Polyiso Insulation: The Foundation for 21st Century Roof Systems

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Keywords

Polyiso, insulation, energy efficiency, high density coverboard, dimensional stability, energy code, reroofing, life cycle analysis, recycling, cuppage, edge collapse, Z-direction compressive strength (ZCS), rolling load emulator

Abstract

High performance roofing systems currently are required to be energy efficient, durable, sustainable, and versatile. Polyisocyanurate insulation, currently a common insulation for roofs, ideally is suited to address these opportunities in this century's roof systems. Energy codes - past, present and future - are reviewed and compared across all eight climate zones in the U.S. By 2012 R-values will have increased more than 80 percent on average compared with 2004. A strong argument is made that increasing the energy requirements for reroofing will significantly affect energy efficiency in the U.S.

The total environmental assessment of polyisocyanurate insulation from raw materials to final installation is called Life Cycle Analysis. It briefly is discussed and its effects are compared to other carbon abatement strategies. The recycling content of polyisocyanurate insulation is outlined and promising new recycling opportunities also are noted.

An in-depth study of cell dynamics as related to dimensional stability is reviewed and discussed. The role of temperature, pressure in the cells and diffusion of gases is outlined. The importance of the 2.4-meter (8-foot) edges of a standard 1.2-meter (4-foot) by 2.4-meter (8-foot) board and especially its strength as measured by the Z- direction perpendicular compressive strength is correlated to the board's overall dimensional stability. And finally, physical properties and performance characteristics of high-density cover boards are reviewed.

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Introduction

Polyisocyanurate insulation has been successfully used in roofing assemblies for more than 30 years. During the past few years, energy efficiency has risen in importance as energy costs have increased, reliable supply has been compromised and the environmental concerns about unfettered energy use have increased. Roofing systems currently not only have to deliver reliable energy savings with a dimensionally stable insulation, but be sturdy enough to withstand the use of the roof as a substrate for energy producing elements such as photovoltaics (PV) systems and of course assist with wind uplift resistance, water tightness, fire ratings and other code requirements.

This paper will focus on recent developments with energy efficiency and advances in polyisocyanurate insulation. New energy requirements will be reviewed including the importance of reroofing in terms of net energy savings. Besides the obvious environmental benefits of polyisocyanurate insulation regarding energy savings, the overall life cycle of polyisocyanurate insulation will be discussed and a recycling update included.

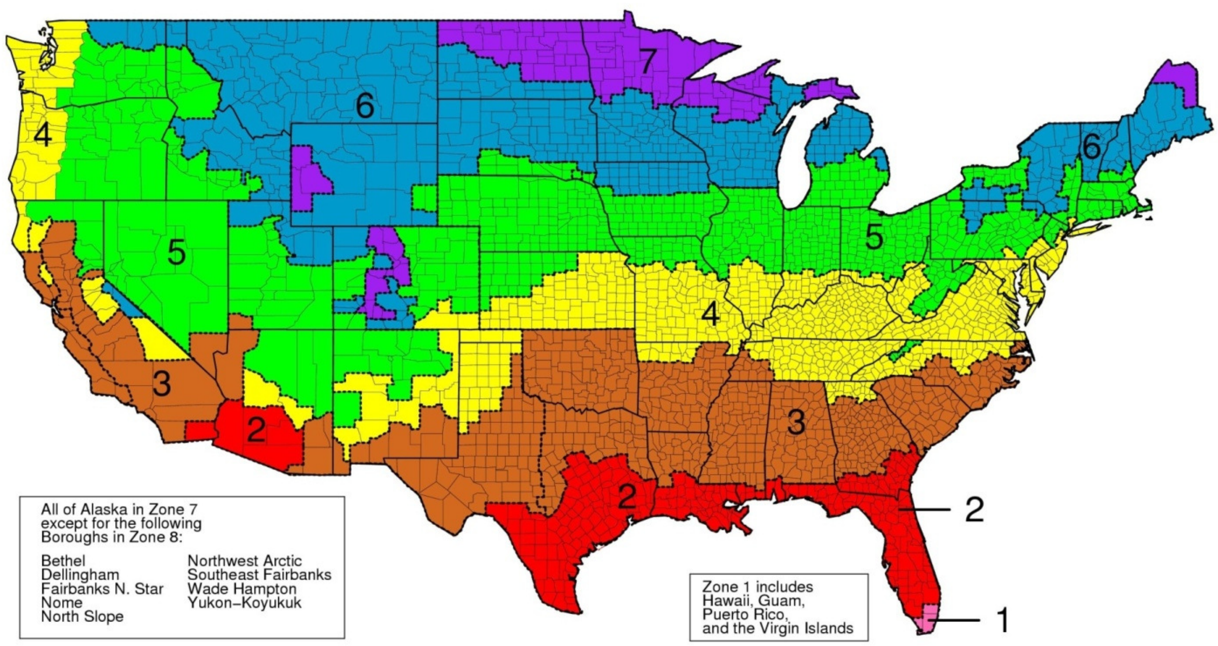
Work will also be shown that outlines the advances in understanding dimensional stability in polyisocyanurate insulation boards and how best to ensure all boards that reach the roof are dimensionally stable.

Finally, to meet current demands, a new product – high-density cover board with coated fiberglass mat facers - has been introduced. This product is ideal for roofs where there is high traffic (new construction and PV) and an ideal substrate for reroofing applications especially with single ply membranes and cold applied modified bitumen, less so for hot asphalt or torch applied.

Energy Efficiency

The ultimate goal in energy efficiency is a zero-energy building, sometimes called a "passive building" and few other names. Similarly, The American Institute of Architects has recommended new constructions should be net energy neutral by 2030. The roofing industry is not there yet, but significant steps are being taken now to improve performance in this area. Figure 1 shows the climate zones for the U.S.; most of the population resides in climate zones 3, 4 and 5.

Figure 1 Climate Zones in the U.S.



In order to accomplish these goals the appropriate standards and codes must be in place. Table 1 illustrates the minimum above deck roof R-values for all eight climate zones as per the past, present and future codes. In general, R-values in ASHRAE 90.1-2007, "Energy Standards for Buildings Except Low-rise Residential Buildings," are 33% higher than R-values ASHRAE 90.1 – 2004 R-values, "Energy Standards for Buildings

Except Low-rise Residential Buildings." Additionally, the recently adopted International Energy Conservation Code (IECC) 2012 code is an average of 35 percent higher than the ASHRAE 90.1 – 2007 code and more than 80 percent higher than the ASHRAE 90.1 – 2004 R-Values. For example in climate zone 4 for roofs the minimum R-value for roofs has increased from 20 to 25. The International Green Conservation Code (IGCC) has gone further and is requiring a 10 percent increase over the current IECC standard. This is a positive step forward. Compared with 2004 these changes reflect the growing awareness of energy efficiency in terms of saving money, reducing our dependence on foreign oil, and reducing our carbon footprint. It is important to note that these are minimum legal requirements.

Table 1 Recent Energy Standards and Codes. R-values for all 8 climate zones as a function of Energy Standards and Codes from 2004 to 2012.

Climate Zone	ASHRAE 90.1 - 2004	ASHRAE 90.1 - 2007	ASHRAE 189.1 - 2009	IECC - 2012
1	1.76 (10)	2.64 (15)	3.52 (20)	3.52 (20)
2	2.64 (15)	3.52 (20)	4.40 (25)	3.52 (20)
3	2.64 (15)	3.52 (20)	4.40 (25)	3.52 (20)
4	2.64 (15)	3.52 (20)	4.40 (25)	4.40 (25)
5	2.64 (15)	3.52 (20)	4.40 (25)	4.40 (25)
6	2.64 (15)	3.52 (20)	5.28 (30)	5.28 (30)
7	2.64 (15)	3.52 (20)	6.16 (35)	6.16 (35)
8	2.64 (15)	3.52 (20)	6.16 (35)	6.16 (35)
Status	"Old Code"	"Current Code"	"Green Code"	"Next Code"

Although these changes to ASHRAE 90.1 – 2007 / IECC 2012 are important and necessary, every time a building is built with these new standards, more energy is used to heat and cool (unless it is a passive building). Therefore, the net amount of energy in the country used to heat or cool has increased with additional new buildings. More needs to be done to reduce the country's net energy used to heat and cool. To have real and sustained effect on reducing our energy dependence, reroofing must be addressed. Energy efficiency in reroofing is sometimes addressed when the local code requires it or there is a desire to replace a roof (tear-off and reroofing). However, currently, roof re-covers are exempt from the 2009 IECC and earlier codes. Specifically, reroofing activity is identified as an exception not subject to the requirements of the code:

> "Reroofing for roofs where neither the sheathing nor the insulation is exposed. Roofs without insulation in the cavity and where the sheathing or insulation is exposed during reroofing shall be insulated above or below the sheathing." (2009 IECC 101.4.3.5)

Jim Hoff, research director for the Center for Environmental Innovation in Roofing[1] has shown that increasing the requirements for reroofing can save a tremendous amount of energy that continues to be saved as the years pass. Therefore, one of the biggest barriers to achieving increased energy conservation, specifically in the reroofing market, is local code adoption of the IECC for all types of reroofing projects.

Figure 2 U.S. Low-Slope Non Residential Roofing Market, 2009

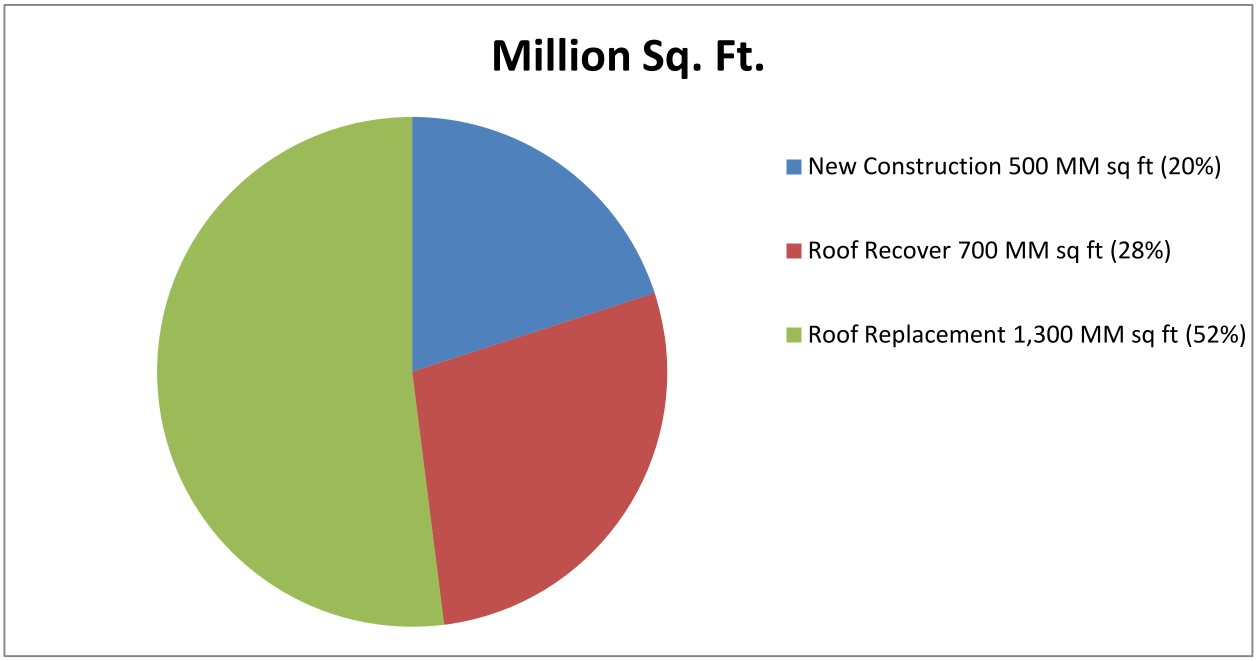
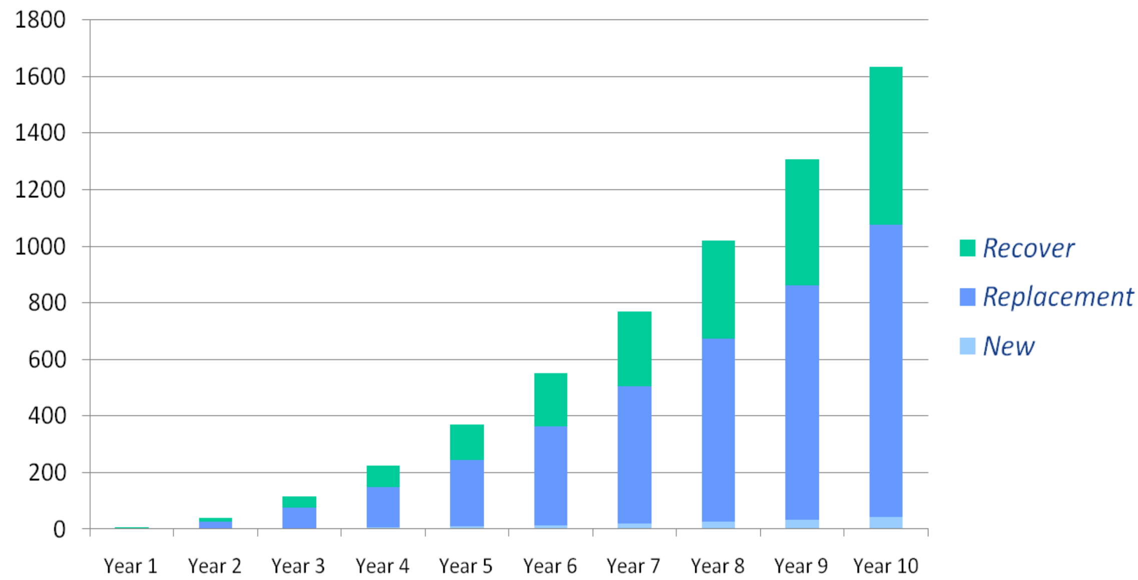


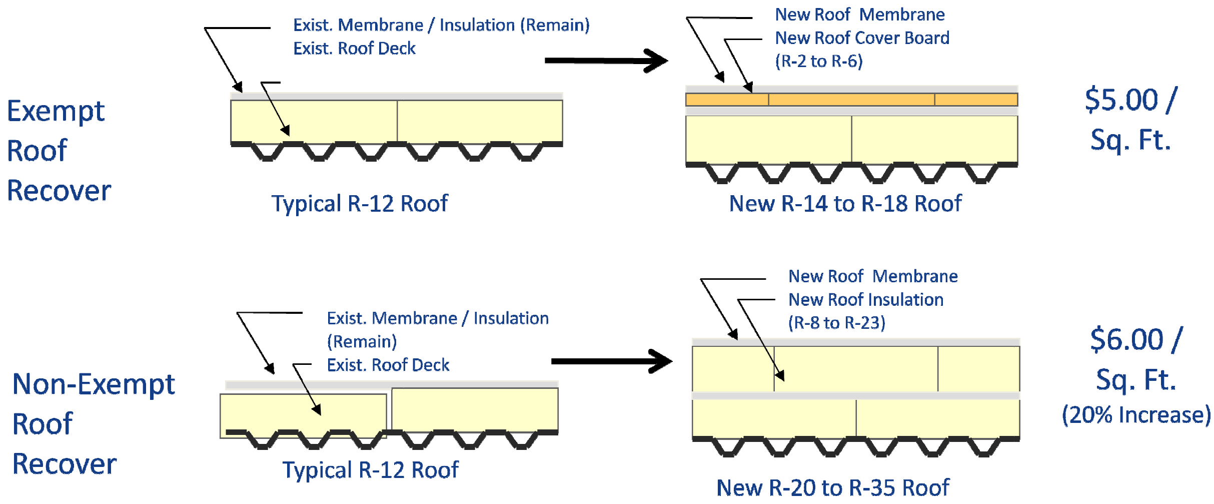
Figure 2 shows the breakdown in the low-slope commercial roofing market for 2009, where the percentage of replacement and re-cover is approximately 80 percent. The annual savings is more than 37,900 Joules (36 billion British thermal units [BTU]) if all of these roofs were upgraded to ASHRAE 90.1, 2007/ IECC – 2009, which during a 10-year period equals 368,900 Joules (350 trillion BTU) – obviously a big opportunity. And if after this first year subsequent roofs are brought up to code every year, the cumulative 10-year savings is more than million Joules (2,000 trillion [or 2 quads] BTU) (Figure 3) – a huge opportunity! It is interesting to examine Figure 3 and see how much the replacement and re-cover market swamps the effect of new buildings.

Figure 3 Non-Residential Roofing Annual Cumulative Energy Savings Year 1-10 TrillionBTU



Although removing the existing insulation and membrane and then adding code-compliant insulation and a new membrane is more expensive (approximately $9 per square foot) than placing a cover board on a existing membrane and insulation and then putting on new membrane (approximately $5 per square foot), Dr. Hoff[1] has calculated that placing code-compliant insulation above existing insulation and membrane and then adding a new membrane (approximately $6 per square foot) is only slightly more expensive (see Figure 4) than the exempt roof re-cover system. These are installed costs, which is an approximate average over all climate zones. Additionally, they don't include the expected energy savings from the increased R-values, which will offset the modest 20 percent increase in the installed costs. More effort, clarity and focus are needed in this area to realize the huge potential energy savings in reroofing.

Figure 4 Code-Exempt Roof Re-cover versus Code-Compliant Roof Re-cover

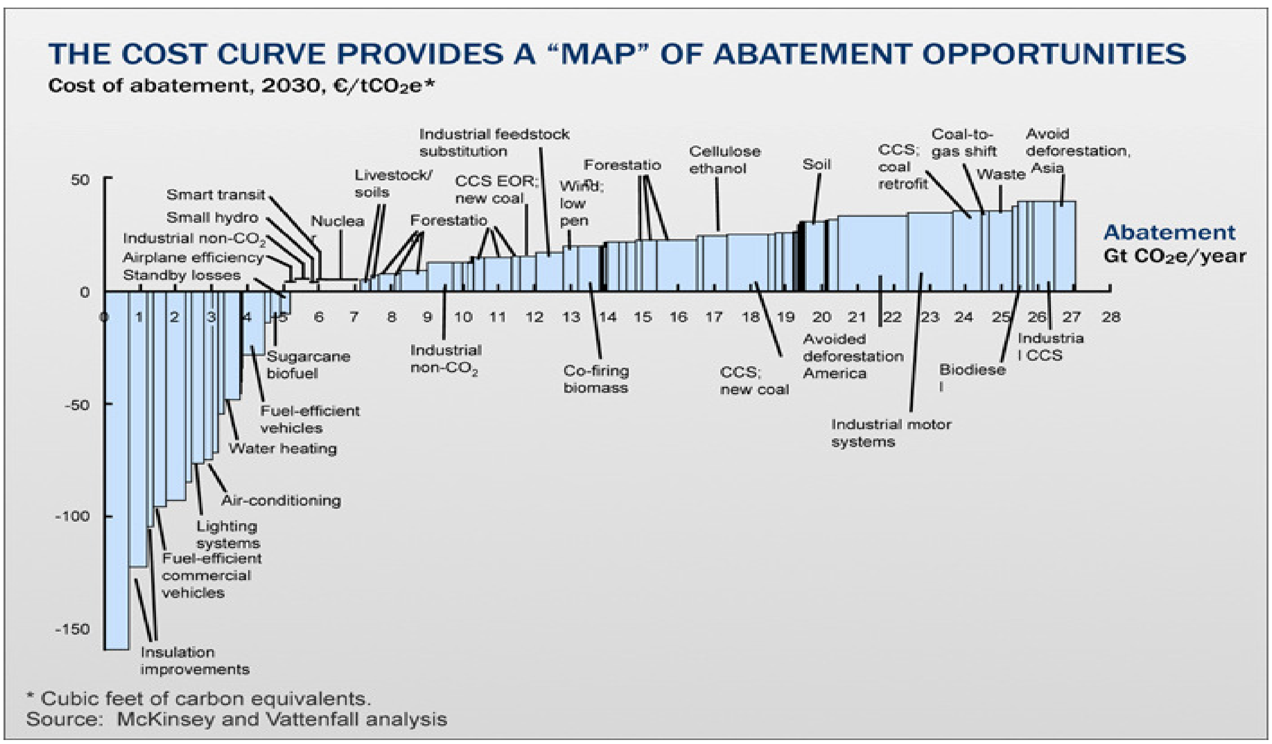


Life Cycle Analysis

A life cycle analysis of a product allows people to assess the relative environmental effects of the product from its raw materials to the end of its useful life. It usually takes energy and some environmental effect (such as the release of carbon dioxide) to acquire raw materials and then later to manufacture the final product. However, some products may have a positive energy and environmental effect during their useful lives that may in some cases vastly offset the initial disadvantage from producing the raw materials and manufacturing the product. This is the case for polyisocyanurate insulation where so much energy is saved with its use that the product quickly and many times over offsets the initial adverse effects of the raw materials and the energy consumption during the manufacturing aspect of the product. Although a final report has not been written it is expected that a code-compliant product in Massachusetts will offset its initial environmental investment approximately four weeks after installation[2]. In other words, the energy used to produce the insulation is offset by the energy saved in about four weeks.

Polyisocyanurate insulation's positive Life Cycle Analysis matches its positive effects on climate change and the reduction of atmospheric carbon dioxide. In order to stay below 500 ppm[3] of carbon dioxide and maintain economic growth a range of abatement strategies have been calculated. A recent report[3] by McKinsey (Figure 5) shows a cost abatement table where the cost range from approximately 50 Euros per ton of carbon dioxide abated to an actual savings up to 150 Euros per ton of carbon dioxide abated. The far left hand side of this graph indicates that insulation such as polyisocyanurate insulation is one of the most cost effective ways to reduce carbon dioxide. As a result, this reduces global warming, which saves building owners money while maintaining growth – a win / win situation.

Figure 5 A Cost Curve of Abatement Opportunities



Recycling Status

Polyisocyanurate insulation, especially Type II, Class 1 in ASTM C1289 "Standard Specification for Faced Rigid cellular Polyisocyanurate Thermal Insulation Board", has both post consumer and post industrial recycled content in the product. Type II, Class 1 typically has for a 2-inch-thick board 24 percent post consumer recycled content by weight and 15 percent post industrial recycled content by weight; most of this recycled content comes from the facer. However, there exists an opportunity to increase these levels. Work is underway to recycle the foam used with polyisocyanurate insulation. Although it generally is easier to recycle a thermoplastic material such as polyethylene, thermoset materials like polyisocyanurate insulation can still be recycled. Recent work suggests that at least some of the raw materials used to make polyisocyanurate insulation foam can use recycled polyisocyanurate insulation foam itself as raw material. Further work is planned.

However, it is important to note that old polyisocyanurate insulation boards are frequently left in place in reroofing applications – in essence "recycled" or re-used. In these re-cover applications it is also recommended that the newer higher R-value cover boards (high-density polyisocyanurate insulation) and / or more standard polyisocyanurate insulation be used to meet the recommended R-values.

Enhanced Testing Methods

Dimensional stability of construction products is a key parameter and it is with polyisocyanurate insulation boards. For a majority of jobs, polyisocyanurate insulation boards are very dimensionally stable in a wide range of climatic conditions. Although there have been cases of dimensionally unstable boards, this is a rare event, and in these cases more likely in the northern states between April and November. However, when they do occur costly remediation is sometimes needed. When the author first arrived, the company had more “dimensional stability” problems than it wanted and there appeared to be some confusion regarding what the real problem was. Therefore, efforts were expended to better understand the problem.

When the chemicals are mixed in a plant to produce the polyisocyanurate insulation boards the physics of the developing foam and the individual foam cells is approximately described by the Ideal Gas Law (PV = nRT) where P is pressure, V is Volume, n is essentially the amount of material in the cell, R is a constant and T is temperature. If we look at the cells at manufacture and then approximately two weeks later, there are some insights that will help us better understand what is happening in the cell which translate to field performance.

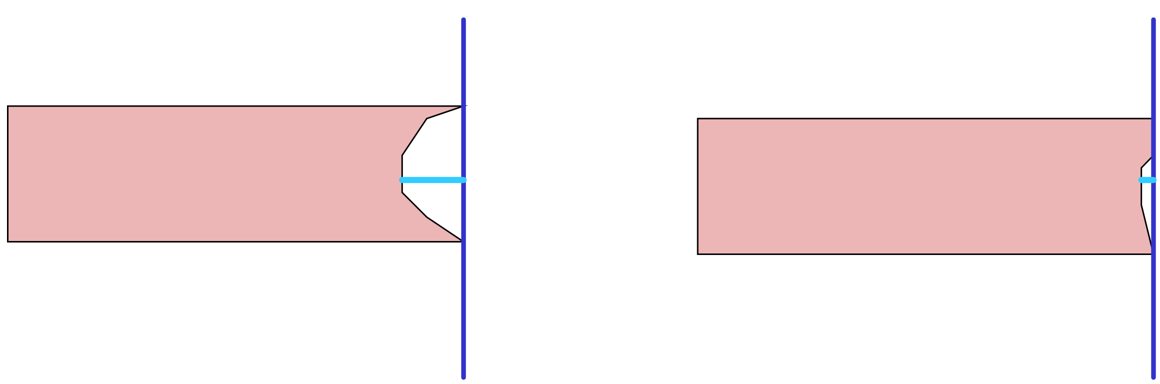
If we compare these two equations of the Ideal Gas Law at two different times, they can be simplified.

$P_mV_m = n_mRT_m$ $P_{2w}V_{2w} = n_{2w}RT_{2w}$, where $_m$ is at time of manufacture and $_{2w}$ is two weeks later.

Because the volume (V) and the amount of material (n) for all practical purposes remains the same at manufacture and two weeks later and the constant R is the same in both equations the equations above can be reduced to $P_m = T_m$ and $P_{2w} = T_{2w}$. At time of manufacture the blowing agent and cells are very hot (more than 148 C (300 F)) from the exothermic reaction of the chemicals which allow for the vaporization of the blowing agents, expanding the developing foam. The pressure of the expanding blowing agent has to overcome the atmosphere's pressure (approximately 101 kilopascals (14.7 pounds per square inch)). Later, when the foam cools down, the temperature inside the cell is close to room temperature and - as previously shown in the equation $P_{2w} = T_{2w}$ - the pressure inside the cell is lower. These lower pressures mean there is for a period of time a partial vacuum in the cells. In most cases the cells are strong enough to withstand this vacuum and maintain the dimensional integrity of the cell walls and of the polyisocyanurate insulation board. However, there is a section of the board where conditions are more susceptible to dimensional stability concerns – the 8-foot edge sections in a standard 1.2- by 2.4-meter (4- by 8-foot) board.

Observation and analysis of boards from the field with dimensional stability problems revealed that most of the shrinkage was associated with the 2.4-meter (8-foot) edges of a standard 1.2- by 2.4-meter (4- by 8-foot) board. More than 90 percent of these boards had edge collapse or cuppage. Cuppage is when the foam in between the facers along the 2.4-meter (8-foot) edges caves inward and the facers began to migrate towards each other (see Figure 6). Why is edge collapse or cuppage the prominent feature of the majority of boards with shrinkage concerns?

Figure 6 Schematic of Edge Collapse or Cuppage



As mentioned before the chemical reactions to produce the board are exothermic (they generate heat). The foam reaches 148 C (300 F) and thermocouples placed in the bundle between boards show temperatures that decrease the closer they are to the edges of the bundle. Therefore, the board's edges of the board are the coolest part of the board. A key reaction, the formation of the dimensionally stable trimer bond, is most effective around 71 C (160 F), which means – all things considered – the board's edge is not as highly cross-linked as the center of the board. This coupled with cold ambient temperatures, which reduces the blowing agent vapor pressure in the cells, can lead to contraction of the cells and cuppage unless the cells are properly stabilized. As is typical, once the exact problem has been identified a proper solution or solutions can come to the forefront (see the discussion later in this section).

Analysis of a board with modest amounts of edge collapse showed that the core densities in the middle have remained the same whereas the foam near to the 2.4-meter (8-foot) edges of the board has increased in density, which basically means that part of the board has somewhat shrunk. Table 2 illustrates this point. Two boards were analyzed for core density across the width of the board every 25 mm (inch). The core densities were consistent except from 0 – 50.8 mm (0 – 2 in.) and 1168 – 1219 mm (46 – 48 in.). The shrinkage noted on the full board is actually localized along the 2.4-meter (8-foot) edges. The question sometimes comes from field representatives with this issue regarding whether the rest of the board is stable or whether the board will continue to shrink over time. The answer is the rest of the board is very stable and no further shrinkage is expected. Incidentally, shrinkage along the 1.2-meter (4-foot) edge of a standard 1.2- by 2.4-meter (4- by 8-foot) board is very rare because of the presence of the knit lines among other factors. A knit line is the connection line between two streams of expanding foam that meet in the process of filling out the board. The different levels of dimensional stability that may exist in a typical 1.2- by 2.4-meter (4- by 8-foot) board explains at least partially why a 2 percent linear width and length specification in ASTM C1289 in a 304- by 304-mm (12- by 12-inch) sample does not correlate to 2 percent overall board shrinkage in a 1.2- by 2.4-meter (4- by 8-foot) board. Therefore, in this case the (304- by 304-mm (12- by 12-inch)) sample typically is a more severe test than testing the full 1.2- by 2.4-meter (4- by 8-foot) board. In essence, if most of the board is inherently dimensionally stable and only one part of the board (the 2.4-meter [8-foot] edges) is at risk and a smaller sample (304- by 304-mm [12- by 12-inch]) contains that part of the board (the 2.4-meter [8-foot] edges), then the (304- by 304-mm [12- by 12-inch]) sample could be a more severe test than a full board. This hypothesis has been shown to be the case before and most recently in a paper[4] by Huntsman Polyurethanes and the author's company.

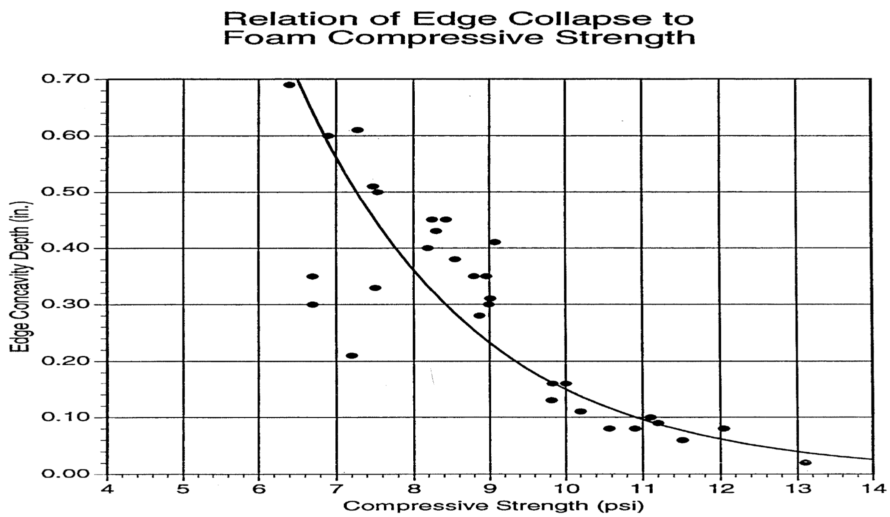
Table 2 Physical Properties of Boards with Edge Collapse

	Sample 1	Sample 2
Core Density, Kg/m3 (pcf)		
Average	27.0 (1.69)	28.3 (1.77)
Middle 1117 mm (44 in.) of bd	25.6 – 28.3 (1.60 – 1.77)	26.9 – 28.8 (1.68 – 1.80)
End 101 mm	27.8 – 31.7 (1.74 – 1.98)	32.5 – 33.4 (2.03 – 2.09)

(4 in.) of bd		
Crease depth, mm (in.)	3.04 – 8.12 (0.12 – 0.32)	7.36 – 15.49 (0.29 – 0.61)
Width of bd, mm (in.)	1207 – 1211 (47.53 – 47.71)	1195 – 1198 (47.06 – 47.19)

If cuppage or edge collapse along the 2.4-meter (8-foot) edges of the board is the source of most of the few dimensional stability concerns, how can it be measured and ultimately controlled? The resistance to this cuppage or edge collapse is related to how strong the foam is in what is called the cross machine direction or Z –direction (z as in the x, y, z coordinates). It would be expected that the stronger the foam is in this direction the less cuppage would be expected. This is in fact what happens and has been shown to be true in the author's laboratory and in the plant numerous times. A systematic study[5] was conducted several years ago by the Stepan Co., Northfield, Ill., supplier to the polyisocyanurate industry of aromatic polyester polyols, which correlated the amount of edge collapse or cuppage with the compressive strength of the foam along the edge of a typical 1.2- by 2.4-meter (4- by 8-foot) board. A graph of this correlation is shown in Figure 7. It is important to note that the sample must to be taken right at the edge of the board.

Figure 7 Edge Collapse Relative to Foam Compressive Strength at the Edge



Using this graph and correlating processing parameters and formulations it is possible to manufacture boards with acceptable compressive strengths (called ZCS – Z Direction Compressive Strength) and therefore a board with little or no cuppage / edge collapse.

As has been demonstrated above cell physics is a dynamic process. Although a board is initially a little more susceptible to edge collapse on the 2.4-meter (8-foot) edges as time goes on this situation reverses and the board and the 2.4-meter (8-foot) edges are more dimensionally stable. During the course of an investigation into a dimensional stability problem (edge collapse along the 2.4 m [8 foot] edges) a number of years ago, it was discovered that boards (in bundles) returned to the plant because of cuppage (discovered at the job site) returned to normal during the summer. The cuppage observed at the job site decreased over time in the plant and ultimately completely disappeared. A subsequent study in the author's laboratory showed that boards with cuppage can at least in some circumstances return to normal with no cuppage. For example, a board with cuppage was subjected to approximately 30 days at either (37 C (100 F) or 65 C (150 F) and re-measured at various times. Figure 8 shows the effects of temperature on cuppage. The reason for this is air is diffusing through the cell walls and expanding the foam.

Figure 8 Effect of Temperature on Boards with Edge Collapse or Cuppage

Measurement of the ZCS during production, however, is limited because of the time needed to cut the appropriate sample and measure it. Typically, this means only one or two boards are tested per batch and then not the entire 2.4-meter (8-foot) edge of each board is tested - only a section.

In order to ensure that every thick (greater than 50 mm [2 in.]) board is evaluated, an in-line ZCS unit was developed[6]. This unit measures the compressive strength continuously along both edges of the board as it exits the laminator. The ZCS number is continuously read at the pour station and adjustments can be made to increase or decrease this number. Correlation to these in-line ZCS numbers can be made with the final ZCS number when the product is tested. Typically, there is only a modest difference between the in-line ZCS number and the final ZCS number. Over time the operator learns which in-line ZCS numbers will yield acceptable final ZCS numbers. The net effect is customers obtain dimensionally stable boards.

High density Polyisocyanurate Cover Boards

A couple of years ago high density polyisocyanurate insulation cover boards were introduced in the market place. Although there are a number of different types of cover boards in the market place these high-density boards typically offer higher R-value (from 0.176 – 0.44 [1.0 to 2.5] depending on thickness), easy cutting and relative light weight, while maintaining toughness. This is especially important in some new construction roofing systems where roof traffic is expected to be excessive or in emerging technologies such as PV or vegetative systems which are installed over the installation. However, it is in the reroofing area as a re-cover or cover board where they have even greater utility because of their easy application and inherent toughness.

This toughness is evident in their high resistance to facer delamination with typical passes on the RLE (Rolling Load Emulator) of 6000. The RLE was developed to measure the resistance of construction materials (typically insulation and cover boards) to facer delamination. The pounds-per-square inch rolling load can be varied but typically it is set at 138 kPa (20 psi). Although these products are very strong they are not considered structural components. A list of board's physical properties is shown in Table 3.

These products typically pass ASTM D 3273 for mold resistance and absorb low amounts of water. Fire ratings for these types of products are very good, but they don't have the highest fire ratings typically seen with fiberglass mat faced gypsum products. Additionally, high-density fiberglass mat faced polyisocyanurate cover boards are still combustible, albeit less so than standard low-density polyisocyanurate insulation boards. These high-density polyisocyanurate products are also not recommended for hot asphalt systems.

Table 3 Physical Properties of High-Density Polyisocyanurate Cover Boards Versus Other Cover Boards

Property	Fiberglass Mat Faced Polyiso (HD)	Fiberglass Mat Faced Gypsum	Woodfiber
Thickness, mm (in)	25.4 – 50.8 (¼ - ½)	25.4 (¼)	50.8 (½)
R-Value	0.176 – 0.44 (1.0 – 2.5)	0.049 (0.28)	0.246 (1.4)
Board Weight 1.2 m X 2.4 m (4' X 8'), Kg (lb)	5.44 (12)	17.41 (38.4)	9.29 (20.5)
Ease of cutting*	Yes	No	No

Mold resistance (D 3273)	Yes	Yes	No
Water Absorption	<3%	10%	10%
Dimensional Stability	Excellent	Excellent	Excellent; poor if wet

*Contractor's comments

Conclusions

Polyisocyanurate insulation products and testing have changed and evolved to meet the demands of 21st century roof systems. Below are some key conclusions:

1. The IECC 2012 code has significantly increased the minimum insulation requirements by approximately 80 percent when averaged over all 8 climate zones compared to ASHRAE 90.1 -2004 and polyisocyanurate insulation is well positioned to meet these requirements.
2. Reroofing offers a huge opportunity for energy savings which could be realized with changes in the energy code. Some representative economics by Dr. Hoff suggest that the economics concerns are less than expected.
3. The relative environmental benefit of insulation was demonstrated and exciting opportunities in recycling discussed.
4. Work over the last decade has elucidated how dimensional stability problems originate and tests (ZCS and in-line ZCS) have been developed and implemented to ensure boards perform in the field.
5. Finally, rugged, high R-value cover boards were described, which provide the roofing community another option to meet the tough field demands associated with roofing systems such as PV or vegetative.

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