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NRCC-37773

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October 1993

A version of this document is published in / Une version de ce document se trouve dans:
Journal of Thermal Insulation and Building Envelopes, 17, (Oct), pp. 106-117, October-93

Introduction to the Third International Workshop on Long-Term Thermal Performance of Cellular Plastic Insulation

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ABSTRACT: Methodology for the evaluation of long-term thermal performance of cellular plastics is being developed under a collaboration of North American foam industry with the National Research Council of Canada. The mechanism of this collaboration includes a joint research project between the Society of Plastics Industry and the NRC Canada.

To evaluate long-term thermal performance (LTTP) of cellular plastics the aging process must be accelerated. This can be done either by means of elevated temperature or by the use of thin layers of the foam. The first approach changes the permeability and solubility coefficients of different gases to such a degree that predicting the foam performance under field conditions is difficult.

Only the thin layer approach is used in the SPI/NRC project, though the relation between aging of thin layers and that of full board is treated differently, depending on the foam uniformity. When unfaced foam is homogenous enough to permit a simple arithmetic operation, known as the scaling technique, this relation can be used to calculate foam aging for layers with different thicknesses. When, however, the cellular structures of skin and core layers differ significantly, or the foam is provided with impermeable facers, then the scaling technique is not appropriate and the aging models (models of heat and mass transfer) must be used.

There is, however, a number of material characteristics needed as the input to these models, and the manner in which these material characteristics are generated decides upon the scope of application of this methodology. Therefore, much of this research relates to the methods of material characterization.

This presentation outlines the main elements of methodology developed under the SPI/NRC project and highlights future research needs.

1065-2744/93/02 0106-12 $06.00/0

1. BACKGROUND

CHLOROFLUOROCARBONS (CFCs) ARE non-toxic, non-flammable, non-corrosive and stable gases that were used in many ways, for instance as blowing agents for polyurethanes, phenolic and extruded polystyrene thermal insulations. CFCs escaping into the atmosphere pose a long-term danger, because chlorine breaks down the ozone and thereby reduces effectiveness of the ozone layer in protecting the earth from the sun's ultraviolet radiation. When the extent of the problem became apparent, in 1987, an international agreement known as the Montreal Protocol was signed by 24 nations restricting use of CFCs and halons.

Time limits were further shortened, following the public reaction after signing of this international agreement, leaving the manufacturers of foamed plastic insulations with very limited time to respond. As a result, manufacturers associated with the Society of the Plastics Industry (SPI) modified a fellowship program at the National Research Council (NRC) laboratories [1]. A joint SPI/NRC research project was established [2] to which both the industry and NRC contributed equally and where decisions were made by a Steering Committee. Technical support was provided by two advisory groups—a Polyurethane and a Boardstock Subcommittee.

When a similar project was created in the USA between PIMA and ORNL [3] (also supported by SPI and EPA) and a third project was sponsored by DuPont at NRC with a focus on the blowing agents, the need for enhanced coordination became apparent. The first international workshop on long-term thermal performance of cellular plastic insulations that took place in Canada in 1989 was to erase the existing communication gap. Organized by the members of SPI/NRC advisory groups and co-chaired by NRC and DuPont representatives, the workshop outlined both the existing knowledge and the research needs [4].

It became evident that there was more to this research area than replacing blowing agent A with blowing agent B. It was more like a change of technology because so many things must be changed in the foam cellular morphology to obtain the same thermal performance of foams when using blowing agents with lower thermal effectiveness. Techniques for material evaluation had to be developed and linked with the development of new materials, otherwise the knowledge acquired over 20 years of incremental improvements in technology could be erased.

This and the next workshop helped to define the SPI/NRC program as a research project with several dimensions. Initially, to set the linkage between material and test method development, a generic and homogenous product was developed. It was called Base 88 because it represented industrial technology of sprayed polyurethane foams that existed in 1988. This generic foam product was manufactured by three companies (BASF, ICI and Demilec). Then, a subproject was aimed at developing methods for improved control of application variables. Improved control of application variables permitted this generic sprayed polyurethane foam to become highly reproducible and suitable for comparative research [5]. This generic sprayed polyurethane foam was then manufactured with different alternative blowing agents: CFC-11, HCFC-123, HCFC-141b, and combinations of HCFCs with and without water [6].

Research on long-term thermal performance of sprayed polyurethanes formed a starting point for developing a universal methodology [7]. This methodology contains two subsets: a simplified approach called slicing and scaling applicable for homogeneous foams, and a universal approach based on the DIPAC aging model (distributed parameters continuum model) applicable to any combination of polymer(s) and blowing agent(s). The latter approach is being verified under laboratory and field exposures using extruded polystyrenes, polyisocyanurates, phenolic and modified resole foams.

2. DEFINITION OF THE PROBLEM

There are two challenges involving evaluation of thermal performance of the insulation materials [8]. One is to characterize the key factors affecting their field performance such as settlement of loose fills, aging of gas-filled foams, effect of convective air flow on fibrous insulations or effect of moisture on thermal performance of different insulations. The second challenge is to develop evaluation methods that simulate field performance of these insulations.

These challenges have not been fully realized in North America where specifications are developed mainly for comparing products. Typically, material standards and specifications require thermal resistance to be tested at 24°C mean temperature using dry, fresh specimens of thermal insulating products. Conversely, the European Community aims to resolve the discrepancy between field and laboratory performance of building materials by introducing concepts of the "declared" and "design" thermal properties [9].

The declared value, a statistical estimate, is the expected value of the thermal characteristic of a building material or product assessed through data measured at a reference temperature and thickness and stated with a given confidence level. The design value, however, is the value of the thermal characteristic of a building material or product in selected sets of conditions (e.g., representing typical installation, climate and use conditions).

The approach taken in the SPI/NRC project is as follows. We first determine a declared initial r-value of the thermal insulation, i.e., the average initial thermal resistance of the product. We then address effect of time on thermal resistance of the product (i.e., examine product's aging under laboratory conditions). In the next stage we consider the effect of environmental factors on aging rate of the product, i.e., we select conditions that could represent "typical" or "extreme" sets of field conditions and examine their effect on aging rate of the foam.

Field performance of the foam, however, is affected by both production and application variables and therefore this evaluation methodology should not be expected to give more than a general estimate of the field performance.

3. THIN LAYER METHODOLOGY FOR PREDICTING THERMAL PERFORMANCE OF CELLULAR PLASTICS

3.1 Initial Thermal Resistance of the Product

This element of evaluation is common for any thermal insulating product. The mean thermal resistance of the product is established with appropriate consideration of variability in the manufacturing process ([10]). At NRC, unless a statistical sampling plan is applied, two or three specimens are randomly selected from each of three different production batches. Normally, these are 600 × 600 mm square, full thickness specimens. They are tested for thermal resistance in accordance with the ASTM C 518 test method 14 to 28 days after manufacture.

3.2 Normalized Aging Curves for Surface and Core Layers

Some specimens with *r*-value close to the mean thermal resistance of the product are cut into 30 cm × 30 cm slabs and further sliced into four layers, two to include the original surfaces and two the core [11]. To control the diffusion process undergone by these slices, their surfaces are selectively encapsulated with epoxy resin [12]. Performing periodic measurements of thermal resistivity and presenting them in the form of "normalized aging curves," (where *r*-value at any time is represented as a fraction of the initial *r*-value), permits comparison between specimens with different initial *r*-value, but similar aging behavior.

Figure 1 [13] shows four normalized thermal resistivity curves, representing skin and core in two applications of the same sprayed polyurethane foam (sprayed either on a polyethylene film or on plywood). Even though the initial thermal resistivities of the surface layers were as much as 20 percent different, the character of the normalized aging curve is similar, indicating that effective diffusion of oxygen, of nitrogen and of the glowing agent are similar to those of the core layers. Despite differences in the initial thermal prop-

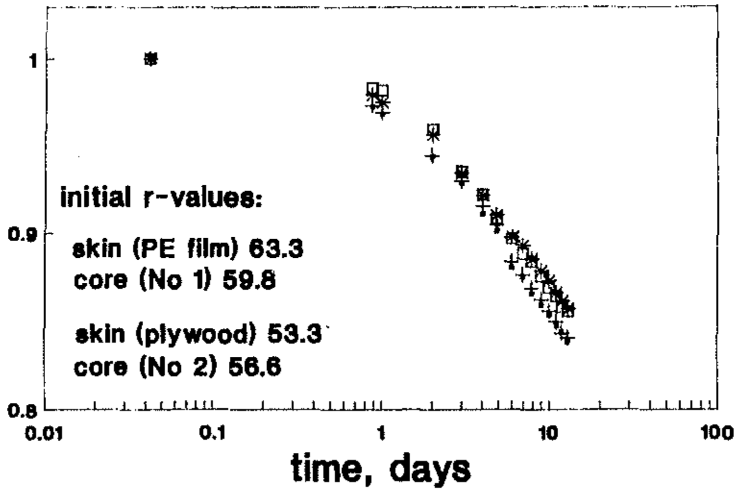

FIGURE 1. Normalized thermal resistivity of thin layers cut from a polyurethane foam sprayed on different substrates. An initial *r*-value of the foam layer adjacent to a plywood substrate was measured as 63 (m K)/W, that for the layer sprayed on polyethylene film was 53 (m K)/W, and the intermediate *r*-values were measured on the core layers. Yet, the normalization process showed that the aging curves of each layer were similar.

erties of these layers, the same rate of diffusion, as shown by the normalized aging curves, permits the application of the scaling approach [14].

On the other hand, Figure 2 [15] shows a significant difference in the aging character of surface and core layers that eliminates use of the scaling approach. In such a case the modeling approach would be more appropriate [16].

3.3 Predicting Long-Term Thermal Performance (LTTP) of a Foam Aged under Laboratory Conditions

3.3.1 USING THE SCALING APPROACH

The SPI/NRC methodology includes the slicing technique originally introduced by Isberg [17], but is much broader in many regards [6,18]. Instead of estimating thermal resistance of the foam product from the value measured on thin material layers alone, the SPI/NRC approach combines the initial thermal performance of the product with the effect of time.

If normalized aging curves determined on both surface and core layers show sufficient agreement, then, a dimensionless factor may be used to correlate the degree of aging measured on thin layers with that expected for full thickness of the foam product. The dimensionless scaling factor is the ratio of the squares of the thicknesses of thin layers and the full boards. By multiplying the mean initial thermal resistivity (resistance) by the scaling factor, the value of thermal resistivity at any given service period and thickness of the foam can be derived.

3.3.2 USING THE DIPAC MODEL

An aging model [19,20] uses data obtained under controlled laboratory conditions and extrapolates them to other boundary conditions, e.g., service conditions. This aging model incorporates effects of time and temperature on thermal resistance and is applicable to all types of cellular plastics (polystyrenes, phenolics and polyurethanes).

This extrapolative model needs input of measured thermal resistivity of thin material layers as a function of time. As this input is related to either a surface or a core of the product, the model permits variation of the physical properties depending on their location [21]. In this process, some material characteristics may have to be modified to reach agreement with the measured aging curve. However, once the material characteristics are established they will not be changed during the subsequent calculations. For this reason, this model is labeled as "extrapolative" [22].

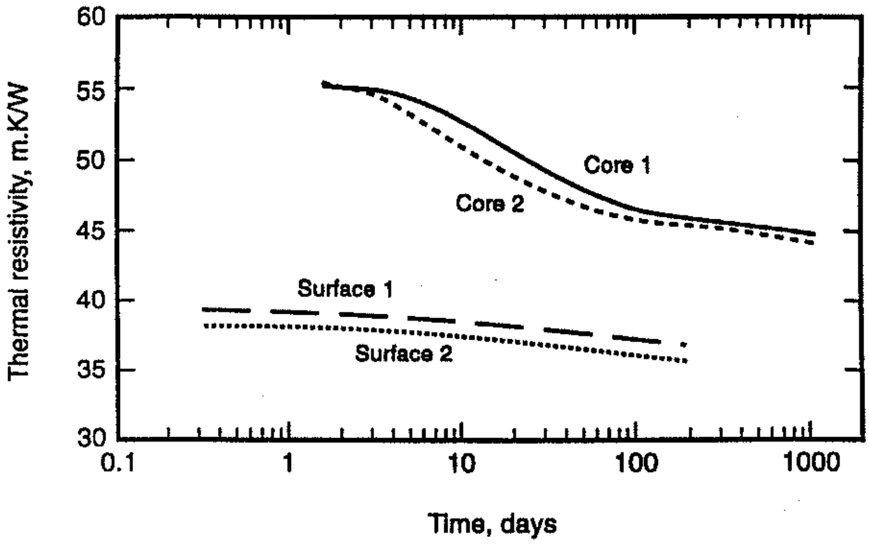

FIGURE 2. The surface and core layers cut from a polyisocyanurate filled panel show large differences in thermal resistivity as the function of time precluding application of the normalization process.

3.4 Validating the LTTP Predictive Methodology under Field Conditions

A standard evaluation procedure must, during a period of 6 months or less, give a prediction of an average thermal performance under service life, say 10 or 25 years. To calculate the value of thermal resistance integrated over the selected period of service life, one must combine laboratory testing with calculational procedures (scaling factors or aging models). Furthermore, one must validate the laboratory predictions by actual field performance of the foam products [23].

3.4.1 COMPARISON OF PREDICTED AND MEASURED FIELD THERMAL PERFORMANCE

Field performance data were used to validate results obtained from the predictive procedure. First, laboratory testing of field exposed specimen was compared with the results measured under actual field conditions. Finding sufficient agreement [24] permitted us to use either of these two types of measurements to validate the model predictions.

3.4.2 EFFECT OF ENVIRONMENTAL FACTORS ON AGING RATE

The standard predictive procedure, when validated and generally agreed upon, will replace field testing. However, the effects of environmental conditions (temperature and moisture) on integrity of the cellular structure and other physical properties are not known today. Foam products are under constant change and evolution. For these reasons the Boardstock Subcommittee decided to develop a bench mark, which today is a set of arbitrary environmental conditions applied in the laboratory to see if the specific polymer foam will be affected [25,26].

Thermal testing of thin material layers provides non-destructive means of assessment if a specific environmental effect may lead to a major breakdown of polymer integrity (e.g., significant rupture of cell walls). This method combined with measurements of effective diffusion for characterization of material response to environmental stresses may be used to evaluate the effect of environmental factors. Factors such as thermal gradient alone or in conjunction with humidity gradient or freeze-thaw conditions were selected.

Thermal resistance changes as a function of time are measured on small specimens exposed to four types of environmental conditions for a period up to 180 days:

(a) Isothermal at room temperature and humidity ranging between 30 and 50%. This is the control exposure.
(b) Dry cube. The dry cube placed in the laboratory has four specimens

positioned in the vertical sides of a cube; air in the cube is maintained at 70°C and humidity is that of the room air. This exposure relates to the effect of thermal gradient only.

(c) Wet cube. As the dry cube above, but by placing a large open container with water in the cube, RH of the interior air is maintained above 95%. This exposure relates to the effect of thermal gradient in the presence of moisture.

(d) Freeze/thaw cycling. The specimens are placed between the laboratory environment and a freezer which is cycled between −20°C and RH above 90% for a six-hour period and is then allowed to warm for a six-hour period when the interior of the freezer reaches +5 to +10°C. This exposure relates to the effect of thermal gradient in the presence of moisture flow (water vapor diffusion) towards a freezing zone.

In effect, the Boardstock Subcommittee selected conditions similar to those recommended by ASTM D2126 for exposure on one surface of the specimen leaving the other surface open to the room conditions. While these laboratory conditions do not represent field conditions they may provide information on relative significance of the environmental effects for the specific polymeric foam structure.

4. STATE OF THE ART

The SPI/NRC project has already addressed a number of issues. It developed comprehensive methods for testing thermal resistance of thin layers as a function of time [6,11] and temperature [12], with or without their encapsulation [24]. It applied and validated the scaling approach for such materials as sprayed polyurethane [13], extruded polystyrene [11] and modified resole [18]. This project addressed material characterization by means of gas diffusion measurements [27,28] (improving the MIT developed technology [29]) and incorporated foam characterization with image analysis system [30] into the DIPAC model. The SPI/NRC project developed new techniques for field measurements [23] and improved laboratory equipment such as four station Heat Flow Meter Apparatus or Thin Heater Apparatus [31]. Furthermore, the thin layer approach was even used for selecting components of a foaming system (screening their compatibility) [32].

The SPI/NRC project is currently assessing the LTTP of several boardstock products such as extruded polystyrenes, polyurethanes, polyisocyanurates, and phenolics. Several Canadian and US manufacturers have produced materials which are being exposed in laboratory as well as on a test roof. Thermal properties of these specimens are being continuously monitored and the data gathered from these two exposures are used to verify the applicability of the model.

When corrected for the specimen temperature, the aging curves measured under field and laboratory conditions agree with each other indicating that the prevailing environmental effects did not affect the foam structure to a measurable degree. In this situation, the model predicts thermal performance of the foams, quite well. Could there be a situation where material performance under field conditions is not identical with its performance under laboratory conditions, and how can we distinguish between these two situations?

Our knowledge is insufficient to answer these questions. More research on moisture accumulation under actual field conditions and effects of moisture on foam durability is needed to answer this question.

5. RESEARCH NEEDS

5.1 Predicting Effect of Moisture on Thermal Performance of Foams under Field Conditions

Incorporating calculations of moisture movement may further improve the aging model and permit both estimating thermal resistance under service conditions and analysis of the foam durability. As moisture usually has a significant impact on structural integrity of the polymeric matrix, inclusion of moisture transport would allow assessment of materials under specific field applications.

A considerable amount of work has already been performed on methods for measuring [33] and calculating moisture movements through building materials at IRC [34] and these developments together with the DIPAC model could be incorporated into an envelope system model.

5.2 Predicting Efficiency of Gas-Barrier in Reducing Foam's Aging

To reduce aging, foam may be protected with a gas barrier. The effect of impermeable facer may, however, be greatly reduced by lateral diffusion in a thin layer of the foam adjacent to the facer. Even though this layer is only a few cells thick, the rate of gas diffusion parallel to the barrier may greatly exceed the rate of diffusion in the direction of the foam rise and reduce thermal performance of the foam system. Three reasons may be associated with the phenomenon of diffusion parallel to the impermeable gas barrier: (1) the roll-over of the cells during the lamination process, (2) the poor adhesion of the gas barrier to the foam, and (3) the collapse of cell walls under a shear stress introduced by the differences between the expansion coefficient of the metallic gas barrier and the foam. These effects may reduce the efficiency of the gas barriers in retarding the aging process, and therefore the long-term performance of foams provided with gas barriers must be carefully tested.

One of the techniques to measure efficiency of the gas barrier could be based on testing partially encapsulated surface layers [32]. The verification experiments proved, however, that the bond between the gas barrier and the foam showed intimate dependence on sample preparation making this technique not applicable. Another method of sample preparation or perhaps another technique based on rapidly diffusing gas with low solubility, e.g., helium, may be more suitable for development of a gas barrier efficiency test.

6. CLOSING REMARKS

Normally, information on long-term field performance is unavailable until after several years of use of the product. Furthermore, engineers do not actually predict long-term field performance; rather they correlate laboratory estimates with field data.

However, the pursuit of insulating foams free of chlorofluorocarbons (CFCs) demonstrates the viability of a different approach to estimating long-term performance. The challenge created by the need to replace CFCs demanded that a new evaluation methodology be developed. Change in physical properties that affect field performance of the foam emerge very slowly and the CFC replacements were needed quickly. Since no one could wait for several years to measure the actual performance of new foams, a methodology has been developed to extrapolate data from short-term laboratory testing and to estimate long-term thermal performance of foams with new blowing agents.

This methodology is yet incomplete as the environmental effects and efficiency of gas barriers require further research. Yet, the substantial progress achieved over the last 4–5 years has already shown the merits of a common predictive methodology. The development of common predictive methodology under a joint research performed together by the industry and the national research laboratory has also proven to be a correct way of addressing these issues. This project provides benefits to the construction designers (users) as it leads to evaluating products with a view to their long-term performance under field conditions. This project also provides benefits to the foam manufacturers as it facilitates product development with a view to the specific field performance requirements.

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