TRANSITION TO THIRD-GENERATION POLYISOCYANURATE BOARDS: A SYSTEMATIC APPROACH

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The transition to a third generation of blowing agents will happen some time in the near future. Although it is not possible to predict exactly when this change will occur (in fact, one manufacturer has started producing pentane-blown insulation board at one plant), the process to evaluate the change to third-generation blowing agents for polyisocyanurate insulation board will follow proven development protocols at the author's company. The evaluation will involve a system's approach to determine whether the change has an impact on roof systems and thereby on our customers, roofing contractors. This paper will outline the steps being taken to evaluate the effect of third-generation blowing agents in polyisocyanurate insulation boards and the roof systems.

Additionally, the transition to second-generation blowing agents hydrochlorofluorocarbon-141b (HCFC-141b) from chlorofluorocarbon-11 (CFC-11) in the early 1990s and the lessons learned from that transition will be reviewed. New analytical tools, which will be discussed, are now available to more accurately predict the behavior of polyisocyanurate insulation boards in the field.

Finally, some preliminary results with two third-generation blowing agents will be discussed.

KEYWORDS

Testing Protocol, Polyisocyanurate Insulation, Systematic Approach, Blowing Agents, Pentane, HFC-245fa, Dimensional Stability, Rolling Load Emulator, Test Roofs.

INTRODUCTION

The general focus of this paper is to outline the steps to be taken when a company changes a raw material within a critical component of its roof systems. The process of switching to new blowing agents in polyisocyanurate insulation boards will illustrate how a company goes about making this transition. The goal is to make this transition as smooth as possible ensuring roofing contractors don't notice the change or experience problems once the change has taken place.

HISTORICAL: TRANSITION TO HCFC-141b

Starting January 1994, most polyisocyanurate manufacturers officially switched to the new blowing agent HCFC-141b from CFC-11. The switch to HCFC-141b (CCl_2FCH_3) reduced effective ozone depletion potential (ODP) by more than 90 percent.[1] In recognition of the industry's efforts, Polyisocyanurate Manufacturers Association (PIMA), polyisocyanurate's trade organization, received the Environmental Protection Agency (EPA's) Stratospheric Ozone Protection Award.

In preparation for the switch to HCFC-141b, extensive trials were conducted in the laboratory and field, and the necessary code approvals were obtained. A slow and cautious approach was taken and the switch to HCFC-141b was not made until the mandated date of January 1994. This direction was driven by a systems approach to introducing new components into our roof systems. The desire to have a high-quality roof system that incorporates a waterproofing membrane and accessories in conjunction with the insulation requires time and effort to ensure the roof system is unaffected by new blowing agents in polyisocyanurate insulation boards.

Before 1994, the roofing industry, in cooperation with the National Roofing Contractors Association (NRCA) and various government regulatory and laboratory organizations put together a Cooperative Research and Development Agreement (CRADA) among the Society of the Plastics Industry Inc.- (SPI-) Polyurethane Division, PIMA, NRCA and Oak Ridge National Laboratory (ORNL) to more thoroughly investigate the practical feasibility of HCFC-141b and other hydrochlorofluorocarbon (HCFC) blowing agents in second-generation blowing agent insulation boards. The results of this CRADA and related work have previously been published [1, 2]. At this time, it is not known if a similar agreement will be constructed to evaluate these third-generation blowing agents; however, it is important to cooperate and participate in an industry-wide investigation if one is arranged.

On balance, the transition to HCFC-141b went well considering that HCFC-141b has a higher boiling point and greater solubility in the polymer network than CFC-11 (CCl_3F). However, there were some early problems related to the dimensional stability of the boards primarily at the edges. Changes in the formulation helped to minimize these problems. A deeper understanding of the role of the blowing agent and its effect on cellular performance [3, 4, 5], along with the development of new analytical tools, contributed to an almost complete elimination of these problems.

[1] HCFC-141b's ODP is 0.11 (vs. 1.00 for CFC-11); however, its effective ODP relative to CFC-11 is lower because its boiling point is higher (89.6°F [32°C]) (74.9°F [23.8°C]) and relative to CFC-11, it requires 15 percent less material on a weight basis to expand the foam to the same density, which taken together correlate to less material in the environment.

In accordance with EPA requirements today, and in part to meet the requirements of the Montreal Protocol on these chemicals, production of HCFC-141b is scheduled to cease as of January 2003. This means that the polyisocyanurate industry has until then to produce boards with zero ODP. Various candidates are being considered, including the pentanes, hydrofluorocarbon-245fa (HFC-245fa), and hydrofluorocarbon-365mfc (HFC-365mfc). One manufacturer has already started limited production of polyisocyanurate boards with pentanes [6].

TRANSITION TO THIRD-GENERATION BLOWING AGENTS: BACKGROUND

What steps does a company take and what has the industry learned that will make the upcoming transition even better than the transition from CFC-11 to HCFC-141b.

Before the early 1990s, the urethane industry had only one class of blowing agent: chlorofluorocarbons. Since the 1960s, the dominant blowing agents were CFC-11 and chlorofluorocarbon-12 (CFC-12). They had good thermal performance and were nonreactive, nontoxic, nonflammable and noncorrosive. Unfortunately, it was later determined that these types of chemicals attack the earth's ozone layer. The subsequent transition to second generation blowing agents, HCFCs, required research and development and was the first major change the industry had faced in many years. In fact, the industry had never undergone a blowing agent change. The process and experience gained during the transition to second generation blowing agents should make the transition to these zero ODP third-generation blowing agents easier.

Although there is a large number of blowing agents that could be used to expand the polymer, there are a number of practical considerations that limit the number of possible candidates. The blowing agent must be nontoxic, have a zero ODP, have a low thermal conductivity, be relatively inexpensive, not react with the main components of the polyisocyanurate, and be readily available. When these parameters are taken into account as well as business margin expectations and anticipation of any future problems, such as global warming, the list of candidates is reduced to a relative few. The main candidates as shown in Table 1 are the pentane isomors HFC-245fa, HFC-365mffm, carbon dioxide either generated from the reaction of isocyanate with water or as a pure component, and blends thereof.

HFC-245fa and the pentanes are being investigated. There are numerous reports in the literature on the efficacy of these third-generation blowing agents [7, 8, 9, 10]. Preliminary work to date shows that either type of blowing agent can be used successfully to produce an insulation board that will perform in the field. Very little work has been done on carbon dioxide because carbon dioxide leaves the cell relatively quickly, which leads to dimensional stability concerns and the loss of R-value. Although initial work with HFC-245fa would seem to merit more work with this material, its projected price is expected to be three to four times higher than that for the current blowing agent, HCFC-141b. Because HFC-245fa is more than 7 percent of the raw material, this coupled with the need for approximately 15 percent more HFC-245fa than HCFC-141b on a weight basis in a typical two inch thick board precludes the use of 100 percent HFC-245fa in a polyisocyanurate insulation board. That essentially leaves the pentanes and blends of pentane with HFC-245fa or HFC-365mfc as the only realistic choices. Preliminary work with polyisocyanurate boards expanded with pentanes has been shown to perform well as a replacement to HCFC-141b.

Perhaps most reassuring to those unfamiliar with the urethane industry is the knowledge that European manufacturers have been using pentane blowing agents for more than five years. Many in Europe, partly as a result of government mandates, went directly to zero ODP blowing agents from CFCs. The pentanes (cyclopentane, isopentane and N-Pentane) were Europe's choice for its second-generation blowing agent. Until recently, the European market has manufactured a rigid insulation board slightly different from the board made in the United States. The European board is a polyurethane board that uses polyether polyols and has an index typically around 120 and incorporates a flame retardant, whereas the U.S. board is a polyisocyanurate board that uses a polyester polyol and has an index of 250. The latter boards tend to perform better in fire tests [11], but require more sophisticated processing. Recently, the European insulation industry has begun the transition to boards closer to polyisocyanurate expanded with pentanes.

NEW ANALYTICAL TESTS TO PREDICT FIELD PERFORMANCE

Over the last 8 to 10 years, a greater understanding of the dynamics of long-term dimensional stability of polyurethane and polyisocyanurate insulation boards has been attained. As a result, new analytical tools have been developed to predict long-term dimensional stability in these boards. Additionally, a testing apparatus has been built to determine a board's resistance to delamination under a rolling load. Following is a discussion of the basis for dimensional stability of a polyisocyanurate board and descriptions of a test method developed by ICI Polyurethanes Group to determine the ultimate stability of a rigid board, as well as a test used to quickly determine the inherent board stability at its edges. Following this discussion, a new test will be described that measures a board's resistance to delamination under a rolling load.

Dimensional Stability

A board's dimensional stability is a key performance parameter. It is not well known that the gas pressure inside the foam cell is below ambient temperature soon after manufacture. This is because the board is expanded hot, and the cell walls are cured under the influence of heat and catalysts. Then when the board cools, the gas pressure decreases (gas pressure is related directly to temperature). In a closed vessel of constant volume, the higher the temperature, the higher the pressure, and conversely, the lower the temperature, the lower the pressure. Some water is used to improve flow and build early board strength in the manufacturing process; however, the carbon dioxide generated from the reaction of water with polymeric isocyanate leaves the cells and board relatively quickly, which can lead to even lower cell pressures. Lower cell pressure can lead to partial or total collapse of the cell leading to dimensional stability problems with the insulation board. ICI Polyurethanes Group[5] developed a test called the "Dim Vac" test. This test removes the carbon dioxide quickly and then subjects the board to a cold environment. In this way the inherent stability of the board can be assessed. This avoids the situation in which boards manufactured in the plant and subjected to standard tests for dimensional stability showed no problems but developed dimensional stability problems (typically edge cavitation and shrinkage in a cold environment) in the field weeks afterward.

Although the Dim Vac test is an excellent gauge of a particular formulation or type of board, it is not a timely test because it takes several days to obtain results. A quicker, in-plant test was needed to gauge the performance of the polyisocyanurate board, especially at the edges. A polyisocyanurate board requires high temperatures to fully cure. Because the edges have relatively cooler temperatures, this is the area most susceptible to collapse or dimensional instability. The bulk of the polyisocyanurate board is very dimensionally stable.

A test is in use to measure the perpendicular compressive strength along the 8-foot (2.4-m) edges. A core 1.5-inch (38-mm) cube sample is taken at the mid-line for boards 2 inches (51 mm) thick and greater. One face of the 1.5-inch (38-mm) cube is common with the 8-foot (2.4-m) edge and is in the direction of compression. Compressive strength in this key area is directly related to dimensional stability, with the higher the compressive strength, the better the dimensional stability along this key 8-foot (2.4-m) edge.

Another test instituted to gauge the dimensional stability of polyisocyanurate insulation board is the uncured freezer test. Boards are taken directly off the line and stored in the warehouse, uncured. They are subjected immediately to -40°F (-40°C), and any visible change is noted. If there is a change, another piece from the same sample is put into the freezer and evaluated again the following day. This is repeated until the product passes the test by not exhibiting any visible change in the sample. If the boards pass the uncured freezer test, the bundle-cured samples (typically 24 hours per inch [25 mm]), are expected to perform well.

Within a few hours after boards are manufactured and stacked in a bundle, the temperature inside the bundle can approach 300°F (149°C) before cooling to ambient conditions. During this time, the boards complete their final cure. However, the edges of the boards do not reach these temperatures. Therefore, it is important during the hours/days after manufacture that the edges of the boards are not put in a cold environment, otherwise, edge cavitation, among other problems, can occur.

Resistance to Delamination

Something that happens infrequently, but is a concern when it does happen, is facer delamination. A performance-based test has been developed that mimics the kinds of traffic that typically occurs on roofs, using an apparatus called the Rolling Load Emulator (RLE). Approximately, 20-psi (140-kPa) load is applied to a standard piece of insulation by a steel roller cycling in the machine (or eight foot long) direction. Figures 1 through 3 are photographs of the RLE from three different angles. The number of passes is recorded until 25 percent of the area is delaminated. Typically, once the delamination starts, it progresses quickly. Currently being evaluated is what constitutes high resistance and low resistance to delamination to more fully correlate RLE performance with field performance. However, almost without exception, a facer on any polyisocyanurate board will delaminate or be severely compressed if the load and the number of passes are high enough.

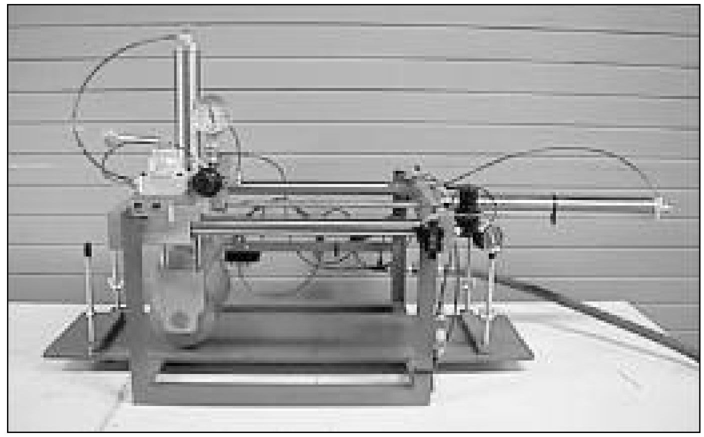

Figure 1.

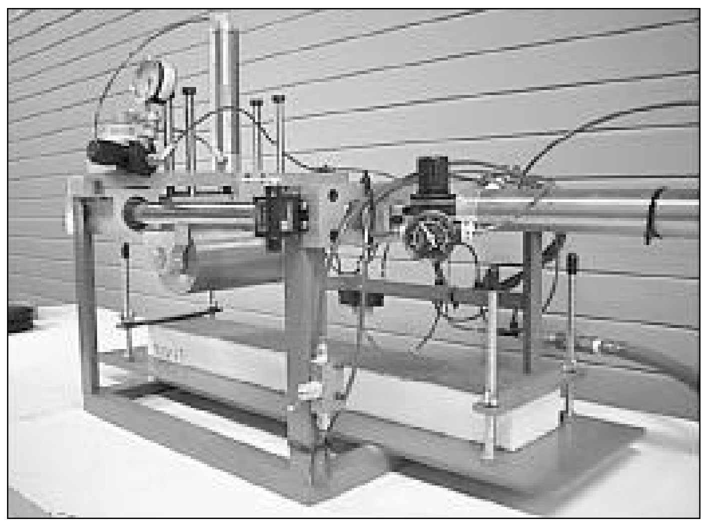

Figure 2.

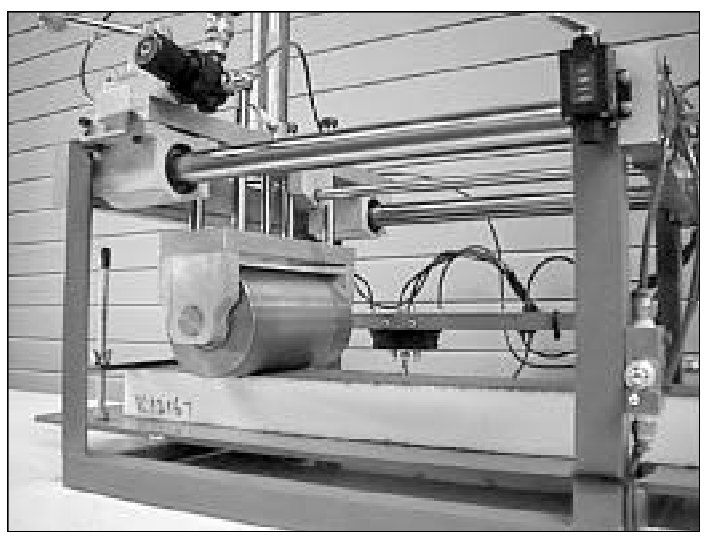

Figure 3.

PERFORMANCE PARAMETERS

The minimum specifications for rigid polyisocyanurate boards are listed in ASTM C 1289-95. The most common product sold today is Type II with fibrous felts or glass fiber facers on both sides of the board. Below are discussions of the major tests in this standard and discussions of any changes expected with the introduction of a third-generation blowing agent. A short paragraph is included to illustrate the need to be alert for any unusual occurrences.

Compressive Strength (ASTM D 1621) psi (kPa)
Compressive strength is a key performance parameter. The minimum required by ASTM C1289 is 16 psi (110 kPa), although 20 psi (140 kPa) is more common [12]. Analyses of insulation boards made with different types of third-generation blowing agents indicate that a typical 20 psi (140 kPa) should not be difficult to maintain.

Dimensional Stability (ASTM D 2126) percent linear change
Cold Aging -40°F (-40°C)
Humid Aging (158 F [70 C]/97% RH)
Dry Aging (200°F [93°C]/amb. RH)

Dimensional stability can be affected by the blowing agent in several ways. The vapor pressure of the gas at various temperatures can change the gas to liquid ratio in the cell. The higher the gas to liquid ratio at a given temperature, the more resistant the cells are to shrinkage in a cold environment, and the more prone to expansion in a hot environment. Additionally, the amount of blowing agent used in total, the solubility of the blowing agent in the polymer matrix and heat of vaporization (the amount of energy needed to go from a liquid blowing agent to a gaseous blowing agent) of the blowing agent can affect the curing process. The more soluble the blowing agent is in the polymer matrix and the higher the heat of vaporization, the more catalyst is needed. Also, the more blowing agent needed on a weight basis, the more catalyst is needed, everything else being equal. However, too much catalyst can affect flow, which can have a detrimental effect on edge stability and other physical properties.

HFC-245fa has a lower boiling point than either CFC-11 or HCFC-141b, hence it should improve cold aging. Although approximately 15 percent more HFC-245fa is needed, its lower solubility in the polymer network and its lower boiling point show that it will be similar to CFC-11 in cold age performance. Data generated[7] in the open literature indicate that humid aging and dry aging will not be a concern.

The dimensional stability of boards expanded with pentanes will depend on the type or types of pentane used. Table 2 is a list of physical properties of CFC-11, HCFC-141b, HFC-245fa, and cyclopentane, isopentane, N-pentane and carbon dioxide. The higher the ratio of cyclopentane, the more likely the board will shrink in a cold environment. Therefore, the key to manufacturing a dimensionally stable board under a variety of temperatures and humidities is to use the proper ratio of pentanes. Two combinations that appear to work well are 80/20 and 70/30, cyclopentane to isopentane. With these combinations, dimensional stability should not be a problem, although further work is required to confirm these initial results.

Facer Adhesion (ASTM D 1623) (ASTM C 209 also can be used) psi (kPa)
Adhesion is necessary for a product that is placed between facers. The amount of adhesion strength can be measured. If adhesion is not adequate in a single-ply, fully adhered roof system, a high wind event can lead to facer delamination as the membrane/facer is peeled from the foam. Fortunately, urethane foam adheres well to most substrates. Spray polyurethane foam uses this adhesion to adhere to the roofing substrate, and many commercial adhesives use urethane chemistry in their formulations.

Good facer adhesion is necessary and should mean that a board is resistant to delamination under load. However, with the transition to HCFC-141b expanded boards, a more careful study of the causes of delamination under load led to the development of a test (RLE) that is more indicative of performance in the field. Examination of delamination showed that many facer delamination problems are cohesive rather than adhesive in nature-the failure plane is usually a few cells below the facer. RLE reproduces this failure mode, which can develop from excessive traffic and/or high loads.

The third or next generation rigid insulation board will first be evaluated for adhesion and then evaluated for resistance to delamination. Formulation and processing conditions can be modified to improve resistance to delamination.

The change in blowing agents should not have a major impact on this physical property. Results to date indicate this is true with boards expanded with HFC-245fa or pentanes.

Thermal Conductivity (R-Value) (ASTM C 518) Btu•in/h•ft²•°F (W/m•°K)
There are many factors that affect thermal performance, including cell size, cell orientation, composition of cell gases, type and length of conditioning, types of raw material that constitute the foam, and density. In all cases air infiltrates into the cell slowly and the blowing agent leaves the cell even more slowly (half-life of more than 100 years has been measured). Both of these diffusions are dependent on the polymer network and type of blowing agent. Data to date suggest that some pentanes leave the cell environment slower than HCFC-141b. Although the initial R-value of pentane foams may be lower, the final number may in fact be higher.

ASTM C 518 is the common method to measure R-value, although other methods are used such as ASTM C 177 and ASTM C 236. Typically the R-value is taken at a mean temperature of 75°F (24°C). When it is measured is as important as the measurement itself. The most common conditioning or aging procedure is outlined in PIMA Technical Bulletin 101. After 180 days at approximately 73°F (23°C) and 50 percent relative humidity, the R-value reaches a near plateau where additional decreases in R-value are low.

When a long-term or design R-value is needed, a slicing and scaling method can be used as outlined in ASTM C 1303 and modified by PIMA. This method accelerates the aging of thermoset (e.g., polyisocyanurate) and thermoplastic (e.g., extruded polystyrene) foams and produces relatively conservative values, because it does not take directly into account the decrease in aging afforded by the skins or densified layers of cells.

Results from boards expanded with HFC-245fa indicate that the R-value was very similar to HCFC-141b expanded polyisocyanurate. The investigation of the pentanes started later, and it is too early to predict what their R-values will be relative to HCFC-141b.

E. Other parameters

Other performance issues that will need to be investigated include moisture vapor transmission rates (ASTM E 96), flexural strength (ASTM C 203), moisture resistance (ASTM C 209), and friability (ASTM C 421). To date, all of these parameters appear to be within normal ranges. Commercial sized 4-foot-by-8-foot (1.2-m-by-2.4-m) boards have been made with HFC-245fa and pentanes. However, only pentane boards have been used in test roofs.

It is important to be alert for any subtle change in performance not normally tested for when evaluating polyisocyanurate boards produced with the new blowing agents.

FIRE PERFORMANCE

The following fire tests should be conducted: FM 4450 Calorimeter, the original (pre-1998) UL 1256 (tunnel test), E108 (UL 790), E84 (UL 723) and E119 (UL 263). Preliminary results with boards expanded with third-generation blowing agents indicate that these boards can be formulated to pass these tests. Because polyisocyanurate is a thermoset insulation, it forms a protective char-like layer, much like wood, in the presence of fire. This char-like layer forms regardless of the blowing agent used.

ASTM E84 data is required only if the assembly is not part of a class A-, B- or C-rated system and has not passed one of the two code-required fire tests (Factory Mutual 4450 Calorimeter or UL 1256 [original pre-1998 version]). These tests measure the roof assembly for underdeck flame spread, a critical fire performance criterion. It is important to note, however, that residential sheathing requires a flame spread of less than 75 and a smoke density of less than 450, as measured in ASTM E84.

ASTM E108 measures the surface burning characteristics from an exterior fire on a roof system. Fire-resistive ratings can be determined via ASTM E119. A controlled degradation is required to pass this test. In other words, the temperatures from the interior fire must not increase too fast nor should the roof system insulate the fire too much and lead to premature collapse of the roof assembly.

Results to date indicate that polyisocyanurate boards blown with any of the third-generation blowing agents can be formulated and manufactured to satisfy these fire performance requirements.

FIELD PERFORMANCE

Systems Approach

An important approach when evaluating any new material is to look at it in terms of the total roof system from the perspective of the full range of base membranes, including thermoset (e.g., EPDM), thermoplastic (e.g., PVC and TPO), modified bitumen (APP and SBS), and built-up roofing. Different installation designs (ballasted, mechanically attached and fully adhered) each stress one or more of the attributes of polyisocyanurate insulation. With EPDM, for example, a ballasted design focuses on the compressive strength and, to a lesser extent, the resistance of a board to delamination. Mechanically attached EPDM systems require good compressive and flexural strengths, as well as resistance to pull-through at fasteners. In the case of fully adhered EPDM, the adhesion of EPDM to the facer and of the facer to the foam is also critical to the roof system. Hence, the resistance of this roof system to foot traffic and ballooning of the membrane is important.

Test Roofs

A key component of the evaluation process that checks for any significant change in a roof system is a test roof. Laboratory results may show that a change is insignificant, but a test roof is key. Nothing overrides the results collected from a test roof. While it is not feasible to simulate all possible conditions in every kind of roof system, the more test roofs are completed, the greater the company's confidence that the change will not affect the performance of the roof system.

A test roof system set in the Midwest presents most of the potential problems that can happen on a roof system in any region of the United States. The summers are hot and humid, the winters cold, and the spring and fall wet. Test roofs in the Southwest and in South Florida are very illuminating, they subject the roof systems to extremely hot or hot and humid weather, respectively.

It is important to look for test roofs that stress the components of interest. Fully adhered EPDM roofs are good test roofs. If a component has an effect on the adhesion of the facer to the foam or the EPDM to the facer, it can impact EPDM roof system. Additionally, in the southwest region of the United States, a fully adhered EPDM roof system will focus the maximum roof temperatures on the membrane, insulation and accessories.

PRELIMINARY RESULTS

(Full-Sized Boards: 4-foot-by-8-foot [1.2-m-by-2.4-m]) HFC-245fa

Preliminary results indicate no visible change in the boards except, upon close inspection, possibly finer cells. Table 3 illustrates the decreased aging found with HFC-245fa vs. HCFC-141b in a 1-inch-thick core sample [7]. The initial R-values for boards made with HFC-245fa tended to start a little lower than those made with HCFC-141b but the boards were conditioned to about the same value (or better). HFC-245fa is a bigger and bulkier molecule than HCFC-141b, which may explain, along with the greater air pressure in the cells, the reduced tendency for air to enter the cells and for HFC-245fa to leave the cells.

Selected physical properties of a 3-inch-thick board expanded with HFC-245fa at a manufacturing facility are shown in Table 4. Compressive strengths were higher relative to HCFC-141b, probably because HFC-245fa is a not as soluble in the polymer matrix as HCFC-141b. If a blowing agent is soluble in the polymer network, the blowing agent can plasticize the polymer network, which can lead to lower compressive strengths. Also, the greater air pressure in the cell with HFC-245fa may have contributed to the good compressive strengths. Humid aging and cold aging results were excellent. Facer adhesion was slightly above average, and flexural strength was within ASTM specifications.

Pentanes

In general, pentane expanded polyisocyanurate insulation boards yield very fine cell structure. Because pentanes boards require approximately 40 percent less blowing agent than HCFC-141b, there is less blowing agent to plasticize the polymer network. However, the type of pentane plays a role. Cyclopentane is more soluble in the polymer network than isopentane or normal pentane. Hence, if a combination of pentanes is used, the amount of and its effect on compressive strength and cold age dimensional stability needs to be taken into account.

Cyclopentane's boiling point is 120.7°F (49.3°C). Therefore, when the environment is cold, a significant portion of the cyclopentane can condense to a liquid. Introduction of minor amounts of isopentane, which has a boiling point of 82°F (28°C) increases the cell pressure at cold temperatures and ensures that the foam is stable. Results to date indicate that compressive strength will not be a problem with pentane expanded polyisocyanurate insulation boards.

Table 5 illustrates physical properties for a nominal 2 inch (50.8 mm) thick board recently produced with a blend of cyclopentane and isopentane. The compressive strength was above average for a pentane expanded board and the percent linear change from either cold or hot/humid aging was excellent. Facer adhesion was slightly above average as well. This board also passed the RLE test. Finally, flexural strength was well above the industry minimum of 40 psi (280 kPa). Thermal conductivity performance is not available at this time.

CONCLUSIONS

The industry is in the midst of evaluating third-generation blowing agent rigid insulation boards. Although we can not say today with certainty what the blowing agent or blowing agent combination will be, preliminary results with HFC-245fa and pentanes are very encouraging. The two most promising avenues are the pentanes and possibly HFC-245fa in combination with pentanes.

More importantly, the industry has the tools today to adequately evaluate any new blowing agent in terms of critical roof system performance. These tools include:

- "Dim Vac" test for ultimate dimensional stability
- Perpendicular Compressive Strength at the edge of the board for site specific dimensional stability
- Uncured Freezer test for dimensional stability
- Rolling Load Emulator for resistance to facer delamination

These in conjunction with our systems approach to these types of changes, will ensure that our customers, roofing contractors, will purchase a high-quality insulation board that will perform well over the life of the roof system.

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Chemical	Representation
Cyclopentane	CH_2 CH_2 CH_2 CH_2 CH_2
N-Pentane	CH_3 CH_2 CH_2 CH_2 CH_3
Isopentane	(CH_3) CH_2 CH_2 CH_3
HFC-245fa	CF_3 CH_2 CHF_2
HFC-365mfc	CF_3 CH_2 CF_2 CH_3
Carbon Dioxide	CO_2

Table 1. *Potential third generation blowing agents.*

Time	HCFC-141b	HFC-245fa
Initial	7.51 (42.6)	7.47 (42.4)
7 Days	7.03 (39.9)	7.17 (40.7)
28 Days	6.43 (36.5)	6.83 (38.8)
3 Months	5.96 (33.8)	6.41 (36.4)

Tested as per ASTM C518 at a mean temperature of 72.5°F (22.5°C).
Conditioned at approximately 70°F (21°C) and 50 percent relative humidity.

Table 3. *R-value per inch of 1-inch core foam.*

Property	CFC-11	HCFC-141b	Isopentane	N-Pentane
Molecular weight	137.4	116.9	72	72
Normal boiling point F (C)	74.8 (23.8)	89.6 (32.1)	82.0 (27.8)	97.2 (36.2)
Vapor pressure at 86°F (30°C) / psia (kPa)	2.65 (18.3)	1.97 (13.6)	2.32 (16)	1.72 (11.9)
Vapor pressure at 68°F (20°C) / psia (kPa)	1.85 (12.8)	1.45 (10)	1.63 (11.3)	1.20 (8.3)
	Cyclopentane	**HCFC-245fa**	**HFC-365mfc**	**CO2**
Molecular weight	70.1	134.1	148	44
Normal boiling point F (C)	12.1 (49.3)	59.4 (15.2)	104 (40)	-109 (-78.6)
Vapor pressure at 86°F (30°C) / psia (kPa)	1.11 (7.7)	3.72 (25.7)	1.52 (10.5)	NA
Vapor pressure at 68°F (20°C) / psia (kPa	0.71 (4.9)	2.58 (17.8)	0.98 (6.8)	NA

Table 2. *Physical properties of past, present and future blowing agents.*

Compressive strength, psi (kPa)	28.4 (195)
Cold age -40°F (-40°C), percent linear change, 7 days Length Width	 -0.02 -0.02
Humid age (158°F [70°C] / 97%RH), percent linear change, 7 days Length Width	 0.24 0.58
Facer Adhesion, psi (kPa)	9.6 (66)
Flexural strength, psi (kPa) Machine direction Cross-machine direction	 73.8 (509) 70.8 (488)

Table 4. *Physical properties of HFC-245fa board (3 inches thick).*

Compressive strength, psi (kPa)	25.5 (176)
Cold age -40°F (-40°C), percent linear change, 7 days Length Width	 -0.1 0
Humid age (158°F [70°C] / 97%RH), percent linear change, 7 days Length Width	 0 0.43
Facer Adhesion, psi (kPa)	9.9 (68)
Flexural strength, psi (kPa) Machine direction Cross-machine direction	 68.1 (470) 57.1 (394)

Table 5. *Physical properties of a cyclopentane/isopentane board (2 inches thick).*