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Testing Long-Term Thermal Resistance of Sprayed Polyurethane Foam

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INTRODUCTION

WHEN SPRAYED POLYURETHANE foams are fabricated under field conditions, they usually form a continuous layer that controls the flow of heat, air and moisture through the building component they cover. However, the replacement of blowing agents such as chlorofluorocarbons (CFCs) with partially halogenated hydrochlorofluorocarbons (HCFCs), which have thermal insulating performance inherently lower than that of CFCs, has raised the question of the long-term thermal performance of such foams.

SPI/NRC research [1] indicated that HCFC blown polyurethane sprayed foam may have excellent and lasting performance. Sprayed polyurethane foam manufactured with alternative blowing agents may have a long-term thermal resistivity (inverse of thermal conductivity) as high as 44.4 (m K)/W or 6.4 (ft²hr°F)/(Btu in). Nevertheless, to incorporate technological changes in the sprayed polyurethane foam products and ensure the adequate field performance of a complete construction system, a significant obstacle must be overcome, namely the lack of continuity in the process of quality management.

Since the spray foam is fabricated on the construction site, Willingham [2] asked whether "a product which is essentially prepared and applied on-site, will conform to the same specifications and standards *each time it is installed*." This question can be answered by the sprayed polyurethane foam industry developing and enforcing an industry-wide quality management program. From a drum of chemicals manufactured by a system house through the designer or specifier who incorporates sprayed foam in a given construction el-

ement to the contractor who fabricates the foam, every step must be judged by the final result, i.e., the field performance of the construction element. The industry must review the manufacturing and fabrication processes with a view to ensuring the excellence and long-lasting performance of construction systems with sprayed polyurethane foam.

Field performance of the sprayed polyurethane foam depends on manufacturers of raw materials and chemical systems (the latter blends raw materials), manufacturers of the equipment and the spray foam contractors. In contrast to development of traditional spray foam systems which contained gradual improvements accumulating over many years, sprayed foams with alternative blowing agents were developed almost "instantly." While research [1,3,4] showed that possibility of excellent long-term thermal performance exists, it has also shown that some of the new sprayed foam systems have field performance inferior to the traditional CFC-based sprayed foams. In this situation, Alumbaugh [5] and Bomberg [1], underlined that the sprayed polyurethane contractors (field fabricators) have no choice but to acquire the technical knowledge allowing them to select the best foam systems available and promoting their application in a manner that benefits customers.

This note is based on five years of NRCC's experience in testing thermal performance of sprayed polyurethane foams with alternative blowing agents and provides practical recommendations on testing and evaluation of long-term thermal performance of sprayed polyurethane foam.

HOW TO DETERMINE LONG-TERM THERMAL RESISTANCE FOR COMPARATIVE PURPOSES

Sprayed polyurethane foams, like many other thermal insulating foams, are subject to aging (thermal drift) process. Aging means that thermal resistance of the material changes during its service period, mainly because of the changes in composition of the gas contained within the closed cells of the foam. Since aging is a very slow process and occurs over many years of service, one must accelerate aging during the laboratory test. One of the proven means to reduce the period of laboratory testing is to measure aging of thin layers. This method should be used in combination with extensive testing of the initial thermal performance of the foam product.

In effect, to estimate long-term thermal performance (LTTP) for sprayed polyurethane foam product the following steps are necessary:

1. Determine a mean value of the initial thermal resistance of the foam product.
2. Measure initial thermal performance of the specimens before they are sliced.

3. Cut thin layers, age them under room conditions and measure their thermal resistance at the prescribed stage of aging.
4. Determine the aging factor as the ratio of thermal resistance at the prescribed aging stage (end of the considered aging period) to the initial thermal resistivity.
5. Determine the long-term thermal resistance as the product of the aging factor and the mean initial thermal resistance of the foam product.

A Mean Value of the Initial Thermal Resistance of the Foam Product

To represent the initial thermal performance of the sprayed foam product, a number of thermal resistance tests must be performed and their results averaged. Each test should be performed on a specimen cut from a slab sprayed on a different day. Unless the number of tests is specified by a chosen sampling plan (for instance ASTM-C-390 [6]), a minimum of three specimens cut from three different batches should be used to establish the mean value representing the initial thermal performance of the sprayed foam product.

Determination of the initial thermal resistivity normally involves testing specimens cut from 7 to 14 day old polyurethane, 75–100 mm (3–4 inch) thick slabs sprayed on a 12 mm (1/2 inch) thick plywood substrate. After delivery to a testing laboratory, the foam slab should be conditioned for 2 days at room conditions, then cut into test specimens (600 × 600 mm or 300 × 300 mm, i.e., 24 × 24 or 12 × 12 inch square) and placed into a Heat Flow Meter (HFM) apparatus within 24 hours after cutting. The ASTM-C-518 thermal resistance test is performed at mean temperature of 24°C (75°F). It is recommended that 50 to 75 mm (2 to 3 inch) thick test specimens be tested; 75 mm thick when using a larger HFM and 50 mm thick when using a smaller apparatus.

Measure the Initial Thermal Resistivity and Slice Two Specimens into Thin Layers

To study the aging process, thermal resistance of thin layers is measured at the prescribed stage of aging¹ and compared to the initial value. ASTM-C-518 test method is also used but with a HFM apparatus using 300 × 300 mm (12 × 12 inch) or smaller square specimens. As when testing the mean initial thermal performance of the foam, a minimum of two thick slabs²

¹A proposal for "the standard test method for estimating the long-term change in the thermal resistance of unfaced closed cell plastic foams by slicing and scaling under controlled laboratory conditions" has already been approved by the ASTM Committee C-16 on Thermal Insulation and is in the process of the Society approval.

²ASTM recommendation calls for a minimum of five specimens to be tested. With three specimens used to establish the mean initial thermal performance and two specimens used for measuring the rate of aging, this recommendation is met.

(sprayed on different days) should be delivered to the testing laboratory. After one or two days of conditioning in the laboratory, an approximately 50 mm (2 inch) thick specimen is cut from each of them and its initial thermal resistivity is measured.

The initial thermal resistivity is measured on a thick specimen, just before slicing it into thin layers, because of the rapid changes in thermal resistivity immediately after cutting into slices could introduce significant experimental errors.

Prepare Slices and Measure Their Thermal Resistivity at the Prescribed Time of Room Aging

Two 6 to 10 mm thick layers are cut from each of the 50 mm thick specimens on which the initial thermal resistivity was determined and their thermal resistivity is measured at the prescribed time of room aging.

To establish the aging factor (that is a ratio of thermal resistivity at the prescribed stage of aging to the initial value) one can use a recently proposed ASTM test procedure. More specifically, one must define this stage of aging by selecting the period for which thermal resistance is being evaluated. Should it be the service life of a construction element? Not necessarily, as the expected service life of thermal insulation varies. For roof applications a typical service life is between 15 and 20 years, but for walls the period of 40 to 50 years is not unusual. Yet, under typical use conditions, thermal insulation will result in such energy savings that the actual cost of the insulation is compensated much before the end of the service life. One may argue that 14 to 18 years payback is typical for different construction applications. Therefore, a 20 year period recommended by Smith [7] for evaluation of roofing systems was selected as a basis for evaluation of long-term thermal performance of cellular plastics.

To use the scaling procedure, we must know the actual product thickness or select a comparative thickness of the insulation. For sprayed polyurethane foam this question has already been answered during Spray Foam 93 [1,5] where the following recommendations were postulated:

- type 1 foam (roofing) density 40 to 48 kg/m³ (2.5 to 3 lb/ft³) minimum thickness 38 mm (1.5 inch), recommended thickness 50 mm (2.0 inch)
- type 2 foam (walls) density 32 to 37 kg/m³ (2.0 to 2.3 lb/ft³) minimum thickness 50 mm (2.0 inch), recommended thickness 75 mm (3.0 inch)

The thickness of 50 mm and 20 year aging period were selected for the analysis. Instead of analyzing the total energy loss (or gain in a cooling climate) integrated over the 20 year period, one may, however, select such a reference time at which the thermal resistance of the 50 mm thick foam is equal to the average of the 20 year period. Applying a model of aging [8] for

sprayed polyurethane foams as tested at NRC [1,3,4,9] the reference time was found to be somewhat shorter than the five year period previously postulated by an expert group [10]. Thus, the reference time of 1825 days will be used in further analysis.

Now, one must select such conditions of thin layer testing which give the estimate of thermal resistance of 50 mm thick sprayed polyurethane at the reference time of 1825 days. In principle, laboratory testing should last a minimum of 2 months (and preferably 6 months) because the process of the blowing agent solubility often takes 4–7 months. For most polyurethane foam systems, however, a realistic approximation is obtained already after 2 or 3 months.

A period to achieve the required degree of aging depends on the layer thickness. The relation between the aging period of the thick foam and the corresponding aging period of the thin layer³ is defined by the concept of scaling factors [11,12]. Two specimens with different thickness will reach the same stage of aging at different times, however, the ratio of the square root of these times must be equal to the ratio of their thicknesses. Therefore, for the ratio of $\sqrt{1825}/\sqrt{50} = 0.854$ and for 6.2 mm thick layer the testing period is $0.854 \times (6.2)^2 = 28$ days; while for 7 mm thick layer the test should be performed at $0.854 \times (7.0)^2 = 35$ days.

In practice, when testing a 10 mm thick slice (with a view to predicting *R*-value of 50 mm thick foam at the reference time of 1825 days) the aging period is 72 days (observe that 90 days is required in new ISO standard⁴). Such a test may be performed on two 10 ± 0.5 mm thick slices placed together in the HFM apparatus. Even thinner foam layers may be used for rapid determination of long-term thermal resistance, for instance, as shown above, using three 6.2 ± 0.5 mm (0.25 inch) thick layers this test may be performed after 28 days of aging of the slices.

Determine the Aging Factor

The ratio of thermal resistivity, determined on thin layers, at prescribed stage of aging to the initial thermal resistivity is the aging factor. The initial thermal resistivity is determined on thick specimens, as previously men-

³Note that some cells at the surface are damaged during the slicing operation and that the effective path of diffusion should be used in the scaling factor. A concept of TDSL (thickness of damaged surface layer) was therefore introduced to reduce the geometrical thickness and bring it to the effective thickness of diffusion process. For non-friable materials, TDSL is close to one-half of the mean cell diameter.

⁴Determination of the long-term thermal resistance of closed cell cellular plastic thermal insulation, a draft of ISO/TC 163/SC1/WG7 that has already passed ISO Committee ballot and is in the stage of final approval. For 50 mm thick layer, this standard uses the reference time of 6.2 years instead of 5 years recommended by the authors.

tioned, because thin layers (slices) exhibit a rapid change in thermal properties immediately after the slicing operation.

If the initial thermal resistivities of all specimens were identical, the thick boards as well as slices, one could measure thermal property at the prescribed stage of slice aging and directly use it for the product evaluation (as stated in the ISO method). However, in practice this is not the case. Then, as shown elsewhere [9] different aging curves exhibited by individual specimens can be brought together by normalizing them with the initial thermal resistivity value. The aging factor represents one point on such a normalized aging curve. Thus, the purpose of using the aging factor is to improve precision of the long-term thermal performance evaluation.

Determine the Long-Term Thermal Performance of the Foam Product

Having determined aging factor at the end of the period (selected so that a time-weighted 20 year average thermal resistance of the 50 mm thick foam is obtained) one multiplies the aging factor with the mean initial thermal resistance of the foam product to derive the LTTP.

The following section applies this methodology to establish LTTP for four types of commercial sprayed polyurethane foams.

MEASURED LTTP OF SPRAY POLYURETHANE FOAMS

Table 1 shows determination of the initial thermal resistivity of a roof-type spray foam manufactured with HCFC-141b.

Four slices (425-162) with thickness about 10 mm were prepared and aged in a laboratory room. The ratio of 72 day thermal resistivity of these slices to the initial value of the foam specimen is 0.79. The long-term thermal resistivity of this foam, calculated as a product of the mean initial thermal resistivity of the product and the aging factor, is equal to: $0.79 \times 50.5 = 39.9$ (m K)/W or 5.8 (ft²hr°F)/(Btu in).

Table 1. Initial thermal resistivity of sprayed polyurethane product M (HCFC-141b).

Batch Code	Density		Thermal Resistivity	
	kg/m ³	(lb/ft ³)	(m K)/W	(ft ² hr°F)/(Btu in)
425-129	55.3	(3.4)	50.4	7.27
425-135	54.6	(3.4)	50.3	7.25
425-141	55.0	(3.4)	50.9	7.34
Average	55.0	(3.4)	50.5	7.26

Table 2. Initial thermal resistivity of sprayed polyurethane product C (CFC-11).

Batch Code	Density		Thermal Resistivity	
	kg/m ³	(lb/ft ³)	(m K)/W	(ft ² hr°F)/(Btu in)
396-50	37.5	(2.3)	59.9	8.64
396-54	35.0	(2.2)	59.9	8.64
396-55	35.0	(2.2)	61.1	8.81
Average	35.8	(2.23)	60.3	8.70

The example in Table 2 shows that initial thermal resistivity of CFC-11 blown, wall-type, spray foam was significantly higher than the *R*-value for HCFC-141b blown foam (Table 1).

Again, as four 10 mm thick slices were tested [1], the ratio of 72 day thermal resistivity to the initial value was found to be 0.71 and the long-term thermal resistivity of this foam becomes $0.71 \times 60.3 = 42.8$ (m K)/W or 6.2 (ft²hr°F)/(Btu in).

Another HCFC-141b based sprayed foam is shown in Table 3. Four, 7 mm thick slices (426-116) were tested and the ratio of 35 day thermal resistivity to the initial value was found to be 0.767 and the long-term thermal resistivity of this foam is calculated as $0.767 \times 53.5 = 41.0$ (m K)/W or 5.9 (ft²hr°F)/(Btu in).

Another HCFC-141b based wall-type sprayed polyurethane foam is shown in Table 4. Four, 10 mm thick slices (426-199) were tested and the ratio of 72 day thermal resistivity to the initial value was found to be 0.79. Thus, the long-term thermal resistivity of this foam is calculated as $0.79 \times 49.1 = 38.9$ (m K)/W or 5.6 (ft²hr°F)/(Btu in).

Table 3. Initial thermal resistivity of sprayed polyurethane product R (HCFC-141b).

Batch Code	Density		Thermal Resistivity	
	kg/m ³	(lb/ft ³)	(m K)/W	(Imperial)
426-101	37.0	(2.3)	52.6	7.59
426-107	38.7	(2.4)	52.9	7.64
426-117	34.2	(2.1)	55.0	7.94
Average	36.7	(2.3)	53.5	7.71

Table 4. Initial thermal resistivity of sprayed polyurethane product K (HCFC-141b).

Batch Code	Density		Thermal Resistivity	
	kg/m ³	(lb/ft ³)	(m K)/W	(ft ² hr°F)/(Btu in)
426-170	39.0	(2.4)	49.5	7.14
426-176	38.3	(2.4)	49.3	7.11
426-188	31.7	(2.0)	48.6	7.01
Average	34.0	(2.1)	49.1	7.09

DISCUSSION

One may compare initial thermal resistivity of CFC-11 blown spray foam product C (Table 2) with that of HCFC-141b blown foam products (Tables 1, 3 and 4). The HCFC blown foams have 12 to 18 percent lower initial thermal resistivities than the CFC-11 blown foam used for comparisons. Yet, the difference between the LTTP values of these sprayed foam products were much smaller than the initial differences. Product R (Table 3) showed LTTP highest of the three HCFC blown products. It was only 4 percent lower than that of the CFC-11 blown foam. The lowest long-term thermal resistivity, shown by product K (Table 4) was 9 percent lower than that of the CFC-11 blown foam. The difference of five percent highlights importance of foam optimization with regard to its long-term thermal performance.

One may also examine the effect of density on the long-term thermal performance. Traditionally a higher density roofing foam would be expected to have thermal performance better than a lower density wall-type foam. Product M was a roof-type foam while product K was a wall-type foam. Yet, the wall-type foam (product R, Table 3) had the long-term thermal resistivity equal to 41.0 (m K)/W or 5.9 (ft²hr°F)/(Btu in) that is better than roof-type foam (product M, Table 1) with the long-term thermal resistivity equal to 39.9 (m K)/W or 5.8 (ft²hr°F)/(Btu in). One may observe that the improvement of the cellular structure which can be obtained in the process of foam system optimization with regard to its long-term thermal performance appears more important than differences in the foam density.

CONCLUSIONS

It was shown in the SPI/NRC research [3] that HCFC-141b blown foam can be optimized to have long-term thermal performance identical to a CFC blown foam. While the SPI/NRC project examined performance of a generic

sprayed polyurethane foam system and showed a potential for improvement of sprayed foam systems manufactured with alternative blowing agents, this research examined commercially available foam systems, three blown with HCFC-141b and one manufactured for comparative purposes with CFC-11. The importance of foam optimization with regard to long-term thermal performance was once more demonstrated.

It is apparent that polyurethane contractors must demand LTTP data from system houses to ensure that each sprayed foam system was adequately optimized with regard to its long-term thermal performance.

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