru, and Dedecker, 2003; Shankland, 1990].

5. Modeling Capabilities

Models have been used extensively to expand our understanding of foam insulation performance. When model predictions match closely with experimental measurements, they provide assurance in our understanding of the combined physical phenomena. For example, both full thickness and thin slice aging data has confirmed our use of effective diffusion coefficients for homogenous materials [Glicksman 1994 and many others in Appendix A]. Other times, failure to match experimental measurements is also revealing. For example, results from models of foam with barrier surfaces did not match experimental data. This lead researchers to examine why the barriers were not as effective as expected, and to develop new test methods to quantify that effect [Glicksman 1994b].

Most of the models discussed here have been developed as a part of a specific research program and are only available to fellow researchers within that organization. One exception would be the generic thermal conductivity codes that can be used to calculate gas diffusion via the analogy between heat and mass transfer.

As discussed above, the radiation and solid conduction within foam insulation are relatively unchanged over time and are typically modeled using the heat transfer relationships described above and in [Glicksman 1994]. The gas conduction is a function of the gas mixture within the foam, which is variable both in time and space. The gas diffusion, typically modeled using Fick's Law as described above, must therefore be calculated separately for each gas species.

The Distributed Parameter Continuum (DIPAC) model was developed by the Institute for Research in Construction/National Research Council of Canada (IRC/NRC). This work reflects the fundamental physics, including temperature-dependent diffusion coefficients, and has been successfully compared to experimental data [Bomberg and Kumaran 1994]. This model requires input of over 25 parameters with separate information for the core and surface layers, including density, initial blowing agent fraction and polymer index for each blowing agent, and effective diffusion coefficients at two temperatures for N_2, O_2, and each of the blowing agents [Bomberg 1988]. Later work, focused on evaluating surface barriers, benchmarked the 2-D form of the DIPAC model against experimental data. This project was only able to get agreement by tweaking a lateral diffusion parameter, but there were questions regarding experimental factors in that work [Mukhopadhyaya et al. 2004].

The Effective Conductivity Versus Age (ECVA) code was developed at the Massachusetts Institute of Technology (MIT). This tool uses measured foam diffusion coefficients and a numerical solution for foam aging, and was benchmarked against full thickness aging out to about two years. This work showed that most foam surface barriers have little effect on aging, and emphasized the advantages of thin slicing over elevated temperature acceleration methods [Ostrogorsky and Glicksman 1985 and 1986, Ostrogorsky 1987].

The early numerical models ran on computers that were much more limited than those available in 2012. One area of research focused on getting the results more efficiently by using the difference in time constants for gas diffusion vs. thermal conductance to accelerate the convergence of a finite difference model [Wang and Hagentoft, 1998 and 1999]. Other work used implicit methods to improve convergence, comparing a standard analytical solution for a single gas to the results of their numerical procedure before producing multi-gas results [Kondapi, Booth and Yarbrough, 1999].

The Dow Thermal Performance Prediction Model used a semi-empirical approach. It was employed to provide a quality assurance tool using physical measurements that could be made immediately after foam manufacture. This model was also benchmarked against full-thickness measured data for CFC-12 blown foams [Booth. 1993].

The gas diffusion is a mass transfer process analogous to heat transfer in a homogenous specimen. Many of the models used to predict the localized time-variant gas contents are based on similar finite difference or finite element heat transfer models. One such model, Heating 7, was used directly to model the partial pressure for each gas specie in split pipe insulation, where the gas diffusion is much more complex than in the more typically modeled slab geometry (see Fig. 2) [Childs 1993].

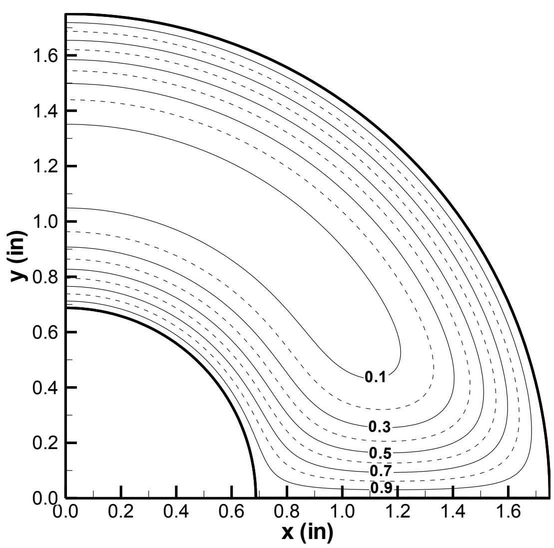

Figure 2 Application of Heating 7 finite difference for 3-D gas diffusion in split pipe insulation showing ingress of nitrogen during initial aging (contours show the ratio of local partial pressure to atmospheric pressure), work by Ken Childs given to this author from work described in [Wilkes, et al., 2002]

Other models have been more complex, looking at a two-zone approach to account for differences in the diffusion coefficients near densified or adhered surfaces. One such model, AgeSim, was developed at Huntsman Polyurethanes and was first validated against measured data for the core foam region. An effective diffusion coefficient for each gas was separately obtained by cell gas analysis and used as input to the model. AgeSim then combined the validated methodology with empirical results to assign a “Calibrated skin factor” from elevated temperature aging data iterated through the model [Singh, Ntiru, and Dedecker 2002 and 2003, Singh and Coleman 2007]. Such ‘tweaking’ factors can be found in many models, and are useful so long as the adjustments are based upon a thorough understanding of the physical process.

During the development of the ASTM C1303 test method, a series representation of the exact solution for simple geometries using Fick’s Law was programed and applied to a two-zone representation of surface and core thin slices. A parametric examination of possible relationships between the diffusion coefficients in the two regions was explored, but did not match experimental measurements well [Stovall and Bogdan 2007].

One set of models focused not on foam aging, but on interior and exterior application factors, using publicly available codes, WUFI and THERM [Lohonyai, Korany, and Ross 2012]. This effort examined the influence of foam density for three possible foam applications to concrete masonry walls.

Appendix A Bibliography of Research in Foam Aging

Three tables in this appendix summarize research since 2002, applications of closed-cell foam insulation, and research pre-2002. Complete citations are found in the references.

Table 1 Post-2002 Research

Polyurethane: Use WUFI for hygrothermal and THERM for thermal performance, initial performance only, no aging. Compare interior vs. exterior applications and two foam densities, University of Alberta, Canada	Lohonyai, Korany and Ross. 2012. Effective Foam Insulation For Single-Wythe Concrete Masonry Walls
2nd C1303 ruggedness test (slice origin, slice thickness, homogeneity screening tests, accuracy compared to 5-year full thickness aging)	Stovall, Vanderlan, and Atchley. 2012. Evaluation of Experimental Parameters in the Accelerated Aging of Closed-Cell Foam Insulation Stovall. 2009. Measuring the Impact of Experimental Parameters upon the Estimated Thermal Conductivity of Closed-Cell Foam Insulation Subjected to an Accelerated Aging Protocol: Two-Year Results Stovall and Bogdan. 2007. Measuring the Impact of Experimental Parameters upon the Estimated Thermal Conductivity of Closed-Cell Foam Insulation Subjected to an Accelerated Aging Protocol
Compares thin slice aging to 180 days at 23C and to 90 days at 60C for spray foam from 25 to 75 mm thick.	Yuan. 2010. Thermal Conductivity of Spray Polyurethane Foam Insulation Materials
Foam field-aged for 6 years. Impermeably-faced products also aged significantly.	Mukhopadhyaya, et al. 2010 In-Situ Long-term Thermal Performance of Impermeably faced Polyiso Foam Boards
Combines model and empirical data to evaluate bias for thin slicing test methods for two materials	Singh and Coleman. 2007. Accelerated Aging Test Methods for Predicting the Long Term Thermal Resistance of Closed-Cell Foam Insulation
Final report on 1st C1303 ruggedness test (TDSL)	Stovall. 2006. Interlaboratory Comparison of the Thickness of the Destroyed Surface Layer of Closed-cell Foam Insulation Specimens

Compares rated R-values based on 2001 version of CAN/ULC-S770 to full thickness at ages < 5 years, finds R-values overstated with that test method.	Graham. 2006. Testing LTTR, Research Reveals the LTTR Method May Be Over-Reporting Results
Important observations and measured data showing impact of blowing agent condensation on foam effectiveness (R-Value) at lower temperatures.	Bogdan, Hoerter, and Moore. 2005. Meeting the Insulation Requirements of the Building Envelope with Polyurethane and Polyisocyanurate Foam
Compare 25 weeks at 70C to model result, supports approach described in EN13165, Annex C – European standard, new in 2003	Dedecker, Baes and Singh. 2003. The Measurement of 'Aged Thermal Conductivity' of Factory Produced Insulation Boards
Model validation: 1) compare test method (S770) to model, 2) compare model to boards aged in lab	Singh, Ntiru, and Dedecker. 2003. Long Term Thermal Resistance of Pentane Blown Polyisocyanurate Laminate Boards
Extending thin-slice methodology to impermeably faced products, initial results in a long-term project	Mukhopadhyaya et al. 2002. Long-term Thermal Resistance of Polyisocyanurate Foam Insulation with Impermeable Facers
Compared results for versions of S770 and C1303 in use in 2002	Stovall, Fabian, Nelson, and Beatty. 2002. A Comparison of Accelerated Aging Test Protocols for Cellular Foam Insulation

Table 2 Foam Insulation Applications

Important observations and measured data showing impact of blowing agent condensation on foam effectiveness (R-Value) at lower temperatures.	Bogdan, Hoerter, and Moore. 2005. Meeting the Insulation Requirements of the building Envelope with Polyurethane and Polyisocyanurate Foam
Compares rated R-values based on 2001 version of CAN/ULC-S770 to full thickness at ages < 5 years, finds R-values overstated with that test method.	Graham. 2006. Testing LTTR, Research Reveals the LTTR Method May Be Over-Reporting Results
Considers both energy performance during lifetime service and lifetime emissions, finds new CFC alternatives will have a reduction in global warming.	Fischer, Fairchild, and Hughes. 1992. Energy and Global Warming Impacts of CFC Alternative Technologies for Foam Building Insulations
Final Report of an expert working group to establish long-term R-values for foam insulation products available at that time.	Kabayama. 1987. Long-Term Thermal Resistance Values of Cellular Plastic Insulations

Comparing impact on foam aging of: (1) plastic and steel sheet facing materials, (2) alternative blowing agents, and (3) a range of aging temperatures. Finding: the time required for a given change in thermal conductivity with aging at 40F was roughly twice as long as for aging at 90F, while the time required at -10F was about 10 times as long as at 90F. Impact of plastic confinement was similar to that projected using measured diffusion coefficients.	Wilkes, Yarbrough, and Weaver. 1997. Aging of Polyurethane Foam Insulation in Simulated Refrigerator Walls, Wilkes, Yarbrough, Gabbard, Nelson, and Booth. 2001. Aging of Polyurethane Foam Insulation in Simulated Refrigerator Panels - Three-Year Results with Third-generation Blowing Agents Wilkes, Yarbrough, Nelson, and Booth, 2003. Aging of Polyurethane Foam Insulation in Simulated Refrigerator Panels - Four-Year Results with Third-generation Blowing Agents
Overview of what was known in 1993, including measured data for field exposed materials.	Bomberg and Alumbaugh. 1993. Factors Affecting the Field Performance of Spray Applied Thermal Insulating Foams
Foam field-aged for 6 years. Impermeably-faced products also aged significantly.	Mukhopadhyaya, et al. 2010 In-Situ Long-term Thermal Performance of Impermeably faced Polyiso Foam Boards
Early work comparing thin slices aged at multiple temperatures to full thickness foam aged in a roof exposed to the exterior environment. Also showed early work to derive diffusion coefficients from aging thermal conductivity data.	Christian, et al. 1991. Thermal Measurement Of In-Situ And Thin-Specimen Ageing Of Experimental Polyisocyanurate Roof Insulation Foamed With Alternative Blowing Agents
10mm thin slice predictions matched field-exposed HCFC-141b blown polyisocyanurate within 3%	Desjarlais, Christian, and Graves. 1993. In-Situ Aging of Roof Systems Containing Polyisocyanurate Roof Insulation Foamed with Alternative Blowing Agents
Foam chemistry related to fire retardants	Singh, et al. 2006. Effect of Formulation Parameters on Performance of Polyisocyanurate Laminate Boardstock Insulation, API 2006
Exterior foundation application – EPS only - no deterioration after 30 months in situ – no aging involved	Swinton et al. 1999. In Situ Performance of Expanded Molded Polystyrene in the Exterior Basement Insulation Systems (EIBS)

Exterior foundation application – spray polyurethane only - no deterioration after 30 months in situ – "The aging process is slowed because the polyurethane foam was sprayed on dry surface of old concrete. In principle, one may consider that the 76-mm thick medium density SPF is exposed to one-sided aging only."	Swinton, et al. 2006 In Situ Performance Evaluation Of Spray Polyurethane Foam In The Exterior Insulation Basement System (EIBS)
Interesting work, 1 inch boards aged for 1 year in various environments.	Zarr and Nguyen. 1994. Effects of Humidity and Elevated Temperature on the Density and Thermal Conductivity of a Rigid Polyisocyanurate Foam Co-Blown with CCl3F and CO2
Compare n-pentane blown polyisocyanurate to HCFC-141b boards. Lower initial thermal conductivity offset by slower aging and smaller cell sizes.	Letts, et al. 2003. Insulation Boards Bridge to the 21st Century
Polyurethane: Use WUFI for hygrothermal and THERM for thermal performance, initial performance only, no aging. Compare interior vs. exterior applications and two foam densities, University of Alberta, Canada	Lohonyai, Korany and Ross. 2012. Effective Foam Insulation For Single-Wythe Concrete Masonry Walls
Compares metal foils to polymeric facings, aged 1-in. thick boards for 600 days.	Soukup and Laughlin. 1991. Development of an All-Purpose Impermeably-Faced Roof Insulation

Table 3 Pre-2002 Research

Comprehensive work – 1st/Best reference: Chapter 5, Heat transfer in foams," by Leon Glicksman and Chapter 6, "Thermal ageing," by C. J. Hoogendoorn. See especially 139-143 describing influence of foam properties on overall conductance	Glicksman. 1994. Heat Transfer in Foams Hoogendoorn. 1994. Thermal Ageing
MIT – GLICKSMAN: Focus on theoretical basis for models, experimental techniques re barrier adhesion	
Early comparison of theoretical models to experimental data, pointing the need for better radiation models and better gas diffusion data.	Valenzuela and Glicksman. 1983. Thermal Resistance and Aging of Rigid Urethane Foam Insulation
Reviews fundamental relationships between foam morphology and conductive and radiative heat transfer through foam.	Schuetz and Glicksman, 1984, A Basic Study of Heat Transfer Through Foam Insulation

Broad research program spanning measurements of polymer properties, guarded hot plate measurements at low temperatures under vacuum to eliminate radiation and gas transport, diffusion measurements, dye techniques to expose inadequate foam-barrier bonds	Glicksman, Ostrogorsky and Chiapetta. 1984. Effective Conductivity of Aging Polyurethane Foam,
Using measured foam diffusion coefficients, presents the equations used in a numerical solution for foam aging, with benchmarks shown to full thickness aging out to ~ two years. Shows most foam surface barriers have little effect on aging. Emphasizes the advantages of thin slicing over elevated temperature acceleration methods.	Glicksman and Page. 1992. Long-Term Performance of Closed-Cell Foam Insulation Ostrogorsky and Glicksman. 1989. Time Variation of Insulating Properties of Closed Cell Foam Insulation Ostrogorsky. 1985. Ageing of polyurethane foams
Proposes a test method to quantify the barrier performance	Glicksman 1994. The Role of Barriers in Reducing the Aging of Foam Panels
CANADA – BOMBERG, KUMARAN: Focus on thin-slicing vs. elevated temperature, support development of CAN/ULC-S770, spray foam	
Final Report of an expert working group to establish long-term R-values for foam insulation products available at that time.	Kabayama. 1987. Long-Term Thermal Resistance Values of Cellular Plastic Insulations
Important observations and measured data showing impact of blowing agent condensation on foam effectiveness (R-Value) at lower temperatures.	Kumaran, et al. 1989. A Method for Evaluating the Effect of Blowing Agent Condensation on Sprayed Polyurethane Foams
Overview of the state of knowledge regarding thin slice aging acceleration in 1989.	Edgecombe. 1989. Progress in Evaluating Long-Term Thermal Resistance Of Cellular Plastics
Early work applying thin-slicing methodology to spray foam.	Bomberg and Kumaran. 1989. Report on Sprayed Polyurethane Foam with Alternative Blowing Agents
Detailed explanation re the measurement of TDSL	Schwartz, Bomberg and Kumaran. 1989. Measurements Of The Rate Of Gas Diffusion In Rigid Cellular Plastics
Overview – interesting reference to experimental work that shows impact of temperature on aging (where/why might get useful data).	Bomberg and Gilbo. 1989. Introduction to Aging of Cellular Plastics

Shows performance after 2 years unaffected by periods of elevated temperature up to 7 months. Also examines influence of differences between diffusion resistance in surface and core regions.	Bomberg. 1990. Scaling factors in ageing of gas-filled cellular plastics
Use of thin-slice accelerated aging to evaluate potential blowing agent substitutions.	Kumaran and Bomberg. 1990. Thermal Performance Of Sprayed Polyurethane Foam Insulation With Alternative Blowing Agents.
Overview of the state of knowledge regarding thin slice aging acceleration in 1989. ALSO, reviews broad range of uncertainty for C518 results for all insulation materials at that time.	Bomberg and Brandreth. 1990. Evaluation Of Long-Term Thermal Resistance Of Gas-Filled Foams: State Of The Art
Review of pre-1991 research re accelerated aging, both heat and thin-slicing, and description of future research needs	Bomberg and Kumaran, 1991. Evaluation of Long-Term Thermal Performance of Cellular Plastics Revisited
Editorial work providing discussion of field performance vs. lab measurements with anecdotal evidence for both fibrous and foam products	Bomberg. 1993. The Evolution of Insulation Research
Interesting 3-way comparison between thin-slice predictions and full thickness aging, both in the field and in the laboratory. Laboratory and field aging agreed within ~1%. Thin-slice predictions agreed with full thickness aging within ~6%	Bomberg. 1993. Predicting Field Thermal Performance of a Modified Resol Foam from Laboratory Data
Overview of what was known in 1993, including measured data for field exposed materials.	Bomberg and Alumbaugh. 1993. Factors Affecting the Field Performance of Spray Applied Thermal Insulating Foams
Describes significant experience with thin-slicing spray polyurethane and need for quality assurance processes for new spray products.	Bomberg and Kumaran. 1994. Testing Long-Term Thermal Resistance of Sprayed Polyurethane Foam,
	Bomberg M.T. and M.K. Kumaran, 1994, Laboratory And Roofing Exposures Of Cellular Plastic Insulation To Verify A Model Of Aging
Demonstrated ability of multiple labs to perform the thin slicing procedure, but with variations of 7 to 25% of the predicted LTTR between labs.	Hofton. 2001. Standard For Determination Of Long-Term Thermal Resistance (LTTR) Of Closed Cell Thermal Insulating Foams, CAN/ULC-S770-99 Round Robin Test Programme

EUROPE	
Early work to differentiate between the conductive and radiative heat transfer through foam	Jones. 1967. The Effect of Thickness and Temperature on Heat Transfer through Foam Polymers
Compares different methods used to rate foam insulation thermal conductivity at that time and recommends a common practice for Nordic countries based on 10 mm slices measured after 3 months. This research covers all the major factors addressed during research between 1988 and 2012, except for the influence of blowing agents not in use at that time. It recommends that measurements taken at 90 days for 10 mm slices are accurate predictions for 25year-aged products +-5% for PUR ($CFCl_3$) of 20-200 mm thickness and for XPS (CF_2Cl_2) of 50-200 mm thickness (30 mm if the surface skin is retained).	Isberg, J. 1988. Thermal Insulation – Conditioning of Rigid Cellular Plastics Containing a Gas with Lower Thermal Conductivity Than Air Prior to Determination of Thermal Resistance and Related Properties
Good early work on thin slicing, discusses general theory and potential error sources	Sandberg, P. I. and J. Isberg, Measurement of Aged Thermal Resistance of Rigid Gas-Filled Cellular Plastics, J of Thermal Insulation, V13, Oct 1989
Considering use of CO_2 as an alternative blowing agent. Includes an excellent description of the Wassiljewa equation for the thermal conductivity of gas mixtures.	Smits and Thoen. 1991. Fundamental Aspects of Thermal Conductivity Aging and Dimensional Stability of Rigid Polyurethane Foams
Describes work including 15 years of full thickness aging for polyurethane boards (possibly concluded in 1998, so boards manufactured in 1983?). Also describes test results for impact of water absorption and other influences.	BING, Federation of European Rigid Polyurethane Foam Associations. 2006. Thermal Insulation materials Made of Rigid Polyurethane Foam (PUR/PIR)
PhD thesis	Svanstrom, M., 1997, Blowing Agents in Rigid Polyurethane Foam
Compares results from 90 day elevated temperature thin-slice accelerated aging methods, pointing out that a correction factor is needed for the 90 day approach but not for the thin slice approach.	Sandberg. 1990. Deterioration of Thermal Insulation Properties of Extruded Polystyrene: Classification and Quality Control System in Sweden

OAK RIDGE NATIONAL LABORATORY: Focus on thin-slice aging, full thickness field exposure	
Uses a fully coupled conductive and radiative algorithm to explore interactions between the measurement device and the specimen that impact the measured value of thermal conductivity.	Fine, et al. 1981. Heat Transfer In Building Thermal Insulation: The Thickness Effect
Aging full thickness boards 3 years in the lab and installed as foundation insulation – show long term average R-value ~7-10% less than the 180-day value	Yarbrough, Graves, and Christian. 1991. Thermal Performance of HCFC-22 Blown Extruded Polystyrene Insulation
Early thin slicing work on PIR boardstock, comparing thermal conductivity measurement apparatus, impact of slice thickness and aging temperature, applying models developed at ORNL and MIT	McElroy et al., 1991, Laboratory Test Results on the Thermal Resistance of Polyisocyanurate Foamboard Insulation Blown with CFC-11 Substitutes – a Cooperative Industry/Government Project
Examining the early heat flow meter apparatus and influence of their accuracy on thin-slice method	Graves, et al. 1991. Interlaboratory comparison of four heat flow meter apparatuses on planed polyisocyanurate boards foamed with CFC-11
Early work comparing thin slices aged at multiple temperatures to full thickness foam aged in a roof exposed to the exterior environment. Also showed early work to derive diffusion coefficients from aging thermal conductivity data.	Christian, et al. 1991. Thermal Measurement Of In-Situ And Thin-Specimen Ageing Of Experimental Polyisocyanurate Roof Insulation Foamed With Alternative Blowing Agents
10mm thin slice predictions matched field-exposed HCFC-141b blown polyisocyanurate within 3%	Desjarlais, Christian, and Graves. 1993. In-Situ Aging of Roof Systems Containing Polyisocyanurate Roof Insulation Foamed with Alternative Blowing Agents
Compares thin slice predictions to field-aged boards in multiple roof types over 3.4 years.	Christian et al. 1993. The Technical Viability of Alternative Blowing Agents in Polyisocyanurate Roof Insulation: A Cooperative Industry/Government Project
Tested slice thicknesses as small as 0.6 mm, using measured TDSL to correct measured values for thermal resistance.	Booth, Graves, and Yarbrough. 1995. Aging of Thin-Slices of PIR Foams Manufactured with Alternative Blowing Agents
Broad study done to support the development of ASTM C1303. Important findings regarding timing of thermal conductivity measurements.	Graves et al. 1995. Interlaboratory comparison on Estimating the Long-Term Thermal Resistance of Unfaced, Rigid, Closed-Cell, Polyisocyanurate (PIR) Foam Insulation – A Cooperative Industry/Government Project

Compares thin slice predictions to field-aged boards in multiple roof types over 5 years, showing they matched within 1.5%. Multiple slice thicknesses were used in the comparison.	Christian, et al. 1995. Five-Year Field Study Confirms the PIMA Standard for Estimating Polyisocyanurate Insulation Long-Term Thermal Performance
Using thin slices, shows variation from 30 to 40% for diffusion coefficients measured gravimetrically to those measured using thermal conductivity. Discusses practical limitations to method.	Booth, Graves, and Yarbrough. 1996. Effective Diffusion Coefficients for CFC-11 by Gravimetric Depletion from Thin Slices of PIR Foam
OTHER U.S. LABORATORIES	
Focus is on the difference between rated/label values for thermal resistance and the changes that occur under multiple aging conditions for the first 2 years.	Desjarlais and Tye, 1987, Experimental Methods for Determining the Thermal Performance of Cellular Plastic Insulation Materials Used in Roofs
Interesting work, 1 inch boards aged for 1 year in various environments.	Zarr and Nguyen. 1994. Effects of Humidity and Elevated Temperature on the Density and Thermal Conductivity of a Rigid Polyisocyanurate Foam Co-Blown with CCl3F and CO2
INDUSTRY: Focus on test method development to facilitate product improvements and product ratings	
Comparison between two field aged PIR specimens, one open cell and one closed cell, over five year period. Compares measured values to predicted values.	Muhlenkamp and Johnson. 1983. In-Place Thermal Aging of Polyurethane Foam Roof Insulations
Points out problems associated with elevated temperature aging, specifically cell rupture and product swelling	Booth, and Drouin. 1989. R-Value Aging of Rigid Foam Insulation Products
Multiple papers re heat aging, thin slice aging, gas diffusion rates, differences between core and surface slices	SPI. 1989. Proceedings 1st Int. Workshop Long-Term Thermal Performance of Cellular Plastics, Canada Some papers reproduced in J of Thermal Insulation V13, April 1990
Collation of manufacturers' data in 1990 with emphasis on aging and variation with temperature	Strzepek, W.R., 1990, Overview of Physical Properties of Cellular Thermal Insulations
Compares full thickness aging after 11 years to full thickness aging after 5 years for foil-faced PIR products.	Hagan and Miller. 1990. Long-Term R-Values and Thermal Testing Requirements for Rigid Insulating Foams

Describes apparatus and analysis along with measured values for multiple gases in multiple foam specimens.	Shankland. 1990. Measurement of Gas Diffusion in Closed-Cell Foams
Major focus on extracting diffusion coefficients from thermal conductivity data.	Booth. 1991. Some factors affecting the long-term thermal insulating performance of extruded polystyrene foams, insulation materials, testing and applications.
Used slices with up to 8% TDSL, Corrections made to all results.	Booth and Grimes. 1993. Comparison of Full-Board and Thin-Slice Aging of XEPS Manufactured with Alternative Blowing Agent
Describes physics used in Dow model and compares results to full-thickness measured data, describes relationship to quality assurance measurements that can be made immediately after foam manufacture	Booth. 1993. An Evaluation of the Dow Thermal Performance Prediction Model for a Database of XEPS/CRD-12 Aged Resistivity and Physical Properties
Gas diffusion rates, finding limits re small slice thicknesses	Bhattacharjee, D. P.W. Irwin, J.R. Booth, J.T. Grimes, The Acceleration of Foam Aging by Thin-Slicing: Some Interpretations and Limitations, J. Thermal Insul. And Bldg. Envs., Vol 17, Jan 1994
Early interlaboratory comparison of C1303 test method found good agreement between laboratories with different slicing techniques, but later analysis was the basis for eliminating hot-wire cutting from the test method.	Fabian, et al. 1997. A Variability Study on the ASTM Thin Slicing and Scaling Test Method for Evaluating the Long[-term Performance of an Extruded Polystyrene Foam Blown with HCFC-142b
Compares a standard analytical solution for a single gas to the results of their numerical procedure before producing multi-gas results.	Kondapi, Booth and Yarbrough. 1999. Transient Gas Diffusion in Closed-Cell Foam Using an Implicit Finite Difference Method
Reviews LTTRs per CAN/ULC-S770-00 for pentane-blown PIR foams from three manufacturers.	Laughlin, et al. 2003. Insulation Boards Bridge to the 21st Century

Appendix B. Standards That Use Long-Term Aging, And Standard Test Methods

EN 13164, November 2008, ICS 91.100.60, Thermal insulation products for buildings - Factory made products of extruded polystyrene foam (XPS) – Specification EN 14307, November 2009, Thermal insulation products for building equipment and industrial installations - Factory made extruded polystyrene foam (XPS) products - Specification	Annex C: Thin slice aging, 10 mm (+- 1 mm), slices taken from throughout the product profile. Number of days (30 to 90) specified for product thicknesses from 120 to 20 mm. Correction for TDSL added. If foil faced, store full-thickness board for 60 days at 23C, then measure.
EN 13165, November 2008, Thermal insulation products for buildings - Factory made rigid polyurethane foam (PUR) products – Specification EN 14308, November 2009, Thermal insulation products for building equipment and industrial installations - Factory made rigid polyurethane foam (PUR) and polyisocyanurate foam (PIR) products - Specification EN 14315-1:2011, Thermal insulating products for buildings — In-situ formed sprayed rigid polyurethane (PUR) and polyisocyanurate (PIR) foam products — Part 1: Specification for the rigid foam spray system before installation EN 14318-1:2011, Thermal insulating products for buildings — In-situ formed dispensed rigid polyurethane (PUR) and polyisocyanurate (PIR) foam products — Part 1: Specification for the rigid foam dispensed system before installation	Annex C: Option 1: 175 days at 70C with safety increments. Safety increments can be modified based on comparison between 23 and 70C aged values. Option 2: Add fixed increment to initial thermal conductivity if pass test based on 21 days at 70C.

EN 14315-2:2011, Thermal insulating products for buildings — In-situ formed sprayed rigid polyurethane (PUR) and polyisocyanurate (PIR) foam products — Part 2: Specification for the installed insulation products EN 14318-2:2011, CEN/TC 88 Secretariat: DIN, Thermal insulating products for buildings — In-situ formed dispensed rigid polyurethane (PUR) and polyisocyanurate (PIR) foam products — Part 2: Specification for the installed insulation products	Companion documents for the specifications (Part 1), reference those specifications, except that EN ISO6946 can be used for complete building elements, corrections for moisture and temperature per EN ISO 10456 may be added.
EN 13166, November 2008, Thermal insulation products for buildings - Factory made products of phenolic foam (PF) - Specification	Annex C: Thin slice aging, 10 mm (+- 1 mm), slices taken from throughout the product profile. Number of days (30 to 90) specified for product thicknesses from 120 to 20 mm. Correction for TDSL added. Option 2: 175 days at 70C or 14 days at 110 C, with correction factors
EN 14314, November 2009, Thermal insulation products for building equipment and industrial installations - Factory made phenolic foam (PF) products - Specification	Annex B: 175 days at 70C or 14 days at 110 C, with correction factors
NORD (Swedish National Testing Institute, Chalmers University of Technology, and NRCC, Isberg, 1988) ASTM C1303 Standard Test Method for Predicting Long-Term Thermal Resistance of Closed-Cell Foam Insulation ISO 11561, 1999, Ageing of thermal insulation materials — Determination of the long-term change in thermal resistance of closed-cell plastics (accelerated laboratory test methods) CAN/ULC S770, Standard for Determination of Long-Term Thermal Resistance of Closed Cell Thermal Insulating Foams	All based on thin-slicing per Fick's Law of diffusion for homogenous materials NORD: Uses 10 mm slices at 91 days to predict the 25 year thermal conductivity of 100 mm products. Uses a full cross section of the original material. S770: Uses separate core and surface slice results at specified times to calculate the 5-year thermal conductivity for full thickness products. Earlier versions used the lowest aged thermal conductivity of core or surface slice stacks. Current version uses a combination of the two results. C1303: Offers prescriptive path, using predictions for 5 years of age, or research path, using full aging curve.

ISO 2440, 1997, Flexible and rigid cellular Polymeric materials – Accelerated ageing tests	Heat and humidity conditions used to age for compression or indentation hardness, not used for thermal conductivity aging
ACERMI – Association pour la Certification de Materiaux Isolants	Maintains the foam at an elevated temperature (70C) for a prescribed period of time (2 months). This produces an accurate simulation of long-term (~20 years) aged value IF blowing agent diffusion rate is << diffusion rates for N_2 and O_2. However, for many new blowing agents, the blowing agent diffusion rate is greater than it was for CFC-11, so this test will instead produce values representative of foam after 1-2 years.[Hoogendoorn 1994 and Bomberg and Gilbro 1989]
PIMA Technical Bulletin #101, 180 Day Sample Conditioning Procedure For Impermeable Faced Polyiso	180 days at 23C, does not profess to represent long-term average performance, rating purposes
US Federal Specification HH-1-530A	90 days at 60C
Canadian General Standards Board (CGSB)	28 days at 100C (problems with foam dimensional stability, product thickness increased)
US Federal Trade Commission "R-Value Rule"	6 months at 23C or 90 days at 60C

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