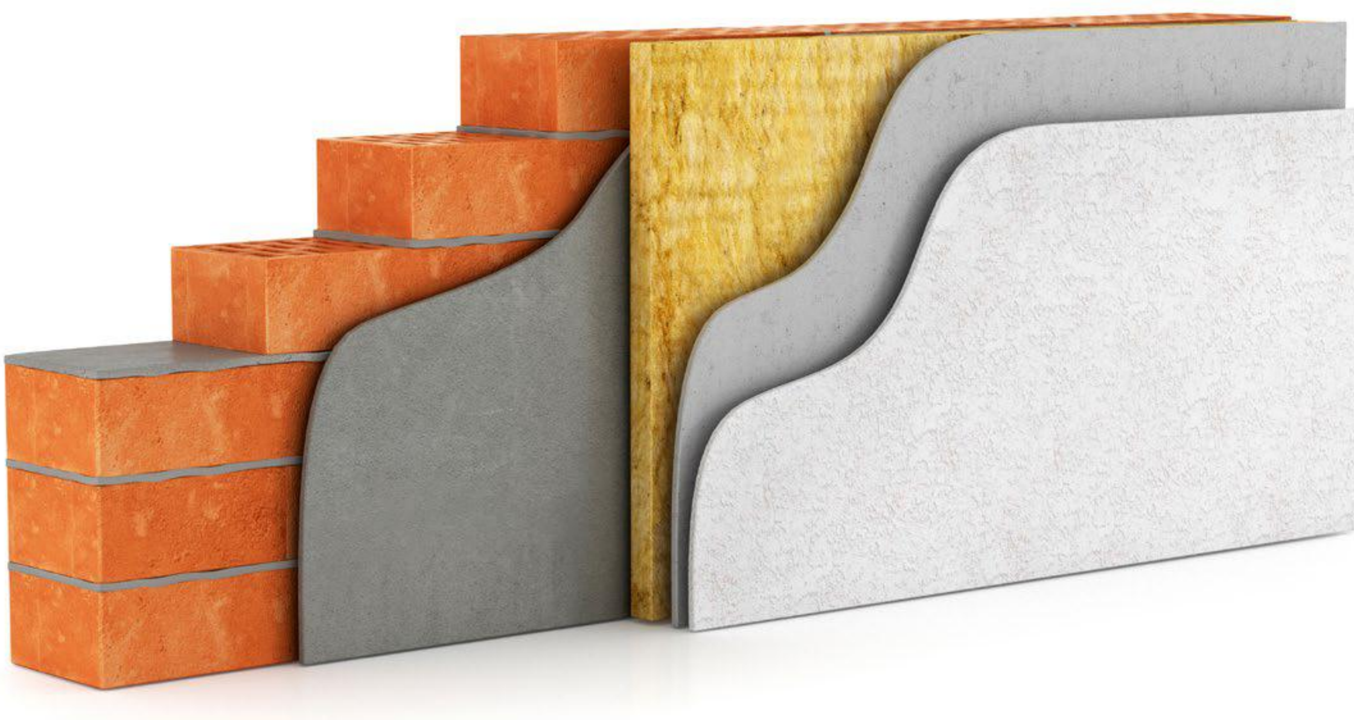
The BuildingGreen Guide to Thermal Insulation

What You Need to Know About Performance, Health, and Environmental Considerations

Fourth Edition



PUBLISHED BY BUILDINGGREEN, INC.

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What You Need to Know About Performance, Health, and Environmental Considerations

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About BuildingGreen

BuildingGreen is an independent consulting and publishing company committed to providing accurate, unbiased, and timely information designed to help building industry professionals and policy makers improve the environmental performance, and reduce the adverse impacts, of buildings.

BuildingGreen's other information resources include:

- The BuildingGreen Report and its predecessor Environmental Building News—since 1992, the trusted source for news and information on green building
- LEEDuser, a website dedicated to helping LEED project teams with credit-by-credit support and forums

Acknowledgments

We offer our many thanks to the numerous professionals who answered our questions and provided invaluable perspective in the making of this report. Special thanks go to Tedd Benson for providing his valued perspective in the Foreword, and special thanks also go to Terry Brennan, Andy Shapiro, Martin Holladay, and John Straube, each of whom provided insightful feedback that helped us shape the insulation recommendations. Many thanks to Steve Baczek for providing architectural details as well as insightful commentary for the course that accompanies this report. We are also grateful for the cost estimates provided by Riv Manning of Vermeulens Cost Estimating, and Peter Morris of Davis Langdon, and to additional cost information provided by Russ Chapman of Leader Home Centers and Jason Thorson at Knez, Inc. Thanks to Eli Gould and his crew for tackling alternative insulation materials hands on. To everyone who provided input, we appreciate the conversations and back and forth that took place, which greatly strengthened our efforts to clarify key issues.

Published by BuildingGreen, Inc.
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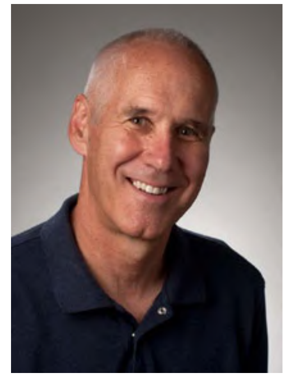
FOREWORD



Tedd Benson,
Bensonwood

We intuitively know that insulation is the obvious solution to a very common problem, but low energy costs have allowed us for too long to give it short shrift. We are certain to grab a good coat on our way out the door on a cold day, yet most of the buildings we inhabit are themselves poorly dressed for the weather they inevitably encounter. Despite having readily available and effective insulation materials for over a century, we've failed to address the insufficient thermal coverings of our buildings, having opted instead to hook them up with all sorts of high-tech mechanical devices to manufacture artificially tempered living environments no matter the necessity. And no matter the energy costs.

Frank Lloyd Wright probably best summed up the oblivious rationale for under-utilizing insulation when he said that while insulation might be worthwhile for roofs, "the insulation of the walls and the airspace within the walls become less and less important. With modern systems of air conditioning and heating, you can manage almost any condition." Armed with that unfortunate logic, we spent decades equipping our buildings with the necessary equipment to "manage almost any condition" instead of pursuing solutions that require less mechanical intervention. The long-prevailing paradigm that Wright's opinion represents is the major reason the energy consumption of buildings rises well above that of both the transportation and industry sectors as our nation's number one fuel-guzzling beast.

Unlike the transportation sector, which must both transport us and condition our indoor environment, buildings are steadfastly stuck in one spot. They can simply sit there, securing their space on the Earth. They don't take us places by land, sea, or air, nor do they do any industrial tasks or produce things for our benefit. As such, buildings haven't been designed to provide any sort of tangible return for the spent fuels. Instead, the largest proportion of that energy is delivered for the sole purpose of creating habitable ("comfortable") environments.

Finding ways to reduce our dependence on fossil fuels is a mighty problem, one that now pulls at us with ever-increasing urgency. Some facets of that predicament appear to be overwhelmingly difficult to solve. Ocean freighters and airplanes burn fantastic quantities of fuel to perform their tasks, as do steel mills and chemical plants. It's hard to imagine how these things will ever lose their energy-hogging ways.

Buildings, on the other hand, are easy. Nearly half of their energy demands come from heating and cooling, and most of that usage could be cut dramatically—even eliminated—by making the building envelope tight and adding lots of insulation. So there is some good news: our biggest energy consuming sector also has the lowest-hanging fruit, and lots of it.

We can literally insulate our way to a much brighter energy future while insulating ourselves from the wildly fluctuating costs of energy. Every highly insulated building is an energy miser forever. Every building weaned from fossil fuels is weaned forever. We can keep warm and cool without resorting to the energy-sucking equipment Frank Lloyd Wright wanted to rely on. The new paradigm shift recognizes that if we don't insulate sufficiently, we'll probably be saddled with big, thirsty equipment running constantly at exorbitant financial and ecological cost.

This is one of those world-changing awakenings that doesn't stem from any kind of brilliance but instead comes from stupidity having a little less dominance. But it's an important change nevertheless, and it's at least beginning to overwhelm the reign of ignorance. Builders, architects, and homeowners across the country are proving that with enough insulation (and airtightness) we can use smaller and simpler equipment and eschew fossil fuels entirely.

Insulation is, therefore, the obvious and simple answer to a big problem. Understanding insulation and using it effectively are key to achieving passive comfort and energy independence. There are no technological barriers to insulating our buildings more effectively and thereby lowering our national energy usage dramatically. You'd think that would be the end of it. We'd employ it, solve that problem, and move on to the next one. Unfortunately, it's not that easy, nor that simple.

First, it's not that easy because the general public still has little interest in insulation. It's invisible and boring. Like reinforcement in concrete, it's often seen as kind of a cost nuisance rather than something you'd want to consider improving. Similarly, "out of sight, out of mind" aptly explains why people don't give much consideration to insulation. Knowing too little about the subject, people are often proud to announce that their home meets code requirements, as if that was like acing a test, instead of what it is: the lowest possible passing grade. Where "minimum" sounds like "maximum," "better" sounds like overdoing it. So we've been stuck insulating most of our buildings at the C-minus level or less for a long time.

Knowing that, consumer awareness is critical to implementing the massive energy reductions we can achieve with our buildings. President Obama tried to encourage people to have a little more respect for insulation when he jovially declared that it is "sexy stuff," and "I get really excited about it." Of course, that was fodder for many days of derision by the critics and comedians. But it's no joke. We have a way to go before people will commonly trade their noticeable A+ features for hidden A+ insulation.

Second, it's not that simple because insulation is a deceptively complicated subject. And that's the reason for this report. As Alex Wilson points out, "No other building element offers such a diverse range of materials and complexity of considerations—environmental, human health, performance, and building science." There are myriad materials, old and new, promising to be the better way to insulate—even as newer "innovative" products are coming out all the time. Attempting to understand the benefits and potential in all these options can easily get confusing and overwhelming.

Like the canoe adventurer (and canoeing guide author) that he is, Alex is our perfect guide. He's been exploring both the quiet and turbulent waters of this subject, and he delivers here an accessible guidebook that clarifies the issues in his typical objective, authoritative way. With the information packed into this small volume and Alex's reassuring guidance, we'll all feel just a bit more comfortable as we continue to chart our own routes toward a steady current of true sustainability in building performance.

– Tedd Benson

Since the early 1970s, Tedd Benson has championed high-performance, sustainable homebuilding—always with an emphasis on innovation, quality, and social responsibility. Since 1974, his company, Bensonwood, has been at the forefront of the timber framing renaissance and building innovation.

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Introduction to the Fourth Edition

So much has changed recently in the insulation industry—most of it for the better. For example:

- The persistent, bioaccumulative toxic flame retardant HBCD has been removed from new polystyrene products.
- Driven by new legislation, extruded polystyrene manufacturers are now offering the option of low-global-warming-potential products.
- Although the U.S. is not a signatory to the Kigali Amendment to the Montreal Protocol, 2020 legislation and a 2021 EPA rule effectively require the U.S. to comply with the amendment.
- Vacuum insulation costs are coming down, and it's become more popular in certain applications.

This new edition of our popular insulation report has extensive revisions throughout for updated accuracy. We hope you enjoy it!

- The BuildingGreen Editorial Team

What Type of Insulation Should You Use?

Thermal insulation is a critical component of any building—and especially of green buildings, which are designed and built to minimize environmental impacts. Insulation reduces heat loss when it's cold out and unwanted heat gain when it's warm, thus reducing the need for fossil fuels and other energy inputs—with their associated environmental impacts. By reducing energy consumption, insulation also saves money.

Determining what type of insulation to install and how much can be complex from many angles—environmental issues, human health, performance, and building science. Articles we have published in recent years on BuildingGreen.com have addressed many of these issues, but we felt that the complexity of the topic called for a deeper look, leading us to publish this guide.

> No other building material offers such a diverse range of materials and complexity of considerations—environment, human health, performance, and building science.

On top of the wide range of common insulation materials, there are new insulation materials and new formulations or variations of older insulation materials appearing all the time. Today, in addition to standard fiberglass, cellulose, polystyrene, mineral wool, and polyisocyanurate insulation, we can purchase insulation materials made from cementitious foam, radiant foil, cellular glass, vacuum panels, gas-filled panels, wool, recycled cotton, and cork. No other building material offers such a diverse range of materials—and material properties. Choosing the best material can be tremendously confusing.

What this guide provides

The BuildingGreen Guide to Thermal Insulation provides accurate, nonbiased information on the full gamut of insulation materials in use today. The guide:

- explains how insulation works (which helps us understand why certain materials make more sense than others in particular applications);
- explains how insulation performance is measured and reported; and
- describes a wide range of environmental considerations that come into play with different insulation materials.

All of the common (and some not-so-common) thermal insulation materials are described in detail, including:

- what's in them;
- how they perform relative to R-value, permeability, and moisture resistance;
- environmental pros and cons;
- where they should be used in buildings;
- how costs compare; and
- what special concerns you should watch out for.

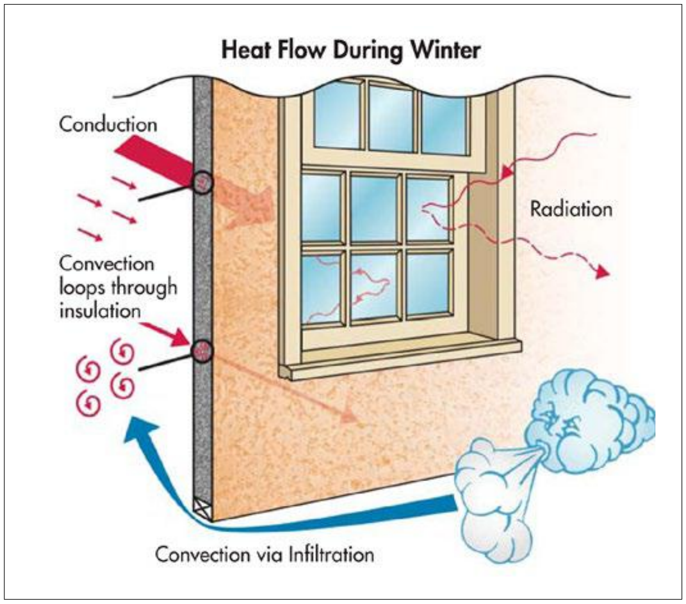
This guide is intended as a go-to source for everything a designer, builder, or knowledgeable consumer needs to know about thermal insulation materials. We hope you'll find that it's a convenient reference to pull up as needed, or read it from cover to cover to become fully versed.

A note on acoustic insulation: this guide does not address products made primarily to control noise within buildings, such as baffles made from woven polyethylene, or acoustic panels. Many thermal insulation products are, however, used for this purpose. For those specifying thermal insulation products for use as acoustic insulation, they should look to sound transmission class (STC) ratings rather than noise reduction coefficient (NRC) ratings.

Sound transmission class (STC) measures a material's ability to reduce sound travelling between different parts of a building, such as through walls or ceilings. The higher the STC rating, the more effective the material is at reducing sound, but an STC rating is not a measure of just the material. It measures sound travelling through the entire assembly, so it includes drywall, studs, and other components as well. STC ratings of stud walls insulated with fiberglass batt, mineral wool, and cellulose insulation are similar. In a 3½″ 25-gauge metal stud wall with ⅝″ gypsum board on each side, the STC values are 49, 47, and 45, respectively. STC does not accurately measure low-frequency sounds below 125 hertz, which can include some road noise and mechanical equipment.

Noise reduction coefficient (NRC) measures the amount of energy a product or material absorbs on a scale from 0 to 1. A 0 means it reflects 100% of sound, and a 1 means it absorbs 100%. NRC is used for products that absorb sound in a room. Again, NRC should not be the metric used for insulation placed in building assemblies.

How Insulation Works



Insulation blocks heat flow that occurs via conduction, convection, and radiation, as illustrated here on a cold day. Blocking air leakage through the building envelope is also important—some insulation products perform this function, while many do not.

To understand insulation materials, it helps to understand the basics of heat flow. There are three primary mechanisms of heat flow: conduction, convection, and radiation.

Thermal conduction is the movement of heat from direct contact: one molecule is activated (excited) by heat and transfers that kinetic energy to an adjacent molecule. We generally think of conduction occurring between solid materials—the handle of a hot cast-iron skillet conducting its heat to your hand, for example—and that is the most efficient mode of conduction. Thermal conduction also occurs within liquids and gases but more slowly.

Convection is the transfer of heat in liquids and gases by the physical movement of those molecules from one place to another. As air is warmed, it expands, becomes more buoyant, and rises—a process called *natural convection*. This occurs with liquids, too, as we experience with certain solar water heaters. Convection can also be *forced*, using fans or pumps.

Finally, *radiation* is the transfer of heat from the surfaces of one body to another via the propagation of electromagnetic waves. When you sit in front of a fireplace and look into the fire, your face is warmed by the radiant transfer of energy from that heat source to your face. That radiant energy is not affected by air currents and occurs even across a vacuum—as we know from lying in the sun and experiencing radiant energy that has traveled 93 million miles through space.

Here on Earth, heat flow is almost always moving in all three modes simultaneously, and our insulation must reckon with that.

Modes of heat flow through insulation

Most insulation materials function by slowing the conductive flow of heat. Materials with low thermal conductivity more effectively block heat flow than materials with high thermal conductivity. The R-value of an insulation material is primarily based on its resistance to conductive heat flow—although other modes of heat transfer do contribute to an insulation material's rated R-value.

Most insulation materials work because of tiny pockets of air (or some other gas) trapped inside them. The performance of that insulation material is determined primarily by the conductivity of the gas trapped in those spaces. With fiber insulation materials, such as fiberglass, cellulose, and cotton, pockets of air are trapped between the fibers. With cellular insulation materials, such as polystyrene, polyisocyanurate (polyiso), and polyurethane, air—or gas from the blowing agent—is trapped within the plastic cells comprising the foam.

Insulation materials are designed to balance—and ultimately reduce—competing modes of heat flow. Since gases conduct less heat than solids, more porous insulation materials are usually more effective. However, convective loops can form within air pockets, particularly larger ones, accelerating heat transfer and potentially offsetting the benefit of that trapped air. Small pockets are better, but if the pockets get too small and the material too dense, conduction can increase.

Note that air leakage is a type of convection and can contribute greatly to heat loss. When conditioned air leaks out of a building and unconditioned air (cold in the winter, hot in the summer) leaks in, the insulated portions of the building envelope are bypassed—doing you no good, even if their R-value is relatively high. In many buildings, air leakage around plumbing chases, eaves, rim joists, windows, through poorly fitting doors, and across poorly detailed walls can sometimes account for more than half of the total wintertime heat loss.

Air leakage can also occur through an insulation material, which can reduce that material's effective R-value. Loose-fill fiberglass, for example, usually allows more airflow than cellulose insulation does.

Don't focus on R-value to the exclusion of air leakage. Throughout this report we'll be looking at R-value in context of the whole building assembly and performance factors, to ensure that you get the value you're looking for.

Closed-cell foams

Among foam insulation materials, some closed-cell foams, such as polyisocyanurate and closed-cell spray polyurethane foam, allow higher R-values to be achieved by using a gas other than air in the cells. If we could keep it perfectly still (no convection), air would insulate to about R-5.5 per inch, based on its low conductivity (as a gas).

The blowing agents used in some foam insulation materials have even lower conductivity than air, so the R-value is higher. Polyisocyanurate foam has an "aged" R-value of about 5.6 per inch, as does closed-cell spray polyurethane foam. When those materials are brand-new, the R-value is higher, but over time some of the blowing agent leaks out and some air leaks in, resulting in R-value drift; to provide a reasonable estimate of actual performance, manufacturers measure the R-value after the material has aged six months.

Radiant barriers

Insulation materials that incorporate *radiant barriers* (foil-faced batt insulation, radiant-barrier bubble-pack insulation, and reflective barriers on rigid foam sheathing) function, in part, by reducing radiant heat transfer. Different materials radiate heat at different rates from their surfaces—some radiate heat very poorly, others very well. Typically, very reflective materials like aluminum foil are also *low emissivity*: the lower the number, the less energy the material absorbs and the better it reflects heat. Conversely, dark materials usually have high emissivity. A low-emissivity material can act as a radiant barrier, but to do so it has to be next to an air space, and the surface must be free of dirt, dust, or any other material that increases its emissivity. (Aluminum foil sandwiched between wallboard and insulation will not block radiant heat flow.)

Most insulation materials work because of tiny pockets of air (or some other gas) trapped inside them.

Inflated claims are often made about the R-values of radiant barriers. In fact, radiant barriers can enhance the R-value of an assembly, but they themselves have negligible R-value. In a well-insulated building, they don't add value in most applications. Applications where they may make sense are areas where there is a large thermal difference between surfaces, such as attics in hot climates.

Comparing insulation and window glazing

Understanding how the heat flow through windows is controlled provides a good illustration of heat flow through insulation materials. Glass is thin and it conducts heat relatively well, so its R-value is very low. Going from a single-glazed window to a double-glazed window significantly improves the R-value because an air space is created. Heat moves across that air space by conduction, convection, and radiation. If we increase the thickness of the air space from ¼-inch to ½-inch, heat loss is slowed because there is a greater distance over which gas-phase conductivity has to occur. If we increase the air space much beyond

½-inch, however, *convective loops* within that air space form, and convective heat transfer increases.

By substituting a low-conductivity gas, such as argon or krypton, the R-value is improved because conduction of heat from molecule to molecule is reduced. This is much the same as using a low-conductivity blowing agent in a closed-cell foam insulation material.

Most high-performance window glazing today includes low-emissivity (low-e) coatings, usually some kind of metal deposited on the glass. These help to control radiant heat transfer—so they are much like radiant barriers in insulation assemblies.

The big difference between glazing and insulation is that glazing also transmits sunlight, which is a flow of heat into a building. We measure this property in windows through their solar heat gain coefficient (SHGC). Passive solar heating is the productive utilization of this solar heat gain. Transparent insulation (see page 81) is a specialized insulation material that transmits some sunlight—for daylighting—in addition to restricting heat flow.

Vacuum insulation

While less common in building materials, vacuum insulation (see page 83) helps to illustrate the interplay between the three modes of heat transfer. By removing most of the air molecules from the space between two airtight skins (by evacuating that space), heat transfer by conduction and convection is effectively eliminated, leaving only radiation as the heat transfer mechanism. In a thermos bottle or vacuum insulation panel, using a material with very low emissivity is key to achieving a very high R-value. Conduction is still an issue at the edges of a vacuum insulation panel, and if the vacuum seal is broken, that reduces the R-value significantly. By encapsulating it in reinforced high-density polyiso or other materials, manufacturers attempt to address both these issues.

Radiant Barriers and Reflective Insulation

Standard insulation—such as batts, boardstock, and spray foam—functions primarily by slowing down two out of the three modes of heat transfer: conduction and convection. Radiant barriers and reflective insulation function by reducing the third type: radiation. This can work, but there is a great deal of misinformation about these systems.

Heat radiates from all objects by way of electromagnetic waves, with the net result being that hotter objects, like the sun, warm up cooler ones. Reflective and low-emissivity materials like aluminum foil can be used as a radiant barrier to control either heat gain or heat loss. A key feature is that they must face an air space to work because radiation moves through space. A radiant barrier sandwiched between two solid surfaces will merely conduct heat.

Radiant barriers are often installed in attics to keep these spaces cooler. A layer of reflective foil can be tacked to the underside of the rafters or roof trusses, or reflective sheathing can be installed with the reflective surface facing the unheated attic. Because they work both by reflecting radiation and by reducing the emittance of radiation, it doesn't make much difference whether the surface faces up or down, as long as it is facing an air space. However, dust negates its effectiveness, so a reflective surface facing down is usually more practical.

In wall assemblies, a dedicated radiant barrier or insulation with a foil facing will improve performance somewhat as long as the foil facing is next to an air space. Reflective "bubble-pack" insulation can achieve greater benefit than a single radiant layer because it provides an additional air space—sometimes two air spaces (with a double layer), and the shiny surface inside the bubbles will stay clean. This will yield some energy benefit in both horizontal and vertical applications; how much depends in part on whether air in the adjacent space is likely to stratify or form convective loops.

Manufacturers of radiant barriers are notorious for exaggerating their benefits. Ads referring to "R-19 paint" or "tested by NASA" are red flags. With no air in outer space, conduction and convection have little effect, so heat loss is mostly by radiant transfer, and radiant barriers are needed to control heat loss. Also, the temperature difference across the walls of the International Space Station may be hundreds of degrees—far greater than what we experience. In space, a reflective ceramic coating may indeed provide an equivalent R-20 or more. That's irrelevant here on Earth.

Payback claims are also exaggerated. If you have an R-2 roof in Phoenix, a radiant barrier or reflective insulation layer might provide a huge benefit. But with a reasonable amount of insulation in the roof system (say R-30 or R-40), the benefit of the radiant or reflective layer will be very small. The better insulated the roof, the less benefit from a radiant barrier or reflective insulation.

Measuring and Reporting Insulation Performance

We typically talk about the insulating performance of insulation materials in terms of *R-value*. R-value measures *resistance* to heat flow over a certain surface area under laboratory conditions. The inverse of R-value is U-factor (U = 1/R), which is a measure of heat *flow* through a material. U-factor (also called U-value) is measured as the amount of heat going through a defined area of material per hour per degree temperature differential ($Btu/ft^2 \cdot hr \cdot °F$) or, outside the U.S., $W/m^2 \cdot °C$. With insulation, higher R-values are better (more insulating), while lower U-factors are better.

R-value is reported for individual materials or layers in a building assembly and can be added up to arrive at a total assembly R-value. Note that the insulation value of a single material is very different from the insulation value of the entire assembly. To give a simple example, a 2x6 wall with 24-inch-on-center wood studs, insulated with nominal R-19 fiberglass batts, is actually closer to R-16 due to the lower insulation value of the studs.

U-factor, unlike R-value, applies only to an entire assembly. To estimate the U-factor of a wall, you would add up the R-values of the component parts (including that of the air films on the interior and exterior), then calculate the inverse of that total R-value. This will tell you the total heat moving through the assembly for each degree of temperature difference across it.

Insulation manufacturers report the insulating performance of their products under guidelines established by the Federal Trade Commission (FTC). Typically, manufacturers will send products to a certified testing laboratory that will use a *guarded hot box* testing apparatus to determine the *steady-state* R-value. In this test, the two sides of the insulation material are maintained at different temperatures (based on test standards developed by the American Society of Testing and Materials, ASTM, most commonly ASTM C518), and the amount of energy needed to maintain a steady temperature on the warm side is used to derive the steady-state R-value.

Steady-state R-values are based on very specific temperature ranges similar to what we see inside and out of buildings. If the difference in temperature across the insulation material (often expressed as delta-T or ΔT) is much greater, a different R-value would be measured. This is one reason that claims of insulation performance "as tested by NASA scientists" are often very misleading—buildings here on Earth experience far lower ΔT than that experienced in the very cold reaches of outer space.

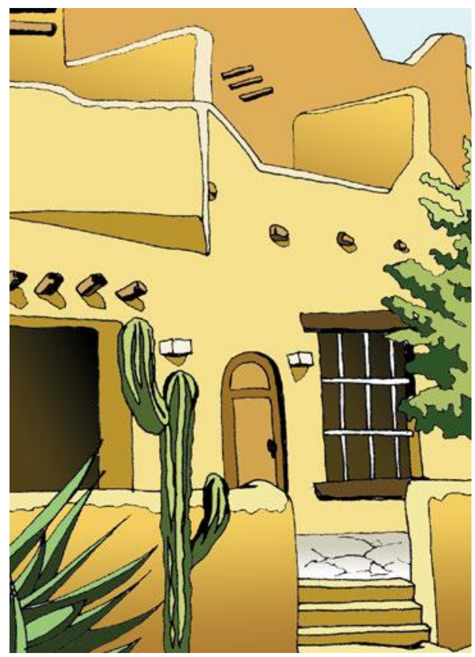
Mass-enhanced or effective R-value

We often hear the term "effective R-value" used in conjunction with masonry materials and building components, such as insulated concrete forms (ICFs). The idea is that because of the *thermal mass*, such materials help to reduce heat loss and, thus, have an "effective" R-value that is higher than the nominal (or steady-state) R-value listed for the material.

This effective R-value (sometimes called "mass-enhanced R-value") is real, but it only works in certain conditions. High-mass materials can hold, or store, a lot of heat. In climates where a high-mass wall (made of concrete block or adobe, for example) receives a lot of sunlight, that wall will absorb solar heat and store some of that heat in the wall. The heat gradually moves through the material (at a speed determined by the thermal conductivity), raising the temperature of the wall. At night, as the outside

R-VALUE VS. U-FACTOR

Outside the U.S., both U-factors and R-values are expressed in metric or SI (système international) units, and while measured the same, watts and degrees centigrade don't line up exactly with Btus and degrees Fahrenheit. To convert SI U-factors to "imperial" U-factors used in the U.S., divide by 5.7. When in doubt as to which type of value you're seeing, the difference in scale of 5.7x should make it contextually apparent.



In most climates, you should be skeptical of manufacturer claims of high "effective R-value." It is only an effective phenomenon in climates like the Southwest U.S.—sunny, with a significant day-night (diurnal) temperature swing.

air cools off, heat flow reverses direction and the wall begins to cool. But because of the heat contained in the wall, the net heat flow outward through the wall from the indoors is slower than it would be based only on the steady-state R-value of the wall material.

This principle of mass-enhanced R-value only works in fairly sunny climates that have a significant day-night temperature swing—as is found in the Mountain West. In Santa Fe or Denver or Salt Lake City, pay attention to the effective R-value. But in most other places, you should be skeptical of manufacturer claims of high effective R-value.

Data sources

R-value data for this report was drawn primarily from the *ASHRAE Handbook of Fundamentals*, with manufacturer data used to fill holes in the ASHRAE data. Refer to footnotes in the specific tables in this report for more information.

How R-Value Is Calculated

R-value, which measures resistance to heat transfer in insulation, is one of the most popular building metrics—but what it does and doesn't tell us is often misunderstood.

There are two test methods that are important to measuring R-value. The first, ASTM C518, is relevant to single materials. In this test, a sample of the material is placed inside a heat flow meter apparatus, between a cold plate and a hot plate. Heat flows from the hot plate to the cold plate through the insulation as the testing device measures how much heat is flowing.

Heat flow moves in three ways—conduction, convection, and radiation—and the test for R-value measures all three. If you were testing a rigid foam board, heat would be moving through the foam via conduction, and through the air bubbles within the foam via radiation. There wouldn't be convection through such an airtight material, but convective loops forming within the air bubbles would speed the transfer of heat through the material and would affect the heat transfer measurements.

By capturing the effect of all three modes of heat transfer through materials, R-value gives us a great way to compare insulation products. In fact, the R-value measurement was created and popularized because it easily communicates relative insulation values.

Everett Shuman, a researcher at Penn State University, proposed the R-value measure in 1945. Prior to that, the primary measure for insulating value was U-factor, which measures heat flow. Remember, U-factor is the inverse of R-value (U = 1/R, and R = 1/U), which measures resistance to heat flow. While "good" insulation has low U-factors—an R-13 fiberglass batt has a U-factor of 0.08—R-value caught on because people apparently find it easier to understand that higher numbers are "better." Round numbers also don't hurt.

When we build enclosures—otherwise known as foundations, walls, and ceilings—the R-value of the individual materials becomes just one of several things to watch. ASTM C1363 is a test of the performance of a wall assembly or a ceiling assembly, and it uses a bigger test apparatus called a guarded hot box. (The "hot box" is the part where the heat is flowing. It is "guarded" by a layer used to ensure that the interior portion of the device sees a steady temperature.)

Illustration: Peter Harris

Heat Flow Meter

This testing, and calculations used in the design process, can capture other subtleties. For example, the thin layer of static air found on the exterior and interior surfaces of vertical walls has measurable R-value—R-0.17 for the exterior film and R-0.68 for the interior film. A one-inch air space (R-1) within an assembly adjacent to foil-faced insulation provides an R-3 layer due to foil's ability to block radiant heat transfer. More conductive components, like studs, significantly reduce the nominal R-value of a wall assembly through thermal bridging.

Health and Environmental Considerations with Insulation Materials

What are the primary considerations when evaluating insulation materials relative to their impact on our health and the health of the planet? In this section we'll explore the health and environmental attributes of insulation materials, with specific examples. Later (see page 30), we'll go through the different insulation materials in detail, reviewing not only environmental considerations but also performance information.

Energy savings

In considering environmental aspects of insulation materials, it's important to keep in mind the key environmental benefit of all insulation materials: saving energy. Energy consumption is the most significant environmental impact of most buildings. Impacts are both direct, such as air pollution, and indirect, including oil spills and global climate change that result from producing and consuming fossil fuels and electricity in our buildings.

All insulation materials can save energy, and an increasingly common goal of green building is to create *net-zero-energy* buildings. These are buildings that use so little energy that the needed operating energy can be generated using renewable sources, such as photovoltaic (PV) panels on the roof or site. Increasingly, in addition to net-zero energy, we're also interested in *carbon neutrality*. Here, again, insulation materials play an important role.

High levels of insulation can be justified economically through lower heating and cooling costs. Given the uncertainty about future costs of energy and the security of having a building that will maintain livable conditions in the event of extended power outages or interruptions in heating fuel ("passive survivability"), it often makes sense to invest significantly more in energy efficiency than a simple "payback" analysis might suggest.

Raw material acquisition

Insulation materials vary tremendously in terms of what they're made of, from spun glass to recycled newspaper and the petroleum and natural gas used in a wide range of foam-plastic insulation materials. Raw materials vary from agricultural fibers (cotton and wool) to inorganic cementitious materials extracted from seawater and aluminum mined as bauxite ore. There is really no other component of our buildings that can be made from such a diverse group of materials—making selections quite complex.

It often makes sense to invest significantly more in energy efficiency than a simple "payback" analysis might suggest.

From an environmental standpoint, green building practitioners look for materials that impart as little impact and use as little energy as possible during their manufacture. We try to avoid hazardous ingredients or materials that are in limited supply. We choose recycled-content materials whenever possible—because they typically require less energy to produce, depend less on raw material extraction, and help to keep waste out of landfills and municipal incinerators. Fiberglass insulation, for example, is the second-largest market for recycled glass in the U.S. (after beverage containers)—accounting for more than one billion pounds per year.

Embodied energy and embodied carbon

Much of the environmental impact from manufacturing insulation materials comes from energy that goes into production and shipping; we refer to this as *embodied energy*. Embodied energy includes "feedstock" energy (the fossil fuels, for example, that go into foam-plastic insulation materials), processing energy at the factory, and shipping both raw materials and finished products.

In addition to considering embodied energy, concern about climate change has increased the focus on *embodied carbon*: the greenhouse gas emissions associated with a given material. Usually, most of the embodied carbon associated with a material comes from the energy use—so calculating the carbon numbers is simply a conversion from the embodied energy. To make that conversion, you have to know the carbon emissions associated with that energy consumption. That's pretty straightforward with natural gas and diesel fuel but gets more complicated with electricity, which comes from many different sources. Such assessments also consider the "carbon-equivalents" of non-CO_2 greenhouse gases. This is important with certain insulation materials that are made using HFC blowing agents (see discussion of greenhouse gases).

Table 2 shows both embodied energy and embodied carbon estimates for selected insulation materials. This data was compiled by the Sustainable Energy Research Team at the University of Bath in the U.K. These numbers are approximate because they have to average the energy use at different plants in different places.

Hazardous constituents

A variety of constituents of insulation materials are considered hazardous to health or damaging to the environment. These are addressed here, as well as in the product-by-product comparisons in the later section on insulation materials.

Ozone-depleting substances

Years ago, the impact of various foam-plastic insulation materials on the Earth's protective ozone layer was the number-one environmental consideration. Chlorofluorocarbons (CFCs) were used as blowing agents (compounds that produce the closed-cell foam structure) in extruded polystyrene, polyisocyanurate (polyiso), and spray polyurethane foam, and these compounds had been shown to be damaging to ozone, which protects the Earth from harmful ultraviolet (UV) radiation.

An international treaty, the Montreal Protocol on Substances that Deplete the Ozone Layer, was adopted internationally in September 1987 and called for elimination of CFCs, beginning in January 1989. The U.S. banned use of CFCs under the Clean Air Act in 1994, and the insulation industry shifted production from those "first generation" chemicals to "second-generation" blowing agents, hydrochlorofluorocarbons (HCFCs). The HCFCs had just 5% to 10% of the *ozone depletion potential* (ODP) of CFCs. Continued scientific research on stratospheric ozone, though, pointed to the need for further reductions on ozone-depleting substances; revisions to the Montreal Protocol called for a staged phase-out of HCFCs. In 2010, insulation manufacturers then shifted from HCFCs to *third-generation* blowing agents that had zero ODP.

While all insulation being manufactured or sold in North America today is safe for ozone, there are significant differences relative to the *global warming potential* (GWP) of these materials. Signed in 2016, an amendment to the Montreal Protocol, the Kigali Amendment, was intended to reduce the greenhouse gas emissions of blowing agents. Although the U.S. is not a Kigali signatory, 2020 legislation effectively requires the U.S. to comply with the amendment.

The evolution of blowing agents in different types of foam insulation is shown in Table 1, on page 18—showing both ODP and GWP.

Greenhouse gases and global warming potential

Insulation plays a huge role in reducing fossil fuel use and thus reducing emissions of carbon dioxide (CO_2), a leading greenhouse gas, into the atmosphere. But some insulation materials contribute to global warming in another way: through release of blowing agents used in their manufacture.

While blowing agents in foam insulation have had their ozone impact reduced, the compounds now being used are also potent greenhouse gases—with high GWP—a fact that few people focused attention on until the 2010s. Relative to GWP, the second-generation blowing agents (HCFCs) were significantly better than CFCs, but the shift to third-generation blowing agents has been a mixed bag.

Factory-produced polyiso is manufactured today with hydrocarbon blowing agents (a type of pentane), which has zero ODP and a very low GWP. Many extruded polystyrene (XPS) and closed-cell spray polyurethane foam (SPF) products are still made with hydrofluorocarbon (HFC) blowing agents that are potent greenhouse gases—in fact, the HFC-245fa still used in some closed-cell SPF has a higher GWP than the HCFC it replaced. Beginning in 2015, SPF manufacturers began shifting to a fourth-generation hydrofluoroolefin (HFO) blowing agent that has a GWP close to zero. XPS manufacturers have followed suit, using HFO blowing agent blends with GWPs less than 80.

The evolution of blowing agents used in polyiso, XPS, and closed-cell SPF is shown in Table 1. Blowing agents used in foam insulation today have GWP values of 7 for pentane (used in polyiso), 1 for CO_2 (used in open-cell and some closed-cell SPF), 858 for HFC-245fa (still used in some closed-cell SPF), 1,300 for HFC-134a (which is being phased out of XPS), and HFO and its blended products (used in SPF and XPS, respectively) that range from 7 (SPF) to less than 100 (XPS).

In addition to the blowing agents in foam insulation, all insulation materials have a GWP based on the embodied carbon of the

Table 1: Ozone-Depleting Potential and Global Warming Potential of Blowing Agents Used in Foam Insulation

Type of Insulation	Blowing Agent	Atmospheric Lifetime (yr)	ODP[1]	GWP[2]
Polyisocyanurate				
Original	CFC-11	45	1	4,660
2nd Generation	HCFC-141b	9.3	0.11	782
3rd Generation	Pentane, cyclopentane	–	0	7[3]
Spray Polyurethane				
Original	CFC-11	45	1	4,660
2nd Generation	HCFC-141b	9.3	0.11	782
3rd Generation	HFC-245fa	7.2	0	858
3rd Generation	CO_2	–	0	1
4th Generation (2017)	HFO-1233zd	< 0.1	0	7
Extruded Polystyrene (XPS)				
Original	CFC-12	100	1	10,900
2nd Generation	HCFC-142b	17.9	0.065	2,310
3rd Generation	HFC-134a	13.8	0	1,430
4th Generation (TBD)	HFO-1234ze[4,5]	< 0.1	0	7

1. Ozone-depletion potential values from U.S. EPA using Montreal Protocol sources. ODP values are relative to CFC-11, which is defined as having a value of 1.0.

2. Global warming potential (GWP) values from IPCC Fifth Assessment Report; 100-year time horizon assumed. GWP values are relative to CO2, which is defined as having a value of 1.0.

3.
From L.D. Danny Harvey, "Net climatic impact of solid foam insulation produced with halocarbon and non-halocarbon blowing agents" in Building and Environment, August 2007 (Vol. 42, Issue 8).

4. Hydrofluoroolefins developed by Honeywell under the Solstice brand.

5. Note that XPS can currently use HFO blends, with most having a GWP <80.

material—in other words, the greenhouse gas emissions associated with the energy use that goes into making and transporting an insulation material.

Flame retardants

As effective as foam insulations are, there is one major problem with them: most are flammable. These insulations then require flame retardants to make them safe to use. Prior to 2018, XPS and EPS insulations in North America used HBCD (hexabromocyclododecane) flame retardant at concentrations between 0.5% and 1.2% by weight.

BuildingGreen explored concerns with HBCD as far back as 2004 (Flame Retardants Under Fire). Namely, HBCD is persistent, *bioaccumulative* (meaning it builds up in an ecosystem more quickly than the system can get rid of it), and toxic in animal studies. The fact that HBCD bioaccumulates in biological systems has been demonstrated by researchers around the world, and it was added to the Stockholm Convention's Persistent Organic Pollutant (POP) list in 2013.

The EPS industry stopped using HBCD in 2015, with the XPS industry following suit in 2018. In its place is a polymeric flame retardant that was developed in 2011 by Dow Chemical under the Bluedge name. A polymeric flame retardant is a "butadiene styrene brominated copolymer," according to the company. Because it has a higher molecular weight, it is no longer bioaccumulative, though it is still persistent in the environment, and its long-term impacts are unknown.

Most polyiso and SPF insulation materials contain phosphate-based flame retardants that are considered far less hazardous than brominated compounds, although phosphate-based flame retardants are often chlorinated phosphates—usually TCPP (Tris(chloropropyl) phosphate), which is 33% chlorine. Many polyiso manufacturers now offer halogen-free boards.

Kingspan's Kooltherm is made from a phenol formaldehyde-based foam and contains no flame retardants. It has the highest R-value of any foam insulation, at R-8, though it's use of formaldehyde is problematic for many in the green building community.

Cellulose and cotton insulation are typically treated with borate-based flame retardants, though some cellulose is treated with less-expensive ammonium sulfate (which is more corrosive than borate). While toxic to insects and decay organisms, borates have generally not been considered hazardous to humans—though there has been growing concern, particularly in Europe, about reproductive health impacts of borate flame retardants.

Flame retardants used in a few selected building insulation materials are shown in Table 2.

Chemical byproducts and residuals

Some insulation materials include chemicals that are potentially harmful to humans or the environment. Phenol formaldehyde (PF) or urea-extended phenol formaldehyde has been widely used as a binder in fiberglass and mineral wool insulation. PF is the binder that holds the glass or mineral fibers together. During manufacture, the spun fibers are treated with PF to make them stick together, and most of the chemical is then transformed via a heating process.

The fiberglass insulation industry has eliminated most PF from fiberglass insulation except for select board products. Fiberglass batts no longer use PF binders; they have been replaced with binders based on sugars, which act as binder when exposed to heat during manufacturing.

Most mineral wool insulation is still produced using resins made from formaldehyde, a carcinogen, though some mineral wool batts are now formaldehyde free.

Polystyrene insulation (both XPS and EPS) is made from potentially toxic constituents. It combines ethylene (made from

Table 2: Flame Retardants Used in Building Insulation

Insulation Material	Flame Retardants
Polystyrene (XPS and EPS)	Polystyrene insulation uses polymeric flame retardant (PolyFR), a butadiene styrene brominated copolymer that is not bioaccumulative but is persistent in the environment. Its long-term impacts are unknown.
Polyisocyanurate and both closed-cell and open-cell spray polyurethane foam (SPF)	The most commonly used flame retardant is TCPP, which has both chlorine and phosphorous as active ingredients.
Fiberglass, mineral wool, cellular glass, wool	No flame retardants are required.
Cellulose	Manufactured with borate compounds or ammonium sulfate at a concentration up to 20% by weight.
Cotton	Treated with borate or other non-halogenated flame retardants that are used on fabric.
Wood fiber	Some products contain an ammonium sulfate flame retardant.

Source: *Environmental Building News*

natural gas or petroleum) and benzene (derived from petroleum) to produce ethylbenzene, which is then dehydrogenated to form styrene in a process that produces byproducts benzene and toluene. The styrene is then polymerized to form polystyrene.

Benzene is a known human carcinogen as well as a developmental and reproductive toxicant. Ethylbenzene is a possible human carcinogen, according to the International Agency for Research on Cancer; EPA has deemed it "not classifiable." Styrene is a probable carcinogen and an asthmagen.

Spray polyurethane foam (SPF) also comes with hazards, and these are particularly concerning because SPF is installed in the field, sometimes by homeowners. According to the National Institute for Occupational Safety and Health (NIOSH) at the Centers for Disease Control, isocyanates are “powerful irritants to the mucous membranes of the eyes and gastrointestinal and respiratory tracts.” Isocyanates can also sensitize workers, the institute notes, making them prone to asthma attacks with subsequent exposure. “There is no recognized safe level of exposure to isocyanates for sensitized individuals,” according to EPA. “Isocyanates have been reported to be a leading attributable chemical cause of asthma in the workplace.”

Know your ingredients

Making informed choices about insulation materials based on their ingredients requires knowing what’s in them, and while the information presented here provides some pointers, the industry still has a long way to go in fully disclosing what’s in the products we use.

To find that out, many building professionals turn first to the *safety data sheet* (SDS)—previously referred to as *material safety data sheet* (MSDS). The SDS is designed to address occupational safety and provide a barebones assessment of the chemical hazards in a product. What manufacturers are required to report on the SDS is minimal, though. If you’re looking for useful information to sort out the health and safety of different products, you may need other tools. Here are a few that could help.

Environmental product declarations—EPDs provide a summary of the environmental characteristics of a product in a way that is accessible and consistent. Backed by life-cycle assessment (a methodology that

Table 3: Ingredients in Polystyrene Insulation

Chemical	Classification	Agency
Benzene	Known human carcinogen	International Agency for Research on Cancer California; Proposition 65; U.S. Environmental Protection Agency; European Commission
	Developmental and reproductive toxicant	California Proposition 65; European Commission
Ethylbenzene	Known human carcinogen	California Proposition 65
	Possible carcinogen	International Agency for Research on Cancer
Toluene	Developmental toxicant	California Proposition 65; European Commission
Styrene	Probable carcinogen	International Agency for Research on Cancer
	Known asthmagen	Association of Occupational and Environmental Clinics
HBCD (found in older products)	Persistent organic pollutant	Stockholm Convention on Persistent Organic Pollutants
	Persistent, bioaccumulative toxicant (PBT)	European Chemicals Agency

quantifies environmental impacts from raw-material extraction through end of life), EPDs may offer reliable data about global warming potential, energy and water consumption, and other impacts. However, human-health impacts and localized ecosystem effects are usually not found in an EPD.

Health product declarations—HPDs focus specifically on ingredients and their health implications. The HPD format is designed to enable transparent disclosure by defining the critical information that manufacturers should present so that fair comparisons can be made. The format requires that manufacturers explicitly state the level of ingredient disclosure and provide a hazard profile for 100% of ingredients—even those that aren't identified. Those disclosed at 100 parts per million provide the highest level of transparency.

Declare database and label—Declare provides a database of building products with at least 99% of their ingredients fully disclosed. Introduced early in 2013 by the International Living Future Institute (ILFI), Declare has yielded a free database of products that have labels. These labels may be marked "LBC Red List Free," "LBC Red List Approved," or "Declared." To participate, manufacturers need to know not only what their own ingredients are—including proprietary ones—but also what materials their suppliers use.

Pharos—The Pharos Project from the Healthy Building Network includes both a library of generic building products and a library of chemical and material constituents that may be found in building products. These chemicals go through GreenScreen assessment, which rates them based on their hazard profile, from low to high across a number of health impacts, from carcinogens to reproductive toxicants.

GreenScreen method—The GreenScreen method is a way of identifying health and environmental hazards associated with a particular substance. There are two types of GreenScreen hazard analysis. A full GreenScreen assessment looks at the full life cycle of a substance, including the chemicals it's made from and the chemicals it's likely to break down into. A GreenScreen List Translator screening looks at the hazards that international governmental bodies and toxicology experts have associated with certain substances (but not at hazards associated with manufacture and degradation).

Cradle to Cradle—Cradle to Cradle (C2C) is a multi-attribute certification program that includes a major focus on material health among other attributes like energy and water use. Its material health standard—which uses a different methodology than GreenScreen—has four tiers of chemical categories, from those that are banned to those that are considered benign for human health. The C2C Products Innovation Institute has broken out its material health standard into its own certification, with an associated transparency document called the Material Health Certificate. But unlike other material transparency formats, the Material Health Certificate does not list ingredients. Instead, it shows a percentage assessed, the "assessment rating" (how toxic the materials are based on the C2C material health standard), and a product optimization scale (showing the number of materials and how toxic they are).

Fiber shedding

Additional health and indoor air quality considerations come into play with insulation materials during installation.

In the 1990s, there was concern that fiberglass and mineral wool insulation could, like asbestos fibers, become embedded in lungs and cause cancer. Unlike asbestos, fiberglass and mineral wool fibers are not bioavailable and are no longer considered to be carcinogens, but all respirable fibers can become respiratory irritants.

Fiber shedding and respiratory irritation aren't limited to fiberglass and mineral wool insulation but also cellulose and, potentially, cotton insulation. Dust or fibers from these materials may be irritants to some people. Installers should use respiratory protection.

Moisture and mold

Insulation is a key part of the building envelope—from foundation walls to floor systems, above-ground walls, and the roof. With improper installation, moisture problems can occur, and those can turn into mold and mildew problems. Many people have allergies to mold spores, and certain molds produce more serious toxins. Persistent moisture issues can also cause structural problems.

How much insulation is installed, how that insulation is configured relative to other building enclosure components, how readily air can move through the system, and how permeable those layers are to water vapor are all key characteristics of insulation. The proper use of vapor barriers, vapor retarders, and air barriers is vital, so it's important to manage energy and moisture with equal intensity. It is *hygrothermal*—not just thermal—management that keeps buildings sound and occupants healthy.

To this end, construction detailing for moisture control is critical and should be done with a clear understanding of the moisture dynamics. What works in one climate may not be appropriate for another climate. This topic is big enough for a book—or several—so we won't cover it more here, although we will refer to building science issues throughout the remainder of the report and in the summary table on page 84. See page 26 for a primer on the dynamics of how moisture flows and how thermal insulation affects that flow.

We recommend a series of Builder's Guides from Building Science Corporation covering different climates. These are very useful resources, as are other information resources available on the company's website.

> With improper installation of some insulation, moisture and mold problems can occur. Many people have allergies to mold spores, and certain molds produce more serious toxins. Structural problems can also develop.

End-of-life issues with insulation materials

In evaluating the life cycle of any material, including insulation, we have to consider what happens at the end of its useful life. Most insulation materials can be salvaged and reused as long as they haven't been damaged during use or removal. Salvage and reuse rarely happen, though. Most insulation removed from a building is damaged, making it unfit for reuse, or the building is simply razed with no systematic deconstruction of components. An exception is commercial roofing; it is not unusual for rigid insulation to be removed from low-slope roofs during reroofing. Building reuse and materials salvage organizations sometimes stock this insulation; as long as it hasn't absorbed moisture or been damaged by UV radiation, it should work fine in another application.

If insulation can't be salvaged for reuse, can it be recycled into new insulation or other materials? Polystyrene insulation (XPS and EPS) sometimes is recycled. Polystyrene is a *thermoplastic* that can be melted and reformulated into new polystyrene resin; it is the most recyclable of insulation materials. Polyiso and spray polyurethane are *thermoset* plastics that have gone through a chemical transformation during polymerization, and they cannot be turned back into a resin. Theoretically, fiberglass and mineral wool could be melted and respun into new insulation, but the dirt and other contaminants that accumulate in fiber insulation materials preclude this.

We should also ask whether hazardous chemicals in the insulation can be rendered safe during disposal. Halogenated flame retardants in older products are unlikely to ever be captured. And blowing agents are a growing area of concern. The high-global-warming-potential blowing agents used in many foam insulation products have the potential to be released during disposal. Though by law refrigerants are supposed to be recovered from HVAC and refrigeration equipment, there is no program for capturing similar blowing agents from insulation. Considering the serious nature of our climate crisis, the entire life cycle of insulation should be assessed before purchasing insulation.

Most insulation materials can be salvaged and reused as long as they haven't been damaged during use or removal. This rarely happens, though.

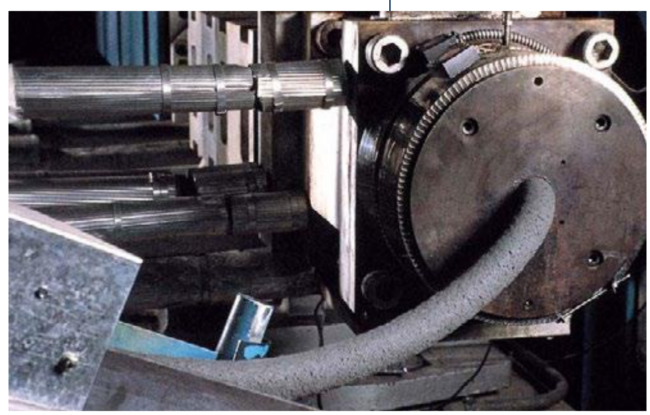


Photo: Tandus Group

Among building products industries, the carpeting sector has been a leader in recycling. Here, post-consumer carpet is being extruded into 100% recycled carpet backing at C&A's Dalton, Georgia carpet reclamation facility. Greater efforts to recycle used insulation while recovering blowing agents and safely disposing of flame retardants would go a long way to reducing the environmental footprint of insulation.

Performance and Durability

In addition to having as little impact on the environment and human health as possible, insulation needs to satisfy its primary function—insulating—and do it well over a long period of time. Insulating performance (R-value) of different insulation materials is addressed in the following section of this report (by material) and in the summary table on page 84. Here, we take a look at the other considerations with insulation performance: the impact of moisture, structural properties, durability of the material, and degradation of R-value.

Moisture dynamics

How different insulation materials respond to moisture is a key factor when we're figuring out which type of product to use in which application. Some materials can be regularly wetted or even submerged in water and still work just fine; extruded polystyrene (XPS) falls into this category, as does cellular glass. Some formulations of spray polyurethane foam (SPF), such as the higher-density formulations used for roofing applications, are also fine. To be impervious to moisture requires a closed-cell structure in a foamed material. Expanded polystyrene (EPS) has an open-cell structure, but higher-density versions can work in ground-contact applications where they will be regularly exposed to moisture—though low-density EPS (1 pcf or lower) may not perform as well.

Some insulation materials will be wrecked if they get wet. Cellulose insulation can absorb moisture and, once soaked, will slump within the building enclosure. Even if it dries out eventually (not at all a certainty), it will not re-expand to fill the cavity, so some of the cavity will likely end up uninsulated. Cotton insulation batts fall into this same category. Provide detailing to ensure that insulation materials like these will remain dry.

Still other materials can get wet but will continue to work well once they dry out. This is the case with fiberglass insulation. When wet, the R-value drops precipitously (because water is highly conductive), but if the insulation dries out, the performance should return to its previous level. In most situations (but not all), soaked fiberglass insulation will even regain its original loft as it dries. Wall and roof systems with such insulation materials need to be designed to allow drying if moisture ever gets into the cavity. Proper detailing of the building envelope helps achieve this drying potential.

Cellular glass, which is impervious to moisture and is therefore one of the few products other than XPS that can be used in foundations and below grade, can still suffer from freeze-thaw cycling—because the open cells at the surface can fill with water and freezing would then cause surface degradation. XPS is skinned over, so moisture can't enter even the outer cells—and the cell walls are more flexible than those of cellular glass.

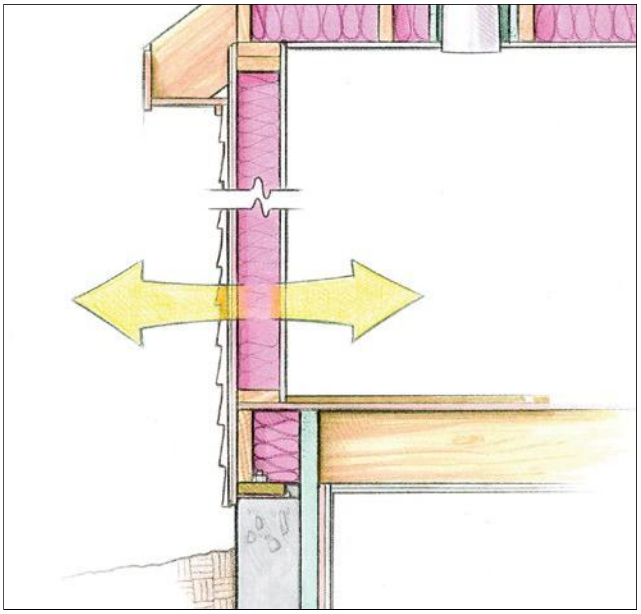


Illustration: Bob LaPointe, courtesy Fine Homebuilding

In this wall assembly with fiberglass insulation, there are no impermeable vapor retarders, allowing drying in both directions—a smart method for managing moisture in building assemblies.

How Water Moves Through Buildings—and What That Means for Insulation

Water moves in, on, and through buildings in the following four ways, which we'll discuss in order of the quantities involved: bulk water involves greater quantity than capillary; capillary more than air transport; and all involve more water than that moved by diffusion. This order of quantity helps us determine management priorities.

1. Bulk water—rain, runoff, and other flows—is driven primarily by gravity but also by wind and pressure differences. Bulk water on the exterior of a building is managed by moving water down and off of the building, while site features move the water away from the building. A system of interconnected flashings, drainage planes or weather-resistive barriers, free-draining spaces, and claddings manage exterior bulk water.

Inside the building, we manage bulk water by preventing or containing plumbing leaks and condensation. Collection trays or pans, sensor-driven shut-offs, and routine maintenance defend against interior bulk water problems.

2. Capillary water moves under tension through porous building materials or narrow channels between building materials that act like tubes. The primary defenses against capillary water movement are capillary breaks in appropriate locations, such as between the foundation and moisture-sensitive materials sitting on it. Capillary breaks are nonporous materials—such as sheet metal, impermeable membranes, closed-cell foams or plastics—or free-draining air spaces, generally $^3/_8$-inch (10 mm) or larger.

3. Air-transported moisture is the vapor content of air as it leaks out of or into a building. Air leakage is driven by a combination of holes through the building envelope and one of three driving forces: wind, stack effect, or mechanically induced pressure differences (fans) between the inside and outside of the building.

The primary concern (other than the heat content of the escaping or entering air) of moisture-laden leaking air is when it is accompanied by a temperature drop, increasing condensation potential. Air-transported moisture is managed with a continuous air barrier in the building envelope, built with interconnected, air-

Illustration: Peter Harris

impermeable sheet goods, caulks, sealants, and spray foams. To be completely effective, air barriers should be in contact with thermal barriers (insulation).

4. Vapor diffusion is the movement of water as a gas due to differences in *vapor pressure* or relative humidity. Movement is from areas of high concentration to areas of low concentration.

Restricting vapor movement is a double-edged sword: while we may want to control the movement of vapor *into* a building assembly, we should be much more interested in how the vapor permeability of individual building materials and assemblies affects the movement of vapor *out* of building assemblies. While building assemblies can get wet by all four forms of water movement, once water gets in, the main way it can get out is by diffusion, so it pays to make sure that assemblies can dry through diffusion in one or more directions.

Quite often the vapor drive of water into building assemblies is climate- and season-related: vapor drive is from the inside of heated buildings in the winter and from the outside of cooled buildings during the summer. We need to balance the restriction of this climate- and season-based vapor movement into building assemblies with the allowance for drying of the same assemblies. We do this by conducting a vapor profile analysis or hygrothermal modeling.

What does all this detail about moisture management have to do with insulation? Insulation restricts the flow of heat, which in turn reduces the ability of building assemblies to dry out when wet. If we use more insulation, we must in turn manage the movement of moisture with just as much intensity.

Decomposition and decay

Untreated insulation materials are subject to decomposition or decay. Biobased materials, such as cellulose and cotton insulation and low-density wood-fiber insulation sheathing, may decay through biological action—decay organisms that derive nourishment from the cellulosic materials. Borate-based flame retardants also work against decay organisms, though, so this is not usually considered a concern with good installation practices. Of course, borate-treated cellulosic insulation that is exposed to water, through a leaky roof or moisture-laden environments, could have those borates washed out over time, and lose decay resistance. (If that were to happen, the building's owners might have larger problems on their hands, though.)

With foams and other plastic-based insulations, degradation can result from exposure to ultraviolet (UV) rays in sunlight. For this reason, all types of foam insulation should be protected from direct sunlight, both before and after installation.

As might be expected, insects may eat cellulosic insulation materials, but they can also readily tunnel through spray foam and rigid foam insulations, reducing their R-values and structural integrity. This phenomenon is particularly problematic with below-grade installations, as are common with basements. Some manufacturers treat their foam products with an insecticide, usually a borate compound, and some building codes require treating the earth around the building with insecticides. Using an inert insulation material, like cellular glass, or installing the insulation out of harm's way on the inside of the building, can reduce the need for insecticides and improve durability.

Structural properties

Insulation materials run the gamut from highly compressible and nonstructural to rigid with high compressive strength. Compressive strength comes into play when the insulation material has to support loads; this is the case, for example, with boardstock insulation used as roof sheathing or to insulate beneath basement slabs.

Polyisocyanurate boardstock insulation offers adequate compressive strength to use as roof sheathing, but the fact that it can absorb moisture makes it inappropriate under floor slabs. XPS and cellular glass offer fairly high compressive strength, making them suitable for these applications. Some versions of cellular glass are strong enough that they can even be used under footings.

> You might expect insects to eat cellulosic insulation materials, but they also readily tunnel through rigid foam insulation, reducing its R-value and structural integrity.

Fire resistance

Fire resistance is important to consider, both because we want to keep buildings safe from fire and because flame-retardant chemicals added to some foam insulation materials carry potential health and environmental risks. Insulation materials with the greatest fire resistance are inorganic materials—especially mineral wool and cellular glass. While fiberglass doesn't readily burn, per se, low-density products could allow air to flow (and fire to spread) through it. Higher-density and higher-melting-point mineral wool is superior to fiberglass relative to fire resistance.

Among organic foams, polyisocyanurate and spray polyurethane foam (SPF) are *thermoset* plastics, which do not soften and melt when heated, while XPS and EPS are *thermoplastics*, which will melt. Thermoplastics are inherently more dangerous in a fire because the molten plastic can add fuel to a fire. Oddly, the primary test used to determine flame spread of materials (the ASTM E-84 "tunnel" test) was designed so that materials that melt will flow out of the test chamber and not contribute to the fire. This test could potentially benefit thermoplastics, such as XPS and EPS, and fire risks with these materials could be greater than flame spread test results would indicate. As noted above, most organic foam insulation materials are treated with flame retardants to slow ignition and flame spread.

Cellulose and cotton insulation are treated with borate and sometimes other flame retardants to reduce fire risk with these materials. Wool insulation generally does not require a flame retardant because the fibers are inherently fire-resistant, but it does contain borates for pest control.

R-value drift and impact of low temperature

Some insulation materials lose R-value over time, due to settling, moisture intrusion into the material, or loss of blowing agents in certain closed-cell foams. The R-value of polyiso even drops at lower temperatures—when it's needed most. Keeping cavity-fill and loose-fill insulation dry is critically important both to prevent damage to the structure from decay and health concerns from mold and also to maintain R-value. See the earlier discussion on moisture dynamics.

Settling of loose-fill and spray-in insulation (such as cellulose) is a function of installation. In wall applications of cellulose, dense-pack and damp-spray are options that prevent settling; with loose-fill cellulose in attics, a "stabilized" form is sometimes used to minimize settling. (See discussion under cellulose.) Lower-density cellulose installations, which used to be more common and remain common with lower-quality blowers, are more at risk of settling and creating uninsulated areas at the tops of walls.

Loss of R-value due to changes in blowing agents is more complicated and less controllable through installation. Closed-cell foam insulation materials that provide greater than about R-4.5 per inch generally rely on a low-conductivity gas in the insulation cells. This gas used to be a CFC compound, then HCFC, and now either a hydrocarbon or HFC (see earlier discussion on ozone depletion). These gases have lower gas-phase conductivity than air, so heat flow through them is slowed down.

As these low-conductivity gases gradually leak out of the foam and as air molecules leak in over time, the R-value drops. Manufacturers report "aged" R-values of their insulation—usually based on six months of controlled aging. This R-value drop is very gradual, and the rate of decline slows over time. Some manufacturers are more conservative than others in reporting R-values. XPS manufacturers, for example, have long reported R-5.0 per inch for most XPS, while it might be somewhat higher for ten or twenty years. New polyisocyanurate may achieve over R-7 per inch but drops to R-5.6 over several years.

With foam insulation materials that rely on low-conductivity gases for their performance, this R-value decay can be reduced by using non-permeable facings—which is why most polyiso insulation has foil facing. Closed-cell spray polyurethane foam (SPF) will retain its R-value longer when applied to a metal substrate (so that diffusion through that side is reduced). The insulation tables included in this report for closed-cell foams assume aged R-values.

Finally, one type of foam-plastic insulation—polyisocyanurate—drops in R-value at very low temperatures. This is a property of the chemistry, and the impact is modest, but lowering the R-value during the coldest weather—when you most ß on the insulation—is unfortunate. This issue is addressed in a BuildingGreen article, "Polyiso Manufacturers Turn Blind Eye to Problems at Cold Temperatures."

Insulation Materials by Type

This section of the report will review the most common (and some not-so-common) insulation materials, explaining:

- what the material is;
- how it's made;
- where and how we use it;
- energy performance factors;
- environmental performance factors;
- durability issues; and
- indoor air quality considerations.

The materials are separated into broad categories:

Fiber and Loose Fill page 31

Rigid Boardstock page 48

Foam-in-place page 66

Radiant Barrier page 76

Fibrous, Cellulosic, and Granular Insulation Materials

This broad category of insulation materials includes fiber materials (glass, mineral, cotton, and wool) as well as cellulose and various granular materials, including vermiculite and perlite. These materials insulate by trapping pockets of air and provide roughly R-4 per inch, with the actual R-value dependent on density and other factors.

Photo: Thermafiber

Mineral wool is one type of fibrous insulation. Mineral wool batts are similar to fiberglass, but they have significantly greater density, making them more common in acoustical applications.

Fiberglass Insulation

Fiberglass is one of the most common insulation materials in North America. It is produced by melting glass (typically greater than 50% recycled content) and spinning that molten glass in a process much like making cotton candy—at much higher temperatures. Fiberglass is available in batts, loose-fill, and rigid boardstock. To form fiberglass into batts or boardstock, a binder is added during manufacture that glues the fibers together. (A binder may also be used with loose-fill.) The industry used to rely entirely on phenol formaldehyde (PF) as that binder but has largely shifted away from PF due to concerns about formaldehyde emissions (see page 37).

Insulation forms

Fiberglass batts

- Most common and recognizable fiberglass insulation.
- Designed for filling wall, joist, or rafter cavities: available in standard widths for 16-inch-on-center and 24-inch-on-center framing. Higher-density batts provide a better friction fit between studs.
- Available unfaced or faced with various materials: asphalt-impregnated kraft paper, foil-faced paper, or vinyl (plasticized PVC). Facings can aid in installation (stapling flanges), minimize fiber shedding, and help to slow vapor diffusion.

Loose-fill fiberglass

- Used for blowing into attics (loose-fill) or blowing into wall cavities. For the latter, there are several installation options:
  - "Dense-pack," in which the fiberglass is blown in at a high enough density to prevent settling over time.
  - The "Blow-in-Blanket" system, in which a layer of polyethylene mesh is attached to the inner face of the studs and the fiberglass is blown into the cavity formed by that and the exterior sheathing, with drywall installed after blowing.
  - The Johns Manville "Spider Plus" system, in which the fibers are engineered to adhere to each other as well as to the sheathing and framing, eliminating the need for binders or the mesh to contain the insulation until the drywall is installed. With this approach, a motorized roller is used after installation to remove excess insulation even with the inner face of the wall studs or rafters.

Rigid fiberglass

- Much higher density than batt or loose-fill fiberglass. Covered on page 48, with other boardstock insulation materials.

Environmental attributes

Raw materials and recycled content

- Produced primarily from silica sand, with various additives, including boron (of which there is a finite supply).
- Recycled content: All commercially available fiberglass insulation in North America has significant recycled content—averaging 50% according to the North American Insulation Manufacturers Association (NAIMA). Some North American fiberglass insulation has recycled content as high as 73%, according to Owens Corning.
- Pre- and post-consumer: Recycled content is typically a mix of pre-consumer glass cullet from window glass manufacturing and post-consumer recycled glass from beverage containers.

Photo: Owens Corning

Owens Corning EcoTouch formaldehyde-free Fiberglas Insulation.

Pollution from manufacture

- Global warming potential: The GWP of fiberglass insulation varies by product but may be significant due to burning of natural gas to melt glass. Cradle-to-gate life-cycle assessments report GWPs between 0.46 and 0.72 kg CO_2 equivalent per 1 meter sq at RSI 1 (R-5.68) for unfaced fiberglass batts.
- VOC emissions: For the rare product that still uses it as a binder, manufacture involves some emissions of formaldehyde; the curing process heats the fiberglass insulation, volatizing excess formaldehyde; some may escape into the environment.

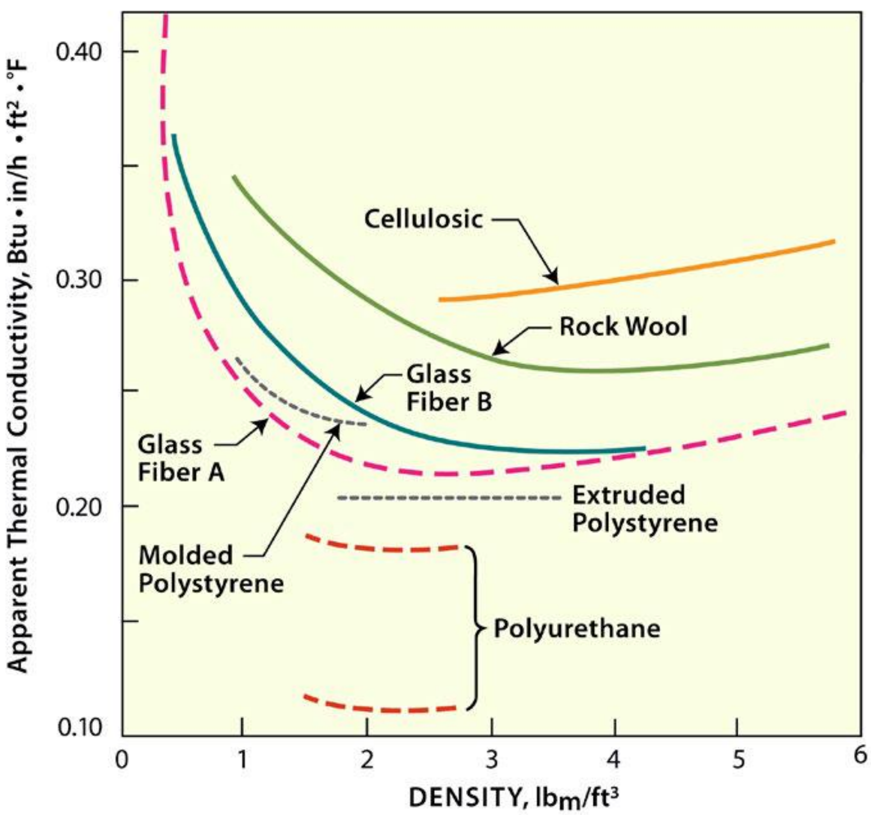
Health concerns

- There was significant concern in the 1990s that airborne glass fibers might be carcinogenic, like asbestos fibers. The International Agency for Research on Cancer (IARC) listed glass fibers as a "possible human carcinogen" in 1988 but changed the listing to "not a known human carcinogen" in 2001. The 14th Report on Carcinogens, released in 2016, maintains its listing of fiberglass but notes that glass fiber used in building insulation is less durable and less biopersistent—and thus less likely to cause cancer—than special-purpose glass fibers such as those used in some high-efficiency air filters and acoustical insulation. The State of California, under its Proposition 65 law, and other jurisdictions no longer list glass fibers from standard fiberglass insulation as a carcinogen.
- Respiratory and skin irritants: Installers should wear proper protection (coveralls, gloves, and a dust mask at a minimum), and all fiberglass should be separated from occupied space by a continuous and reasonably airtight layer, such as drywall. Some builders concerned about their workers and respiratory or skin irritation have switched to other batt products, such as cotton, or other insulation types, such as cellulose.
- Formaldehyde emissions: All North American manufacturers of fiberglass insulation have now converted to a non-formaldehyde binder (see sidebar, page 32) for batt and loose-fill insulation, but not for all rigid boardstock fiberglass insulation. Formaldehyde-free labels are prominent on packaging.

Performance

- R-value and density: At very low density, R-value may be as low as R-2 per inch. Insulating value peaks at about R-4.5 per inch at a density of 3-4 lb/ft^3 (see Figure 1). At greater densities than that, the R-value per inch drops because there is greater conductivity through the glass.
- At standard density (R-11 batt for a 2x4 wall cavity), fiberglass batts insulate to about R-3.1 per inch, but higher-density batts are available, providing up to R-4.3 per inch (R-15 batt for a 2x4 wall cavity).
- In loose-fill attic installations, fiberglass is typically lower-density than batt insulation and, as a result, it has lower R-value per inch: typically between R-2.2 and R-3.0 per inch.
- Air leakage: Because most fiberglass batt and loose-fill insulation is relatively low-density (compared with mineral wool

Figure 1: Thermal Conductivity as a Function of Density for Various Insulation Materials



or cellulose), it is usually not as effective at blocking air leakage—a significant component of overall energy performance. To address air leakage, some contractors spray a thin layer of air-sealing spray polyurethane foam (SPF) and then insulate with fiberglass—a system known as "flash and batt." Knauf has introduced similar systems relying on isocyanate-free spray-applied elastomeric sealant, to be followed by fiberglass insulation.

- Wind-washing: In unheated attics in very cold weather, the R-value of fiberglass insulation can be significantly compromised, especially with loose-fill fiberglass. This is because airflow and convection currents (sometimes referred to as *wind washing*) in the insulation reduce the insulating value—in some cases by as much as 50%. To combat this, a *vapor-permeable* air barrier of some sort, such as housewrap, could be installed along with the fiberglass insulation.
- Effect of thermal bridging: As with many insulation materials, nominal R-values are for the insulation only; average or *whole-wall* R-values are lower because they account for *thermal bridging* through the wood or metal studs (those wall components are less insulating).
- Facings: Facings can provide some utility in reducing air leakage and vapor diffusion—though a separate and continuous air barrier in the building assembly will provide a better air barrier.
- Installation quality: Achieving good energy performance from fiberglass batt insulation requires careful installation—more careful than many do-it-yourself installers or even professionals might provide. To fully fill a wall cavity, the batt should be pushed all the way in, then the paper facing should be pulled back out flush with the inner face of the studs—to avoid creating air voids that run the height of the wall cavity. In walls with wires or pipes running through them, installers should split the batt, so that a portion runs behind the wires or pipes and the rest is in front. Proper installation takes more time, but that extra effort is paid back with better performance.
- Impact of moisture: If fiberglass insulation gets wet, it can dry out without damage, but in some cases it will become waterlogged and slump within a wall or ceiling cavity, then fail to fully fill the cavity when it dries. When it is wet or damp, the R-value is severely compromised, and by holding moisture, wood framing members and other materials in contact with it may be damaged. Because fiberglass is inorganic, it will not decompose if it gets wet.

TRADE ASSOCIATIONS AND MANUFACTURERS

North American Insulation Manufacturers Association (NAIMA)
www.insulationinstitute.org

Owens Corning
www.owenscorning.com

Johns Manville
www.jm.com

CertainTeed
www.certainteed.com

Knauf Insulation
www.knaufnorthamerica.com

Cameron Ashley Building Products
www.cameronashleybp.com

Spray-in-Place Fiberglass

Fiberglass can be spray-applied to achieve higher densities and better performance in terms of air leakage and sound transmission. Like loose-fill fiberglass (see page 32), spray-in-place fiberglass can be installed behind netting in a "blow-in-blanket" system, but it can also be sprayed into an open cavity without netting. The only product of this type currently on the market is Johns Manville's Spider Plus Custom Insulation.

Insulation forms

- Spray-applied glass fibers; can be used with wood or steel framing.
- Range of densities: 1.0–1.8 lb/ft^3. Densities of 1.5 lb/ft^3 and greater provide significant airflow resistance, one of the primary benefits of this insulation type.

Health and environmental attributes

Raw materials and recycled content

- Produced primarily from silica sand, with various additives.
- Recycled content: Lower than typical fiberglass batts, but still a minimum of 25%.

Pollution from manufacture

- Similar to fiberglass batts (see page 32).

Glass fibers

- Similar to fiberglass batts (see page 32).

Binder and antimicrobial

- Spider was originally installed with a polyacrylate binder that was sprayed onto the fibers during installation, but the replacement product JM Spider Plus has been reengineered to eliminate the binder. The fibers have been engineered with a shape that causes them to lock together. A small amount of water is added at the time of installation to minimize fiber breakage, and this also helps control dust.
- Spider Plus contains an added antimicrobial compound to inhibit mold growth, but the company does not reveal the chemical used. Johns Manville literature states that the antimicrobial is listed in the U.S. Environmental Protection Agency's registry of pesticides.

Performance

- R-value: R-3.7 to R-4.2 per inch.
- Impact of moisture: Compared to batts, sprayed-in-place fiberglass is less likely to slump after wetting.

MANUFACTURER

Johns Manville
www.jm.com

Photos: Johns Manville

JM Spider insulation is spray-applied into open cavities by specially trained insulation contractors. A small amount of moisture activates the acrylic binder to hold the insulation in place, so no netting is required.

After spraying JM Spider into open cavities, a special roller is used to trim insulation so it is even with the inner surface of framing members.

Binders Used in Fiberglass

Until 1996, all fiberglass insulation manufacturers used urea-extended phenol formaldehyde as the binder in fiberglass batt insulation. The chemical was sprayed onto the fiberglass to glue the fibers together, and the material was baked to drive off most of the formaldehyde, but residual formaldehyde emissions still occurred. Because formaldehyde is considered a known human carcinogen as well as a respiratory irritant, people concerned about indoor air quality often shied away from fiberglass.

In 1996, Johns-Manville (then Schuller International), of Denver, Colorado, introduced the first non-formaldehyde binder for fiberglass insulation: an acrylic binder. This binder was used in selected products for several years, and in 2002 Johns Manville announced that it was shifting its entire fiberglass insulation product line to the acrylic binder. That conversion was complete by the end of 2002.

In late 2008, Knauf Insulation introduced its EcoBatt fiberglass, the first fiberglass insulation to be produced with a biobased binder (Ecose Technology). This revolutionized the industry, and in the next few years all other fiberglass batt insulations had also switched to biobased resins. (Note: some fiberglass board products still contain formaldehyde.)

Photo: Knauf Insulation

EcoBatt is produced without any dyes, giving the fiberglass a mottled brown appearance.

Cellulose Insulation

Cellulose insulation is made by shredding old newspaper, cardboard, and other paper products with a hammermill to break it down into small pieces. Better cellulose manufacturers then use a *fiberizing* process to break down the paper into individual fibers, resulting in a lower-density product with better lofting and greater thickness per installed bag. Cellulose has long been an insulation product favored by the green building community. With a lot of recycled content, cellulose helps to keep old newspapers out of landfills. While not an air barrier, cellulose also controls air leakage through a wall or ceiling cavity significantly better than fiberglass. Material is sold in bags and installed by mechanically aerating and spraying using specialized blowers.

Insulation forms

- **Loose-fill:** Used in attics, sometimes in a stabilized form that has a moisture-activated acrylic binder to prevent settling.
- **Dense-pack:** Used in wall cavities, both in new construction and retrofit applications. Typically installed at about 3.5–4 pounds per cubic foot (pcf) to prevent or minimize settling.
- **Damp-spray:** Sometimes called wet-spray (though the industry shies away from the latter terminology). Installed by trained insulation contractors using specialized equipment. For open wall cavities in new construction—not retrofit, generally —after wiring has been installed. A small amount of water is added during installation, then a special power-roller or *screed* is used on the wall surface to remove excess and leave the cavity entirely filled. Properly installed, the moisture content should be well below 50%—the drier the better. Allowing the walls to dry for at least 24 to 48 hours, however, is still recommended before closing in with drywall.

Environmental attributes

Raw materials and recycled content

- High recycled content—typically 80%: Generally made from post-consumer recycled content (recycled newspaper, cardboard, and other paper products).
- Manufacturers are typically regional, minimizing shipping costs.
- Flame retardants: Borate flame retardants used in premium cellulose and also increases pest resistance. Ammonium sulfate is sometimes used (by itself or with borate) but is more corrosive.

Photo: National Fiber

Spray-applied cellulose

Pollution from manufacture

- Low energy inputs: Cellulose uses very little energy during manufacture. Because of this, it's among the lowest-embodied-carbon insulation types.
- The greatest energy input is from curbside recycling or delivery of recycled materials to recycling centers; this input is rarely tracked.
- A lot of dust can be produced during manufacture, and control of this is important for air quality in the factory and surrounding area.

Health concerns

- Loose fibers and dust may be a respiratory irritant. A tight-fitting dust mask or respirator should always be used during installation.
- For people with chemical sensitivities, the inks (usually soy-based) used in newspaper printing may be a problem.
- Flame retardants: Most products are treated with borate flame retardants. Health concerns with borates have been thought to be low but are not well known; in 2011 the European Union added boric acid to the "Candidate List" of potentially toxic chemicals in its REACH program, with concern about reproductive toxicity. Some products are treated with ammonium sulfate or a mix of borates and ammonium sulfate.

Performance

- R-value: Fairly consistent at R-3.6 to R-3.8 per inch; less variation in R-value than fiberglass.
- Resistance to air leakage is better than that of most fiberglass.
- Moisture and wetting: Potential for wetting and moisture damage is significant with cellulose. Water-soaked cellulose will often slump, resulting in major voids and loss of insulating performance. Cellulose should be avoided in applications where moisture is a significant concern. Install within an assembly that allows drying to the interior or to the exterior—or both—so that it can dry out if it gets wet.

TRADE ASSOCIATION AND SAMPLING OF MANUFACTURERS

Cellulose Insulation Manufacturers Association
www.cellulose.org

GreenFiber
www.greenfiber.com

Applegate Insulation
www.applegateinsulation.com

Photo: National Fiber

Cellulose being blown in an attic installation

Photo: National Fiber

Cellulose being dense-packed behind Insul-Web

Mineral Wool

One of the oldest insulating materials, mineral wool is similar to fiberglass but is made from molten rock or iron ore slag that is spun into fibers, which are then coated with a binder and formed into either batts or rigid boardstock of various densities. Mineral wool batts typically have greater density than fiberglass, which makes them more appropriate for acoustical applications. High temperature resistance (mineral wool has a considerably higher melting point than fiberglass) is also an important feature for commercial and industrial applications.

Insulation forms

- Batts: Mineral wool batts are more rigid than fiberglass batts. Rather than being packaged in rolls, they are packaged in three- or four-foot pieces, in standard widths for 16 inch-on-center or 24 inch-on-center wood or steel framing (wider batts for metal studs than wood studs).
- Rigid boardstock (see page 48).

Environmental attributes

Raw materials and recycled content

- Plentiful raw materials: Made from rock (usually basalt), iron-ore blast-furnace slag, or a mix of the two.
- High recycled content: Up to 90% recycled content, depending on the manufacturer and product. In 2016, the North American mineral wool industry used approximately 675 million pounds of iron ore blast-furnace slag, and the industry averages 70% recycled content, according to NAIMA.

Pollution from manufacture

- Manufacturing energy: Primary pollution comes from energy consumption. Melting materials requires considerable energy, which means mineral wool can have higher embodied energy and carbon than some other insulation types.
- VOC emissions: Formaldehyde emissions occur with some products during the curing process, when phenol formaldehyde binder may be released during curing.

Health concerns

- Respirable fibers: As with fiberglass, fiber shedding from mineral wool may cause irritation among installers. IARC listed mineral fibers as a "possible human carcinogen" in 1988 but changed the listing to "not a known human carcinogen" in 2001. (See "Health concerns" under Fiberglass Insulation.)
- Installer protection: At minimum, a tight-fitting dust mask, gloves, and coveralls should be worn for protection.

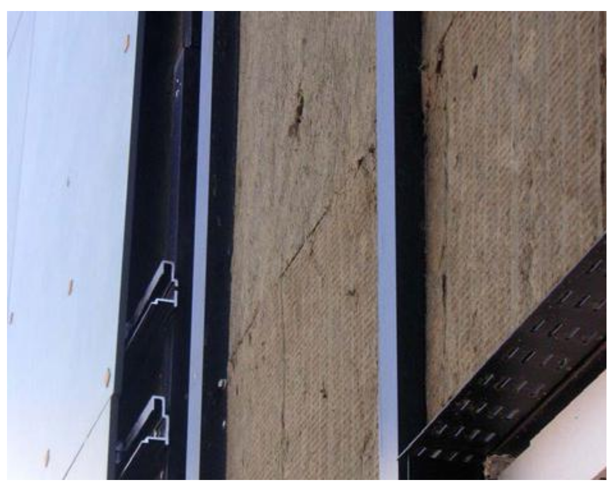


Photo: Thermafiber

Thermafiber's RainBarrier cavity wall insulation, which provides fire protection, controls noise, and sheds moisture, is used primarily in rainscreen applications.

- Formaldehyde emissions: Urea-extended phenol formaldehyde is used as a binder in mineral wool boards and some mineral wool batts. Residual formaldehyde left over from the curing process could be emitted from these products under certain conditions. But Rockwool's mineral wool batts are Greenguard Gold certified for low emissions, and both Rockwool and Thermafiber and now offer formaldehyde-free mineral wool batts. It is unlikely that board products will be formaldehyde free in the near future due to performance limitations of those resins.

Performance

- R-value: R-3.7 to R-4.3 per inch insulating value, depending largely on density.
- Proper installation is key: Performance is significantly compromised by poor installation—such as compressing batts behind wiring in a wall cavity. Greater rigidity of mineral wool batts makes this installation mistake less common than with fiberglass batts, but as with fiberglass, care must be taken to cut batts accurately (with a knife or saw) around electrical boxes, etc.
- Moisture resistance: Generally less absorptive of water than fiberglass batts.

Photo: Rockwool Group

Rockwool makes mineral wool batt insulation for both residential and commercial applications.

TRADE ASSOCIATION AND MANUFACTURERS

North American Insulation Manufacturers Association (NAIMA)
www.insulationinstitute.org

Rockwool Group
https://www.rockwool.com/north-america/

Thermafiber, Inc.
www.thermafiber.com

Industrial Insulation Group, Inc. (IIG)
www.iig-llc.com

Cotton

We know of one manufacturer of cotton batt insulation today: Bonded Logic in Chandler, Arizona, which produces UltraTouch. Cotton insulation is made from recycled denim fabric with added polyester fiber for bonding and loft. The insulation can be installed in wall cavities or attic applications, offering an alternative to conventional fiberglass that does not irritate skin.

Insulation forms

- Batts: Insulation, sized for different cavity widths (see note on page 43, under "Performance").
- Sound-control insulation: There are a variety of products for sound control, including specialized insulation panels for appliances and automobiles.
- Duct liner: The manufacturer produces a variety of duct insulation products.

Environmental attributes

Raw materials and recycled content

- Post-consumer recycled content: Bonded Logic claims total post-consumer recycled content of 80%.
- Borate-based flame retardant: Manufacturers use a mix of ammonium sulfate flame retardants and borates, the latter of which also increases pest resistance.

Pollution from manufacture

- Limited primarily to energy consumption: Minimal process energy, due to relatively low temperatures. Shipping is from single-source factories in Arizona and Georgia, so shipping energy can be significant.

Health concerns

- Although it's less dusty than cellulose, the batts do produce dust on installation, so dust masks are recommended.
- Products are treated with borate flame retardants. Borates have been thought to be benign, but health concerns are not well known; in 2011 the European Union added boric acid to the "Candidate List" of potentially toxic chemicals in its REACH program, with concern about reproductive toxicity.

Photo: Applegate Insulation

As with fiberglass batt insulation, proper installation is very important with cotton batt insulation; that means splitting the batt so that the space behind wires is insulated and gaps do not remain.

Performance

- Cotton batts insulate from R-3.4 to R-3.9 per inch and are available in R-13, R-19, R-21, and R-30.
- Cotton batts are available in a variety of widths for 16” on-center and 24” on-center wood and metal framing. Batts are cut somewhat wider than the stud cavities to ensure that they will fit snugly.
- Cotton batts are compressed prior to shipping and do not expand the same way as fiberglass when unpacked, so follow the manufacturer’s recommendations on restoring loft.
- Cutting UltraTouch cotton batts is more difficult than cutting fiberglass batts. A sharp knife or saw is needed. Batts are available with perforations to aid in fitting, though cutting will still be required for irregular spaces and to work around electrical boxes.
- Water absorption is a concern; cotton insulation is not recommended in applications where insulation could get wet.

MANUFACTURERS

Bonded Logic
www.bondedlogic.com

Applegate Insulation
www.applegateinsulation.com

Natural Wool

Both loose-fill and wool batt insulation are available. The inherent fire resistance and moisture resistance of wool make this an attractive insulation material. Several wool insulation products have recently been introduced in North America.

Insulation forms

- Loose-fill wool for blowing: Havelock Wool offers this form.
- Batt insulation: Bellwether Materials and Havelock both sell wool batts.
- Wool rope insulation is widely used in log homes.

Environmental attributes

Raw materials and recycled content

- Low-grade wool can be used for insulation. Estimates vary, but as much as 90% of wool produced in North America is discarded because it is too coarse, or too costly to process for textile use. Insulation provides a use for what would otherwise be agricultural waste, though wool used for some products is specifically selected for its thermal performance and not because it is agricultural waste.
- Flame retardants and moth prevention: Wool insulation requires a borate compound to prevent pests. Borates are also used as flame retardants, but wool insulation is inherently fire resistant.

Pollution from manufacture

- Because wool insulation is such a small-volume product, there is little reliable data on its impact. Processing wool does not require a lot of energy, but it typically requires a lot of water and pesticides. Improved closed-loop processes for wool insulation have helped minimize these impacts. Although many authorities consider sheep husbandry to have high global warming potential due to methane emissions, Architecture 2030's Materials Palette lists wool insulation as a carbon-sequestering product. Unlike plastic insulations or energy-intensive fiber-based products, wool is a natural product, meaning it has far fewer environmental impacts overall.

Health concerns

- No binders required, eliminating that health concern.
- Wool is naturally mold resistant and can help manage moisture.
- Allergies: Potential concern for those with wool allergies.

Performance

- R-values similar to those of fiberglass. Havelock claims an R-value of 4.3 per inch.
- With loose-fill installations, depending on installed densities, fiber length, and fiber-cluster dimensions, air pockets might remain in a finished wall or attic. As a relatively new product, optimal installation density is not well known.

Photo: Alex Wilson

Handful of Oregon Shepherd loose-fill insulation at West Coast Green.

MANUFACTURERS

Oregon Shepherd, LLC
www.oregonshepherd.com

Bellwether Materials
www.bellmat.wordpress.com/

Photo: Oregon Shepherd

Oregon Shepherd dense-pack blown wool insulation

Hemp

Hemp is a fast-growing, rapidly renewable, carbon-negative material known for its strength and durability. Before plastics, hemp was one of the most common industrial materials, used for paper, rope, fuel, and more. Today, hemp insulation is typically made from industrial hemp held together with fine polyester thread. Though hemp is not a psychoactive substance, U.S. laws against its cultivation and use have made widespread manufacturing impractical. These laws are beginning to change, so hemp will likely become a more viable option in the future.

Insulation forms

- Batt insulation: Available from Nature Fibres and Hempitecture.

Environmental attributes

Raw materials and recycled content

- Hemp is a rapidly renewable material that is grown for its oils, fibers, and more.
- Flame retardants and biocides: Hemp insulation is naturally insect and flame resistance and does not contain borate compounds or other flame retardants or biocides.

Pollution from manufacture

- Hemp is a hearty plant that can be grown in a wide variety of climates and typically requires few pesticides, but the environmental impacts of hemp cultivation vary depending on farming methods. Those using more fertilizer and pesticides will have greater impacts.

Health concerns

- No binders or biocides required, eliminating those health concerns.

Performance

- R-values of around 3.7.
- Hemp insulation is vapor permeable.
- Friction fits in walls.
- With no binders, can be messy to work with.

Vermiculite

Vermiculite is a naturally occurring mineral with small mica-like layers that expand eight- to thirty-fold when heated. The air spaces created when vermiculite expands give the material insulating properties, and this was taken advantage of in its use as a noncombustible insulating material. Unfortunately, the largest vermiculite mine in the U.S., in Libby, Montana, had asbestos deposits that were commingled with the vermiculite, so the vermiculite insulation produced from this mine was significantly contaminated with cancer-causing asbestos fibers. Vermiculite is not being installed today as an insulation material, but it is found in many older buildings.

Insulation forms

- Loose-fill, poured-in-place insulation: Vermiculite was widely used to insulate attics and sometimes used to fill hollow concrete masonry units.

Environmental attributes

Raw materials and recycled content

- Naturally occurring mineral: Approximately 70% of the vermiculite installed in the U.S. between 1920 and 1990 came from a mine in Libby, Montana and was sold under the name Zonolite. W.R. Grace acquired this mine in 1963 and closed it down in 1990 after concerns about asbestos contamination became known.

Pollution from manufacture

- Energy consumption: Significant energy consumption occurs in expanding the mineral to form expanded vermiculite.

Health concerns

- Risk of asbestos contamination: Geologically, vermiculite is often found in association with asbestos.
- With existing vermiculite in an attic, assume that asbestos is present. Consider laboratory testing to confirm this if you need to handle or decide what to do with an existing installation.

Performance

- R-value: R-2.1 to R-2.3 per inch
- Vermiculite absorbs moisture; significant loss of R-value if wet.

Photo: Montana Dept. of Environmental Quality

Asbestos-containing vermiculite insulation.

TRADE ASSOCIATION AND SAMPLING OF MANUFACTURERS

Vermiculite is not currently on the market in North America for use as building insulation.

Perlite

Perlite is an amorphous volcanic rock that has fairly high water content. The natural rock is crushed and then rapidly heated to 1,600°F, which expands the granules from four- to twenty-fold, producing a lightweight insulating material with a density ranging from 1.9 to about 11 lbs/ft^3. Although the original perlite rock (crude perlite) may be light gray to almost black in color, the *expanded perlite* (which we still usually refer to as *perlite*) produced from heating crushed perlite is white. The R-value of expanded perlite depends on its density and ranges from about R-2.4 per inch to as high as R-3.7 per inch. It is noncombustible without flame retardants and is commonly used to insulate hollow concrete masonry units.

Insulation forms

- Loose-fill, poured-in place

Environmental attributes and concerns

Raw materials and recycled content

- Perlite is mined in various locations around the world. The largest producers include the U.S., China, Greece, Japan, Hungary, Armenia, Italy, Mexico, the Philippines, and Turkey.

Pollution from manufacture

- Energy consumption occurs in expanding perlite and shipping it over distances.

Health concerns

- No known health concerns. According to the Perlite Institute, potential health effects of perlite have been thoroughly tested, and "no test result or information indicates that perlite poses any health risk."

Performance

- R-value dependent on density.
- Moisture absorption significantly compromises performance.

TRADE ASSOCIATION

The Perlite Institute, Inc.
(website lists 22 manufacturers)
www.perlite.org

Table 4: Perlite Insulation Performance

Density (lb/ft^3)	R-value per inch
1.9–4.1	3.2–3.7
4.1–7.5	2.8–3.2
7.5–11.2	2.4–2.8

Source: *ASHRAE Fundamentals*

Perlite mine

Photos: The Perlite Institute, Perlite.org

Expanded perlite

Rigid Boardstock Insulation

Rigid boardstock insulation provides a planar insulation layer that maintains its form and offers some degree of compressive strength. A wide range of materials is used in producing rigid boardstock insulation, including foamed plastics, higher-density glass and mineral fibers, cellular glass, and cork. These materials differ widely in their performance, health and environmental performance, and suitability to various applications.

Rigid boardstock insulation can be installed on either the exterior or the interior of metal or wood framing members, providing a *thermal break* to reduce the impact of thermal bridging through the steel or wood. Some types of rigid insulation can be used to insulate beneath a concrete floor slab or on the exterior of a foundation wall—offering enough compressive strength to carry the weight of the slab or the pressure of the foundation backfilling. Some rigid insulation materials are also used in fabricating such building components as structural insulated panels (SIPs) and insulated concrete forms (ICFs).

Photo: Rockwool International A/S

Very high insulation levels are being achieved in Europe with rigid mineral wool, such as this low-energy house in Zielona Góra, Poland. Mineral wool requires no flame retardants, and the primary raw materials are the natural igneous rock basalt and iron ore slag—a post-industrial waste product.

Polyisocyanurate

Polyisocyanurate (often referred to as polyiso or PIR) is the common foil-faced rigid boardstock found in building supply yards. It is a plastic foam insulation produced in a factory by combining two components—polyol and isocyanat—along with a blowing agent, a flame retardant, and other constituents. This process creates a uniform, closed-cell foam with trapped low-conductivity gas. It is a type of polyurethane foam but is produced with a different ratio of the polyol and isocyanate components to give it somewhat different properties. While polystyrene is a *thermoplastic*, which softens and melts as it is heated, polyiso is a *thermoset* plastic that retains its form as it is heated, rather than melting. Polyiso has the highest R-value per inch of any common insulation material (though it could lose that title if phenolic boardstock or vacuum-insulated panels catch on), and it is generally considered the "greenest" of the foam-plastic insulations.

Insulation forms

- Boardstock: Available in various thicknesses.
- Facings: Most commonly faced with foil, which slows the diffusion of low-conductivity gas from the foam and the diffusion of air into the foam (both of which result in loss of R-value). Other facings are used in some products, particularly specialized roofing insulation.
- Use in SIPs: A form of polyiso is used in some "urethane-core" structural insulated panels (SIPs). These are much less common than EPS-core SIPs.

Environmental attributes and concerns

Raw materials and recycled content

- Derived from fossil fuels: natural gas and petroleum.
- With some polyiso, a portion of the polyol component of the foam (up to about 8%) is derived from natural plant oil—a renewable material.

Pollution from manufacture

- Chlorine is used as a feedstock in the manufacture of polyiso and other polyurethane products. Chlorine is very reactive and can be problematic if released to the environment.

Health hazards from manufacture

- Isocyanates are asthmagens and can be respiratory sensitizers. Due to toxicity of MDI (methylene diphenyl diisocyanate), rigorous safety standards are required during manufacturing to protect workers. The U.S. EPA is currently scrutinizing health effects of isocyanates.
- 1-bromopropane: Some polyiso manufacturers use 1-bromopropane in their polyiso. The chemical causes neurological effects and is identified by IARC as a probable human carcinogen.

Blowing agents

- Non-ozone-depleting: While CFC-11 was originally used as the blowing agent for polyiso, that was replaced with a second-generation blowing agent, HCFC-141b, and and then cyclopentane, a non-ozone-depleting hydrocarbon. Today, cyclopentane is used in all boardstock polyiso. Some "urethane-core" SIPs (using a type of polyiso as the foam core) are produced with HFC-245fa, which has zero ozone-depletion potential but is a potent greenhouse gas.

Photo: David Pill

This verified net-zero-energy house in Vermont designed by Pill-Maharam Architects uses continuous polyisocyanurate insulation.

- Global warming potential: Hydrocarbon-blown polyiso has a very low global warming potential. While CFCs and HCFCs have global warming potentials in the thousands (several thousand times as potent as carbon dioxide), the GWP of the cyclopentane blowing agent used in polyiso is about 7—very low. HFC-245fa, used in some urethane-core SIPs, has a GWP of 858 (meaning that it is more than 800 times a potent a greenhouse gas than carbon dioxide). Some are now substituting GWP hydrofluoroolefin (HFO) blowing agents, which have a GWP less than ten, for HFC-245fa.

Flame retardants

- Most polyiso today is produced with chlorinated flame retardants—typically TCPP. Note that some polyiso manufacturers do not list the flame retardant on safety data sheets (SDS), but these compounds are believed to be present. There are health and environmental concerns associated with all halogenated flame retardants, though in general, chlorinated phosphate flame retardants are considered to be less hazardous than most brominated flame retardants.
- Many manufacturers, though, have polyiso made without halogentated (bromine- or chlorine-containing) flame retardants. In 2015, Kingspan, a manufacturer of metal-skinned building panels, began using a non-halogentated polyiso insulation in its insulated metal panels. Many manufacturers have now followed suit, offering it in standard polyiso boards.

Performance

- R-value: Polyiso offers the highest R-value of any common insulation material. It comes out of the factory with a very high R-value: over R-8 per inch (due to the low-conductivity hydrocarbon blowing agents contained in the closed cells of the foam). But the R-value drops as the blowing agent slowly diffuses out of the cells and air diffuses in. Manufacturers list the "aged R-value" of foil-faced polyiso as being around R-5.6 per inch. Polyiso products with foil facings on both sides retain R-value better than products with more permeable facings, such as products with OSB (oriented strand board) on one side.
- Foil facing can boost energy performance. In addition to helping retain the blowing agent (and thus the R-value), when installed next to an air space, the foil facing on polyiso serves as a *radiant barrier* and can boost the overall R-value. It does this by slowing *radiant heat flow*; the aluminum surface has low emissivity. Note that if there is not air space next to a radiant barrier, there is no energy benefit. (See page 76 for more on radiant barriers.)
- Polyiso and moisture: Polyiso insulation can absorb moisture, so is rarely used below-grade. Some builders, especially in Canada, do use polyiso below grade, but they provide good drainage to minimize risk of moisture absorption.

TRADE ASSOCIATION AND SAMPLING OF MANUFACTURERS

Polyisocyanurate Insulation Manufacturers Association (PIMA)
www.polyiso.org

Atlas Roofing Corp.
(ACFoam roof insulation, Rboard and EnergyShield wall insulation)
www.atlasroofing.com

Dow Chemical
(Thermax and Tuff-R)
www.dow.com

Firestone Building Product Company (IsoGuard roof insulation)
www.firestonebpco.com

Hunter Panels
(H-Shield)
www.hunterpanels.com

Johns Manville
www.jm.com

Rmax Operating, LLC
(Rmax Eco-Max and other products)
www.rmax.com

Extruded Polystyrene (XPS)

Extruded polystyrene (XPS) is a foam-plastic insulation material invented by Dow Chemical, which remains the largest manufacturer. Styrene monomer is polymerized to produce polystyrene, and this is extruded into rigid boardstock—a *closed-cell* foam insulation. Because XPS softens and melts when it is heated, it is known as a *thermoplastic*. It is also sold in different densities, with corresponding differences in compressive strength. Owing to its excellent moisture resistance, high compressive strength, and low cost, XPS is a very popular insulation material—particularly for below-grade applications including foundation walls and concrete slabs.

Insulation forms

- Rigid boardstock: Available in a variety of thicknesses, and with square-edge or tongue-and-groove.
- Fan-fold underlayment for walls—often installed beneath vinyl siding when re-siding a building.
- Manufactured into structural insulated panels (SIPs) and insulated concrete forms (ICFs), though not as commonly as *expanded* polystyrene (EPS).

Health and environmental attributes

Raw materials and recycled content

- Derived from natural gas and petroleum.
- Recycled content: Most XPS includes 20% pre-consumer recycled content.
- Recyclable: Because it is a *thermoplastic*, XPS can be melted and made into new insulation, though it is rarely recycled.

Pollution from manufacture

- Hazardous constituents: Benzene, a known human carcinogen and mutagen, is used in producing polystyrene. Styrene (also known as vinyl benzene) is being evaluated for its carcinogenicity. Release of these compounds during manufacture could be hazardous.

Blowing agents

- HFC-134a has been the dominant blowing agent used in XPS, though, because of its high global warming potential, manufacturers are in the process of switching to lower-GWP alternatives to meet regulations being put in place in Canada and the U.S.
- Zero ozone-depletion potential: While originally produced with ozone-depleting CFC-12 and then HCFC-142b, the HFC-134a and newer blowing agents do not damage the Earth's protective ozone layer.

XPS vs. EPS: Extruded polystyrene (XPS) is manufactured under pressure through extrusion; expanded polystyrene (EPS) is made by heat-expanding polystyrene beads. Both are thermoplastics that can be remelted as opposed to thermoset plastics, like polyiso, that undergo a chemical reaction.

Photo: Bensonwood

Unaware of the recently reported GWP implications of certain foam insulation materials, builder Tedd Benson specified four inches of extruded polystyrene (XPS) over 2x6 studs insulated with dense-pack cellulose in this net-zero-energy home.

- High global warming potential (GWP): HFCs are potent greenhouse gases; HFC-134a, which has been the standard blowing agent for XPS, is more than one thousand times as potent as carbon dioxide (GWP of 1,300), but it is being phased out due to new regulations. New XPS blowing agents have GWPs of less than 80.

Flame retardants

- Until 2015, all polystyrene insulation (both XPS and EPS) was produced with HBCD (hexabromocyclododecane) flame retardant, a persistent, bioaccumulative toxicant. Polymeric flame retardant (or PolyFR) "butadiene styrene brominated copolymer" has now replaced HBCD. PolyFR is considered far less hazardous, but it is still a brominated compound that is persistent in the environment, and its long-term impacts are unknown.

Performance

- R-value: R-5 per inch aged R-value.
- Excellent moisture resistance: With low-slope commercial roofs, for example, XPS is the only insulation material that is recommended for an *inverted roof membrane assembly* (IRMA), in which the insulation is installed *on top of* the roof membrane—where it may be wetted frequently. XPS is nonporous and can be used as a capillary break.
- Low vapor permeability: XPS restricts but does not eliminate drying potential.
- Resistance to air leakage: XPS is an air barrier material, and with taped or foamed seams it can contribute to a continuous air barrier assembly.
- High compressive strength: Suitable for use under concrete slabs.
- Affordable: XPS remains a fairly inexpensive insulation material—far less expensive than cellular glass, for example (the only other rigid insulation material recommended for sub-slab applications). XPS is usually more expensive than polyiso, however.
- Relatively low maximum temperature: Not appropriate for locations where temperatures could go above about 150°F.

Table 5: XPS Performance Properties

Insulation Material	Value	ASTM Testing Standard
Water absorption	0.3	C272, D2842
Water vapor permeance	1.5 maximum perms	E96
Compressive strength	15 psi	D1621
Cellulose	40 psi	C203

Source: *Dupont (for Styrofoam)*

TRADE ASSOCIATION AND MANUFACTURERS

Extruded Polystyrene Foam Association
www.xpsa.com

Dow Chemical (Styrofoam)
www.dow.com

Owens Corning (Foamular)
www.owenscorning.com

Pactiv (GreenGuard)
www.pactiv.com

Diversifoam (CertiFoam)
www.diversifoam.com

Expanded Polystyrene (EPS)

While XPS is manufactured through an extrusion process, *expanded* polystyrene (EPS) is made by heat-expanding polystyrene beads. EPS producers buy polystyrene beads (0.5 to 1.3 mm in diameter), which contain 4%–5% pentane. The beads are heated in molds using high-pressure steam, vaporizing the pentane, which expands the beads 40- to 50-fold to form a relatively moisture-resistant, closed-cell foam. Large slabs of expanded foam are cut to the needed boardstock dimensions using hot wires. This manufacturing (molding) process makes EPS much easier to produce on a relatively small scale. As a result, there are many more manufacturers of EPS than XPS, and most of these smaller companies ship their product regionally rather than nationally. This manufacturing process also makes it much easier to produce EPS foam in many different shapes and forms (see below). Like XPS, EPS is a thermoplastic that melts as it is heated.

Insulation forms

- Boardstock: The most common form of EPS, boardstock, is available in various densities, ranging from 0.9 lbs/ft^3 up to about 2.9 lbs/ft^3.
- Molded elements, including insulated concrete forms (ICFs), and concrete block insulation inserts.
- SIPs: Widely used in structural insulated panels (SIPs) as the insulating core material.
- Exterior Insulation and Finish System (EIFS) trim components.

Health and environmental attributes

Raw materials and recycled content

- Recycled content: Some manufacturers claim recycled content of less than 15%, and some have takeback programs, but the reality is that EPS insulation is rarely recycled, for economic reasons.
- Recyclable: Considered recyclable, but there is not a well-established recycling infrastructure for it.

Pollution from manufacture

- See discussion under XPS, page 51.

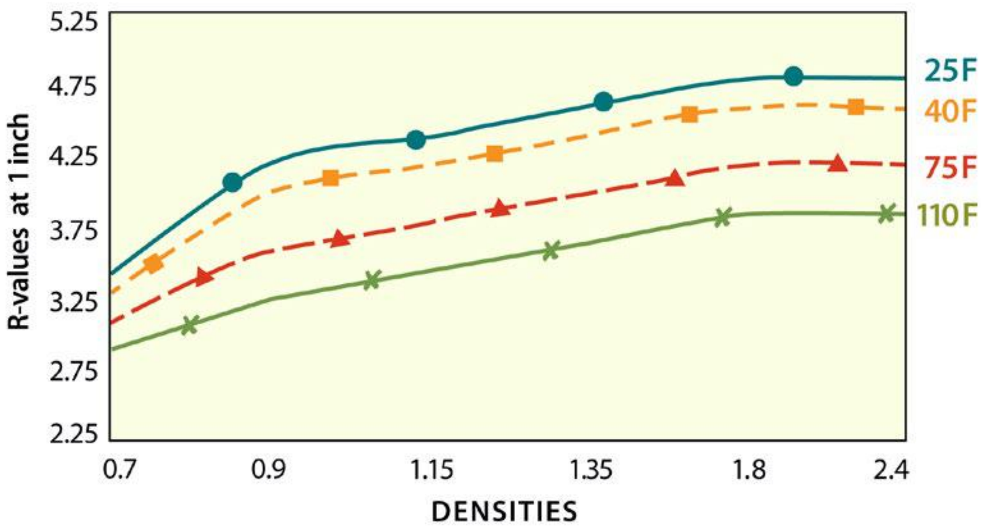
Blowing agents

- EPS is produced using pentane as the blowing agent. Pentane has zero ozone depletion potential and a global warming potential of about seven, which is not considered significant.

Flame retardants

- The same flame retardant as used in XPS, page 52.

Figure 2: Temperature and Density Effect on R-value



Performance

- R-value: Varies from about R-3.6 to R-4.2, depending on density and the temperature at which the R-value is measured (see page 15). Insulation values are most commonly listed for 75°F.
- Compressive strength and moisture absorption: For use below-grade and under concrete slabs, EPS with higher compressive strength and lower moisture absorption is recommended.
- EPS properties by "Type": There are a number of different "Types" of EPS insulation, generally designated by Roman numerals. The most common is Type I, but higher-density Type II or Type IX is often specified for below-grade applications because of its greater compressive strength and lower moisture absorption. Pertinent properties for different EPS Types are shown in Table 6.
- Enhanced R-value with graphite: BASF, the company that invented EPS, introduced a formulation of EPS in 1995 with graphite that has 9%–21% higher R-value, depending on type. The distinctively gray insulation has the following insulating properties at 75°F: Type I (R-4.34); Type VIII (R-4.48); Type II (R-4.53); Type IX (R-4.59).
- Termite resistance: Termites are able to tunnel through EPS, in some cases gaining entry into a building through the insulation. Some EPS manufacturers offer termite-resistant material, including Perform Guard, available with AFM Foam-Control products.

Table 6: EPS Performance Properties

Property	Value	ASTM Testing Standard
Water absorption	4.0%	C272
Water vapor permeance	5.0 maximum perm-in	E96
Compressive strength	10–14 psi	D1621
Flexural strength	25 psi	C203

Source: Carlisle Company (for InsulFoam Type I)

Photo: John Straube

In this deep energy retrofit, tongue-and-groove EPS was used instead of XPS for insulating beneath the concrete slab.

TRADE ASSOCIATION AND SAMPLING OF MANUFACTURERS

EPS Molders Association
www.epsindustry.org

Atlas EPS (ThermalStar)
Byron Center, Michigan
www.atlaseps.com

BASF Corp.
(supplier of EPS beads)
www.construction.basf.us
www.neopor.basf.us

Insulfoam (Division of Carlisle)
www.insulfoam.com

Rigid Mineral Wool

While available in batts (see page 40), mineral wool insulation is also common as a higher-density rigid boardstock product. Rigid mineral wool is sold primarily for commercial applications, particularly for fire safety and acoustic control. It is not widely distributed through retail home centers and building supply companies in the U.S., though it is available through select distributors for both residential and commercial applications.

Mineral wool has high levels of recycled content, ranging from around 75% to more than 90%. This pre-consumer recycled content is primarily iron ore slag.

The high vapor permeability of rigid mineral wool, along with its lack of blowing agents and flame retardants, fairly high R-value, relative affordability, and increasing availability, make it an attractive option for exterior wall insulation when the primary air barrier of the building enclosure is provided by another material, such as taped sheathing.

Insulation forms

- Range of densities: Densities of rigid boardstock vary from about 3 lbs/ft^3 to 8.5 lbs/ft^3.
- Facings: Facings: Most commonly sold unfaced, but also available with foil facing.
- Drainage board: Very effective as foundation drainage board, owing to its hydrophobic properties; also provides moderate insulation.
- Sub-slab insulation: In the past, mineral wool manufacturers were unwilling to recommend rigid mineral wool for sub-slab applications, but at least one manufacturer, Rockwool, now approves this as an acceptable application.

Health and environmental attributes

Raw materials and recycled content

- See mineral wool batt insulation (page 40).

Pollution from manufacture

- Made with urea-extended phenol formaldehyde binder. Note that some mineral wool batt insulations used in interior applications are now formaldehyde-free (see page 40).
- Respirable fibers: Higher density and increased concentration of binder make fiber shedding less of a respiratory concern.

Performance

- R-value: Most rigid mineral wool insulation provides R-3.8 to R-4.3 per inch. Insulating value does not drop over time.
- Moisture: Rigid mineral wool is hydrophobic and repels moisture, with very little moisture absorption. Thus, it works very effectively as drainage board around foundations and can be used as a sub-slab insulation material in some applications.

Photo: Rockwool International A/S

Rigid mineral wool can be an excellent substitute for polystyrene, owing to its moisture repellency and insect resistance.

Table 7: Rigid Mineral Wool Physical Properties

Property	Value	ASTM Testing Standard
Water absorption	1.2%	C209
Water vapor permeance	35 perms	E96
Compressive strength	584 psf at 10% compression 1566 psf at 25% compression	C165
Acoustical performance	0.8 NRC rating (1" thickness)	C423

Source: Rockwool (for ComfortBoard)

Phenolic foam

Phenolic foam building insulation was once a fairly widely used rigid insulation material (made by Koppers), but it disappeared from the U.S. market for many years. In 2016, Kingspan introduced its Kooltherm phenolic foam insulation board to the North American market. This product had been available in the U.K. since 2002. Kingspan has sold KoolDuct duct systems made from phenolic foam in the U.S. since 2001.

Like polyisocyanurate, phenolic foam is a thermoset plastic that doesn't melt as it is heated. While polyiso is made using an MDI-polyol polymer, phenolic foam is a foamed phenol-formaldehyde. Kingspan's Kooltherm is made with a pentane blowing agent that has very low global warming potential (low GWP). Because of phenolic foam's inherent fire-resistant properties, a flame retardant is not required.

Due to the small cell size in Koolspan, the R-value is higher than that of polyiso. It is listed as offering R-8 per inch, making it the best-insulating rigid insulation material on the market except for vacuum panels. The exact rated R-value differs slightly for the different Kooltherm products, largely due to the facings that are used on those products.

According to Kingspan, Kooltherm does not have the same corrosivity problem that earlier phenolic foam board had in the 1980s and '90s. The earlier materials used a more rapid production process that relied on an acid catalyst that could result in corrosion of steel roof decks—this led to a class-action lawsuit against two manufacturers. Kingspan uses a different acid catalyst at levels ensuring that no excess acid remains in the material.

The downside to phenolic foam insulation is potential of formaldehyde emissions, given that the material is foamed phenol-formaldehyde plastic. While phenol-formaldehyde plastics result in cross-linking that prevents formaldehyde from being released, it does contain formaldehyde, which is problematic relative to Living Building Challenge certification. Kingspan has done extensive testing of formaldehyde and VOC levels needed to achieve various European IAQ certifications and found formaldehyde emissions to be less than 10 µg/m3, but as of this report, Kingspan hasn't achieved key emissions certifications used in North America.

Insulation forms

- Boardstock: Different products offered for cavity installation, soffits, wood or steel framing, and rainscreen detailing; most products available in 25mm (1") or 75mm (3") thicknesses.
- Foil facing: Products incorporate foil-composite facings on one or both sides, depending on the product.

Health and environmental attributes

Raw materials and recycled content

- Recycled content: No recycled content

Health hazards from manufacture

- The manufacture of phenolic foam could potentially expose workers to formaldehyde.

Pollution from manufacture

- Unknown

Blowing agent

- Pentane (zero ODP; very low GWP)

Flame retardant

- None added, according to Kingspan

Photo courtesy Kingspan

Performance

- R-value: Approximately R-8 per inch, though some variation depending on the product—with R-value differences due to such factors as the presence or absence of foil facings.
- Compressive strength and moisture absorption: believed to be similar to polyisocyanurate.
- Flammability: Flame spread index less than 25; smoke developed index of less than 450, allowing use as a Class 1 insulation board, though a standard thermal separation is required between the insulation and a living space, such as half-inch drywall.

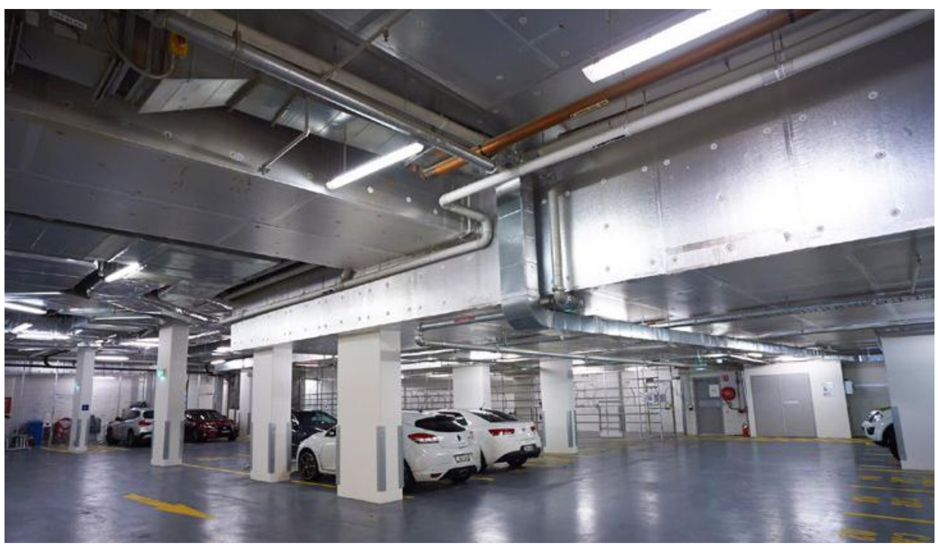


Photo courtesy Kingspan

Rigid Fiberglass

Fiberglass insulation is formed into higher-density rigid insulation form. Rigid fiberglass is made the same way fiberglass batt insulation is made (see page 32) but formed into denser boardstock. It is mainly used for HVAC or acoustic applications.

Insulation forms

- Range of densities: typically 1.5–7.0 lb / ft^3.
- Facings: Available unfaced or faced with foil, foil-skim kraft (FSK), all-service jacket (ASJ), and abuse-resistant nonwoven mat facings.

Health and environmental attributes

Raw materials and recycled content

- Similar recycled content to fiberglass batts (see page 32).

Pollution from manufacture

- Sometimes still made with urea-extended phenol formaldehyde binder. Some products are now formaldehyde-free, similar to fiberglass batts (see page 32).
- Respirable fibers: Higher density and increased concentration of binder make fiber shedding less of a respiratory concern.

Performance

- R-value of 4.0–4.5 per inch.
- Moisture resistance: Low water absorption (typically less than 3%).

TRADE ASSOCIATION AND SAMPLING OF MANUFACTURERS

See page 35.

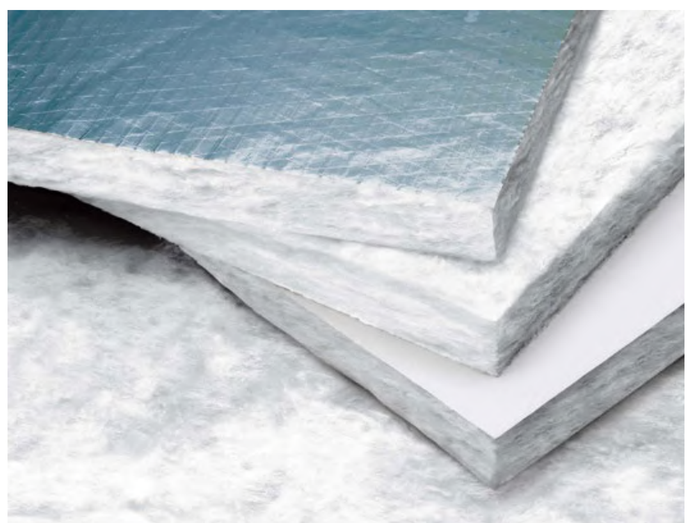


Photo: Johns Manville

Insul-SHIELD fiberglass insulation board

Perlite Rigid Boardstock Insulation

Several manufacturers offer roofing underlayment boardstock insulation material made from perlite (see page 47). Used primarily in commercial roofing applications and available in limited thicknesses, this material may include up to 50% cellulose fibers and up to 30% asphalt to bind it together. It is not widely used, but it provides limited insulation (about R-2.7 per inch), offers extremely good fire resistance, and offers a potential substitute for rigid foam in some applications. Note that perlite insulation is non-structural and non-load bearing.

Insulation forms

- Rigid panels in thicknesses from .05" to 2" and dimensions of 24" x 48" or 48" by 48".

Health and environmental attributes

- No known hazards

Performance

- R-2.7 per inch
- Fire resistance: superb (zero smoke developed, zero flame spread)

MANUFACTURERS AND TRADE ASSOCIATION

GAF Corporation
(EnergyGuard Perlite Board)
www.gaf.com

The Perlite Institute, Inc.
www.perlite.org

Cellular Glass

Cellular glass insulation, under the brand name Foamglas, has been manufactured since 1937 and is currently sold by Owens Corning, with plants in the U.S. and Europe.

Foamglas is produced primarily from sand, limestone, and soda ash. These ingredients are melted into molten glass, which is cooled and crushed into a fine powder. The powdered glass is poured into molds and heated in a *sintering* process (below the melting point) that causes the particles to adhere to one another. Next, a small amount of finely ground carbon-black is added, and the material is heated in a *cellulation* process. The carbon reacts with oxygen, creating carbon dioxide, which forms the insulating bubbles in the Foamglas. This CO_2 accounts for more than 99% of the gas in the cellular spaces, and it is permanently trapped there. The manufacturing process also results in a small amount of hydrogen sulfide gas in the cellular glass; this gas produces a rotten-egg smell if you cut into or scratch the insulation.

The resultant insulation is most commonly used in North America for high-temperature industrial applications where extreme heat resistance is required. The insulation has also (rarely) been used for wall, roof, and below-grade applications, though cost is significantly higher than that of more common insulation materials, such as XPS.

Insulation forms

- Foamglas is available in thicknesses from 1.6″ to 7.9″ and sold in 17.7″ x 23.6″ or 23.6″ x 47.2″ boards.
- Granular form: This form is available through AeroAggregates and Glavel in the U.S.

Health and environmental attributes

Raw materials and recycled content

- Recycled content: Virgin raw materials are used for boardstock in U.S. factories, while up to 66% recycled glass is used in European plants. AeroAggregates uses 100% recycled bottle glass.

Pollution from manufacture

- Energy use for melting glass; no other significant pollutants known.

VOCs, blowing agents, and flame retardants

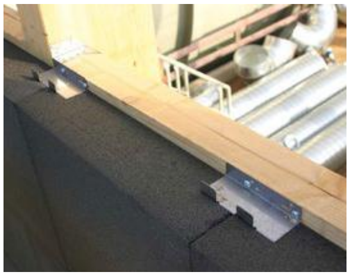
- Free of the high-GWP blowing agents that are currently found in XPS and most closed-cell spray polyurethane foam (SPF).
- No VOCs emitted from product, which is 100% inorganic.
- No flame retardants required to achieve fire resistance.

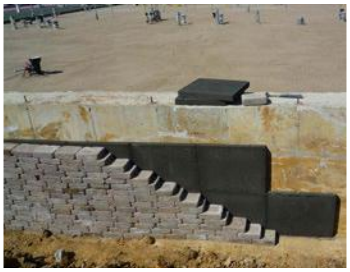
Health concerns

- Foamglas contains hydrogen sulfide, which is toxic and flammable at higher concentrations. Concentrations in Foamglas are less than 2% of the gas, which is trapped in the cell structure.

Performance

- Foamglas is durable, is impervious to moisture, has excellent compressive strength, is inherently fire resistant, and has moderately high R-value. See Table 7 for detailed properties.
- Foamglas is susceptible to freeze-thaw damage, however. If exposed to the elements in a cold climate, the open cells in the outer surface will collect water and then break down the cells as the water freezes. Over time the outer surface will break down due to this process; thus, protection of exposed Foamglas with a waterproof coating is critically important.





Photos: Owens Corning

Foamglas is being applied here as exterior foundation insulation. Unlike XPS, Foamglas contains neither flame retardants nor high-GWP blowing agents.

MANUFACTURER

Owens Corning
www.owenscorning.com

Table 8: Cellular Glass Physical Properties

Property	Value	ASTM Testing Standard
Water absorption	0.1%	C240
Water vapor permeance	0.005 maximum perm-in	E96
Compressive strength	87 minimum psi	C165 Procedure A/ASTM C240
Flexural strength	65.3 minimum psi	C203

Source: Owens Corning

Photo: Pittsburgh Corning

Foamglas Readyboard being used in a sub-slab application

Expanded Cork Board

Expanded cork insulation was one of the first rigid insulation materials, having been developed in the late 1800s and marketed widely in the U.S. by Armstrong Industries (originally the Armstrong Cork Company) from the 1890s into the 1950s. It was often used for insulating ice boxes and cold-storage buildings, such as apple storage barns, but was even installed in a 1951 renovation of the White House in Washington, D.C.

Cork is the outer bark of the cork oak tree (*Quercus suber*), a species that grows primarily in Portugal, Spain, Algeria, Morocco, France, and Italy. It regenerates naturally and can be harvested every nine or ten years. Cork is harvested today with hand tools, much as it has been for 2,000 years.

To make insulation, cork granules—lower-grade and waste material from bottle stopper production—are heated in an autoclave, which expands the granules about 30% and releases a natural binder (suberin) that glues them together into large billets that can be cut into the insulation boards. The finished insulation boards are 100% cork with no binders, flame retardants, or other additives.

Cork insulation is sold under the brand name Thermacork by the Portuguese company Amorim Isolamentos and sold in the U.S. by several dealers. In most areas, however, the product will be hard to find, and thickness options and edge configurations may be limited. Cost is significantly higher than that of conventional foam-plastic insulation (see page 29).

Insulation forms

- Rigid boardstock panels in thicknesses from 1″ to 12″ (metric or I-P thicknesses) and metric dimensions of 500 x 1,000 mm, or I-P dimensions of 18/5-5″ x 39″. Available with tongue-and-groove, lap, or square edges.
- A somewhat higher-density (façade-grade) product is sold as an exterior insulative cladding that is exposed to the weather.
- Available in Europe in laminated products with wood or coconut fiber (coir) for acoustic and other specialized applications.
- Granular cork insulation for loose-fill applications is available in Europe.

Health and environmental attributes

- Rapidly renewable material. Cork harvested on a nine- or ten-year cycle in Portugal and other western Mediterranean countries.
- Many cork forests are certified to Forest Stewardship Council standards and support rich biodiversity. (As the wine industry increasingly shifts to synthetic corks demand for natural cork has dropped, and some cork forests are being clear-cut for other land uses.)
- All-natural material with no chemical additives; naturally fire resistant without chemical flame retardants.
- Thermacork has a slight smoky aroma resulting from the heating process during manufacture, which could indicate some emissions of polycyclic aromatic hydrocarbons (PAHs). Exposure to PAHs in smoke or burnt matter is a major health concern, but between the very minor evidence of emissions here, and the exterior installation of the product, this should not be a significant concern.

Performance

- R-3.6 to R-4.0 per inch
- Density: 7.0 to 7.5 pounds per cubic foot
- Compressive strength at 10% deflection: 15 psi
- Maximum moisture content: 8%
- Permeability of a 40 mm board: 2.2 perms

Photo: Alex Wilson

Thermacork expanded cork board is being installed a continuous insulation over sheathing, which is serving as this home's air barrier.

MANUFACTURER AND SAMPLING OF DISTRIBUTORS AND DEALERS

Amorim Isolamentos, S.A.
www.amorim.com
www.thermacork.com

Small Planet Supply
(distributor and dealer)
www.smallplanetsupply.com

EcoSupply Center (dealer)
www.ecosupplycenter.com

Low-Density Wood Fiber Insulation

Low-density, insulating sheathing made from wood fiber has been available in Europe since the mid-1990s. A handful of European companies produce wood-fiber insulation, and at least three (Agepan, Gutex, and Steico) are distributed in the U.S. Products can range from less than an inch thick to more than six inches thick.

Most wood fiber insulation is made using sawdust and wood fiber with a small amount of paraffin and PMDI binder (a type of polyurethane). They may have tongue-and-groove edges or square edges. Most products are rigid, with relatively high compressive strength, making them effective as sheathing materials.

The lightweight rigid panels are popular in advanced building systems, such as Passive House projects, in part because of their high vapor permeability, which enables good drying potential—especially important for airtight assemblies. The panels are typically installed as exterior insulation when the air barrier is provided by an oriented-strand board (OSB), plywood, or wood-fiber sheathing. Some boards are multi-layered, with wind and water resistance on the exterior.

Insulation forms

- Rigid panels in thicknesses from about .05″ to over 6″ (metric sizing) and metric dimensions that are quite different from those of American sheathings. One manufacturer produces panels that are approximately 25″ x 90″, and another 23″ x 49″. Tongue-and-groove edges are most common.
- Softer, flexible wood-fiber insulation, more like batt insulation, is available in Europe.

Health and environmental attributes

- Renewable material, with some products available with FSC certification
- Some products carry environmental certifications in Europe (such as Natureplus certification in Germany)
- PMDI binder is hazardous before it fully cures, but by the time it reaches the jobsite, this adhesive should be fully cured, and emissions should not be a concern.

Performance

- R-3.1–3.7 per inch
- Density: 9–14 pounds per cubic foot
- Permeability: Very high permeability: 18–21 perms

MANUFACTURER AND SAMPLING OF DISTRIBUTORS AND RETAILERS

Agepan
(manufactured by Glunz, AG of Germany)
Small Planet Supply
(distributor and dealer)
www.smallplanetsupply.com

Multitherm
(manufactured by Gutex Holzfaserplattenwerk, GmbH of Germany)
475 High Performance Building Supply (distributor and dealer)
www.foursevenfive.com

Photo: Martin Holladay

Albert Rooks imports Agepan insulating wood-fiber sheathing through his Small Planet Workshop. The product has caught on with high-performance builders looking for a wall assembly that can dry in both directions.

Foam-in-Place Insulation

Foam-in-place insulation materials are sprayed or injected into a framing cavity, such as a wall cavity, or sprayed onto a surface such as the underside of roof sheathing or the interior of a foundation wall. The material goes through a chemical reaction, expanding in the process to create an insulating cellular foam. Some foam-in-place insulation materials have very little structural strength, while others form a layer rigid and durable enough to serve as roofing. Energy performance depends on the structure of the insulating cells and whether they trap air or another gas. All but one type of foam-in-place insulation is made from plastic.

Photo: Peter Yost

Spray polyurethane foam is a common choice for providing air-sealing and insulation in below-grade applications, particularly with irregular foundations. Here foam was sprayed between nonstructural studs, then shaved flat and also sprayed in the rim joist bays just above.

Closed-Cell Spray Polyurethane

Spray polyurethane foam (SPF) is the most common type of foam-in-place insulation, and closed-cell SPF is the most common configuration. With most closed-cell SPF, two components are mixed as the foam is installed: a polyol (which includes a blowing agent); and an isocyanate. Different densities can be achieved, depending on the exact mixture, to satisfy different needs. The polyurethane adheres extremely well to most surfaces, and the closed-cell structure of the cured foam does an excellent job at blocking air leakage.

The insulating value depends on the blowing agent used, which ends up contained in the cured foam. One-component spray foam sealant is a type of closed-cell SPF that can be installed relatively easily without special training. Like polyisocyanurate, SPF is a thermoset plastic—it does not melt as it is heated; this makes it inherently less hazardous in fires. Polyurethanes are not usually recyclable, and that challenge is compounded when these foams are bonded to other materials.

Insulation forms

- Medium-density closed-cell SPF: Density of 1.5–2.3 lbs/ft^3. Used for spraying into wall and roof cavities. The cavity is typically not entirely filled, so as to not interfere with drywall attachment. Medium-density SPF is typically installed at high pressure by trained installers using specialized equipment with 100–500 board-feet-per-minute capacity. Components are preheated prior to installation.
- High-density closed-cell SPF for roof applications: Density 2.5–3.5 lbs/ft^3. Used for roofing applications in which the foam provides both the insulation and the roof surface. Common in the Southwest U.S., this product provides a finished roof surface. Installed at high pressure by trained installers using specialized equipment; 100–500 board-feet-per-minute capacity. Components preheated prior to installation.
- One-component spray foam sealant: Foam injected from a can or canister (with a reusable foam-gun) at low pressure. This form is used to seal around windows, wiring and plumbing penetrations, as well as for filling small, hard-to-reach gaps. Both high-expanding and low-expanding formulations are available; for sealing around windows, low-expanding sealant is recommended.
- Two-part foam kit or "froth pack." Low-pressure installation that can apply 30–40 board feet per minute. Used for sealing larger areas or insulating small areas—for which it isn't feasible to bring in an insulation contractor with high-pressure foaming equipment. Kits advertised as being usable by contractors without special training. Safety precautions strongly recommended (see below).

Health and environmental attributes

Raw materials and recycled content

- Most products have no recycled content and are nonrecyclable for uses other than as filler at end of life. Some closed-cell foams contain more than 10% recycled plastic.
- Primary components are derived from petroleum.
- Polyol component may contain some soy oil in place of the standard petroleum-based polyol. Percent soy polyol in these foams is typically fairly low (less than 10%, but may be more than 25% with some products). In the past, some products advertised up to 40% biobased material, but these had performance problems, and the percentage of soy oil has been reduced.

Photo: ICP Building Solutions Group

Foam-in-place insulation can provide an effective air barrier in locations such as wall penetrations that are otherwise difficult to seal and insulate.

Pollution from manufacture

- Pollutants associated with petroleum drilling and refining.
- Embodied energy is significant, primarily from the petroleum raw material.
- Chlorine is used as a feedstock in the manufacture of polyurethane. Chlorine is very reactive and can be problematic if released to the environment.

Hazardous emissions

- Isocyanate hazardous: Methylene diphenyl diisocyanate (MDI) is an asthmagen and respiratory irritant, so protection is required during installation. Once fully cured, hazardous offgassing is *usually* minimal. The U.S. EPA is scrutinizing health effects of SPF due to the isocyanates. EPA is particularly concerned about do-it-yourself installations.
- MDI is on the European Union's REACH "Restricted" list.

Blowing agents

- Professionally applied closed-cell SPF is most commonly formulated using non-ozone-depleting HFC-245fa. While safe for ozone, HFC-245fa has a high global warming potential (GWP) of 858. This GWP is considerably lower than the CFC-11 that was originally used (GWP of 4,660) but higher than the second-generation HCFC-141b (GWP of 782).
- Increasingly, the HFC-245fa is being replaced with a low-GWP HFO (hydrofluoroolefin) blowing agent.
- Some closed-cell SPF is water-blown, with CO_2 filling the foam cells. While considerably better from an environmental standpoint, some water-blown SPF has had performance problems from shrinking during the curing process (see below).
- Cans of spray foam sealant may use hydrocarbon blowing agents or HFC. The advantage of hydrocarbon-blown spray foam sealant is the very low global warming potential; the downside is fire hazard during installation.

Flame retardants

- Most SPF uses a chlorinated phosphate flame retardant, such as TCPP (tris(1-chloro-2-propyl) phosphate) or TDCPP (tris(1,3-dichloro-2-propyl) phosphate). While some consider chlorinated flame retardants to be less hazardous than their brominated cousins, one of these compounds, TDCPP, is the flame retardant that was removed from children's sleepwear in the 1970s after significant hazards were identified. The U.S. Consumer Product Safety Commission considers TDCPP a probable human carcinogen, and EPA considers it a moderate hazard for reproductive and developmental effects.

Photo: ICP Building Solutions Group

A contractor using respiratory protection applies spray polyurethane foam (SPF) insulation in an attic retrofit to combat air infiltration and reduce heat loss. EPA is particularly concerned about do-it-yourselfers not using adequate protection, as well as safe re-entry times.

Performance

- R-value: Ranges from R-6.0 to about R-6.8 per inch. Higher initial R-value drops to an "aged" value.
- SPF is an air barrier, doing an excellent job at controlling air leakage in buildings. Closed-cell foam is also a vapor barrier.
- Structural strength: Closed-cell SPF can significantly strengthen and stiffen building assemblies. According to the Spray Polyurethane Foam Alliance, closed-cell SPF doubles the racking strength of wood-frame walls (compared with open walls or fiberglass-insulated walls), while 3" medium-density SPF under roof sheathing increases the resistance to uplift more than threefold.
- Installation concerns and potential shrinkage: Proper performance of SPF depends on proper field installation. While spray-foam cans and froth packs can be used by general contractors, most SPF installation (using high-pressure, high-volume equipment) requires specialized equipment and extensive training. Performance can be compromised by improper conditions (such as cold weather), moist or wet framing components, improper mixing of chemicals, or spraying layers that are too thick. (SPF curing gives off heat; if layers ("lifts") thicker than about 2" are installed in a single pass, heat build-up may cause curing problems and may even be a fire hazard.) There are also field reports of shrinkage or poor performance with some of the water-blown and biobased formulations of SPF.

Photo: BASF Polyurethane Foam Enterprises

Spray polyurethane foam can be used on foundation walls and under slabs as an alternative to polystyrene.

TRADE ASSOCIATION AND SAMPLING OF MANUFACTURERS

Spray Polyurethane Foam Alliance
www.sprayfoam.org

SprayFoam.com
"Spray Foam Insulation Community Portal and Guide"
www.sprayfoam.com

BASF Corporation
(Comfort Foam)
www.spf.basf.com

Icynene
www.icynene.com

ICP Building Solutions Group
(Handi-Foam Sealants)
www.handifoam.com

Premium Spray Products
(Foamsulate)
www.premiumspray.com

Open-Cell Spray Polyurethane Foam

Open-cell SPF is much like its closed-cell cousin, although the density is lower. It is a two-component foam, combining polyol and MDI, but the expansion is significantly greater than with closed-cell SFP—on the order of 100-fold expansion. Water is used as the blowing agent. Open-cell SPF provides excellent adherence, good air sealing, an R-value that is comparable to that of cellulose, and moderate permeability. Unlike closed-cell SPF, the cured foam remains quite flexible, which allows it to move as framing members expand and contract with changing moisture conditions. It does not provide any structural properties.

Insulation forms

- Low-density sprayed-in-place foam: Typical density ranges from 0.5 to 1.4 lbs/ft^3. It is typically installed so that the foam overfills the framing cavities and is pared (screeded) off flush with the surface of framing members—thus leaving no air channels in the cavities once interior finish materials, such as drywall, are installed.

Health and environmental attributes

Raw materials and recycled content

- Usually no recycled content, and nonrecyclable for uses other than as filler.
- Primary components derived from petroleum.
- Polyol component may contain some plant oil in place of the standard petroleum-based polyol. Percent soy polyol in these foams is typically fairly low (less than 20%).

Pollution from manufacture

- Pollutants associated with petroleum drilling and refining.
- Embodied energy results primarily from the petroleum raw material. Because open-cell SPF has approximately one-quarter the density of closed-cell SPF, its embodied energy per board foot is one-quarter as great, though on an R-value basis, the embodied energy is closer to 40% that of closed-cell SPF (because the open-cell foam does not insulate as well).
- Chlorine is used as a feedstock in the manufacture of polyurethane. Chlorine is very reactive and can be problematic if released to the environment.

Hazardous emissions

- Isocyanate hazardous: Methylene diphenyl diisocyanate (MDI) is an asthmagen and respiratory irritant, so protection is required during installation. Once fully cured, hazardous offgassing is *usually* minimal. The U.S. EPA is scrutinizing health effects of SPF due to the isocyanates. EPA is particularly concerned about do-it-yourself installations.
- MDI is on the European Union's REACH "Restricted" list.

Blowing agents

- Water: Water is used as the blowing agent; the foaming process releases carbon dioxide, which expands the foam.

Flame retardants

- Most open-cell SPF uses a chlorinated phosphate flame retardant, such as TCPP (tris(1-chloro-2-propyl) phosphate) or TDCPP (tris(1,3-dichloro-2-propyl) phosphate)—see discussion under closed-cell SPF, page 67.

Performance

- Insulates to between R-3.7 and R-4.0 per inch. Standard, 0.5 lb/ft^3 foam performs at the lower end of that scale, while somewhat higher-density foam provides closer to R-4 per inch performance.
- Open-cell SPF does a very good job at controlling air leakage. While the foam itself is not as airtight as closed-cell SPF, open-cell foam is less likely to separate from the framing members—which can significantly compromise the performance of closed-cell SPF.

Injection-Installed Aminoplast Foam Insulation

Injection-installed aminoplast foam insu–lation is a cavity-fill insulation used most commonly today to fill cores of concrete-masonry-unit (CMU) wall systems in commercial construction. It is essentially a new version of urea-formaldehyde foam insulation (UFFI), with improved chemistry that has less shrinkage and lower formaldehyde emissions.

UFFI was a popular retrofit insulation material for uninsulated cavity walls in the 1970s, but it had significant shrinkage problems, particularly when poorly installed, and emitted significant quantities of formaldehyde—then considered a possible carcinogen and now a known human carcinogen. The U.S. Consumer Products Safety Commission banned UFFI in 1982, but this ban was overturned in 1983.

While there were 39 manufacturers of UFFI in 1977 and about 1,500 installers, today there are only five manufacturers and about 600 installers. Due to past negative publicity, UFFI manufacturers today most commonly refer to their insulation as "injection foam," "aminoplast injection foam," or "amino foam." Some manufacturers refer to the three-part (or tri-polymer) resin or "dry-resin foam" in their descriptions. FDI Enterprises refers to its Tripolymer Foam Insulation as "modified phenolic based methylene bound co-polymers."

But the chemistry of these products is essentially the same as or very similar to that of the old UFFI product, even though you will find little or no reference to formaldehyde or UFFI on company websites. Though similar to UFFI, the chemistry of modern dry-resin amino foam products have most of the free formaldehyde removed prior to packing and rely on sophisticated cross-linking to significantly reduce emissions. Some shrinkage still does occur with these products, however.

Some manufacturers significantly exaggerate the insulating performance—primarily by failing to properly account for the thermal bridging through CMUs.

Insulation forms

- Injection foaming. Two-part foam, with the consistency of shaving cream, is injected into closed cavities—most commonly concrete masonry units. The material expands to a limited extent during installation, but most of the expansion has already happened by the time of installation. Injected under moderate pressure, the foam squeezes through connections between wall cavities to fill the voids. According to manufacturers, the foam can fill vertically up to 12 feet, but rapid setting time means that having the foam flow significant distances is risky.

Health and environmental considerations

Raw materials and recycled content

- No recycled content known.

Pollution from manufacture

- Petrochemical-based components.

Formaldehyde offgassing

- Some offgassing of formaldehyde is likely to occur, though this may be a function of installer skill. Due to concern about formaldehyde, five states—California, Connecticut, New Hampshire, New Jersey, and Massachusetts—either prohibit or restrict sales and installation of aminoplast foam insulation. However, all of these states, except Massachusetts, have moved to ease sales and installation of a product that is based on hybrid resin components (such as InsulSmart MH, produced by cfiFOAM, Inc.).

Blowing agent

- There is no ozone-depleting or high-global-warming-potential blowing agent used with these insulation materials.

SAMPLING OF MANUFACTURERS

cfiFOAM, Inc.
(Core Foam Masonry Insulation, InsulSmart Interior Foam Insulation, and InsulSmart MH)
www.cfifoam.com

RetroFoam
www.RetroFoam.com

Tailored Chemical Products, Inc.
(Core-Fill 500)
www.core-fill500.com

Thermal Corporation of America
(Thermco Foam)
ww7.thermcofoam.com

Flame retardants

- Halogenated flame retardants are not added to aminoplast foams. Phosphoric acid or boric acid, either of which imparts fire-retardant properties, may be added as a catalyst.

Performance

- Typically R-4.6 per inch at 75°F. Some manufacturers list higher R-values (up to R-5.1 per inch), but that is at a lower temperature (25°F) than most advertised R-value measurements.
- Whole-wall R-value with aminoplast-insulated CMUs depends on density of the masonry. Assuming parallel-path testing (per NCMA TEK 101) for 8"-thick, three-web CMU wall values are R-11.3 for 85 pcf; R-8.2 for 105 pcf density CMU; R-6.0 for 125 pcf CMU (per data from cfiFOAM, Inc.).
- Foam density ranges from 0.6–1.3 pcf; foam does not provide any structural capacity and must be contained within a cavity.
- Aminoplast foams flow under fairly high pressure (90-100 psi) and effectively fill hard-to-access voids and cavities, but there is some risk of voids in the resultant insulation. Thermal imaging may be used following installation to identify voids.
- Shrinkage has been a major concern in the past with UFFI and remains something of a concern with the newer-generation aminoplast foams. Typical shrinkage is 0.5%, with shrinkage up to 2% experienced with some products.

Photo: Bob Rueter

An energy audit revealed this aging urea-formaldehyde insulation in a warehouse wall. This was a popular retrofit insulation material in the 1970s.

Cementitious Foam (Air Krete)

While all the other sprayed or injected foam insulation materials are foamed plastics (organic chemicals, derived from petroleum), there is one inorganic, cementitious foam insulation on the market.

Air Krete is made by mixing magnesium oxychloride cement with water, compressed air, and an expanding agent. During installation, the foam has the consistency of shaving cream. The lightweight foam is fireproof without flame retardants, pest-resistant, moisture-resistant, decay- and mold-resistant, and nontoxic. For some chemically sensitive individuals, this may be the only insulation material that can be tolerated.

Air Krete also has downsides. Most notably, for several years its manufacturer has been claiming that the product has an R-value of R-6 per inch, citing alternative test methods that don't comply with Federal Trade Commission (FTC) rules. That level of performance isn't credible, based on BuildingGreen's analysis and that of other experts we've spoken with, and the company does not offer a plausible reason for using an alternative test method. The company also falls short on other areas of performance testing and disclosure, particularly for a product that appeals to projects pursuing high performance with high expectations for chemical disclosure. Read more in BuildingGreen's article, "What About Air Krete? A Deeper Look at the Insulation Alternative."

Insulation forms

- Injected into closed wall cavities and concrete masonry units.
- Used in new wood-frame construction by spraying into an open cavity or injecting through a taut, permeable polypropylene fabric installed flush with the face of studs.

Health and environmental attributes

Raw materials and recycled content

- Magnesium oxide cement derived from seawater.
- No recycled content.

Pollution from manufacture

- Some energy consumption, but energy intensity unknown; petroleum products not used in material.
- The manufacturer says that it removes some carbon dioxide during curing. Similar to Portland cement, magnesium oxide requires calcination during production. This process produces carbon dioxide, some of which is taken up during the curing process but does not account for as much CO_2 as is emitted during production.

Hazardous constituents

- None known: No blowing agents other than compressed air, no flame retardants, and no formaldehyde or other VOCs.

Performance

- R-value: R-3.9 per inch at 75°F and standard density of 2.07 lb/ft^3; lower R-value when installed at higher density to achieve greater resistance to vibration (see below). Note: the manufacturer claims that Air Krete has an R-value of R-6 per inch, but BuildingGreen does not consider this claim credible.

Photo: Ryan Somma

Air Krete from The Goodson House: A Living Green Demonstration Building in Virginia.

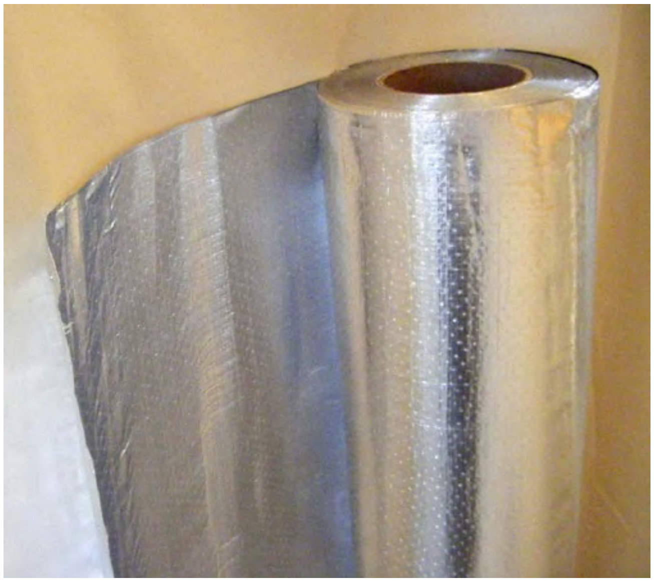
MANUFACTURER

Air Krete
www.airkrete.com

- No shrinkage if properly installed, according to the manufacturer. However, some installers have reported moderate shrinkage occurring in the weeks after installation, which would compromise the insulation and air-barrier properties.
- Excellent acoustical properties, leading the insulation to be used in some sound studios.
- Fire proof with the following ratings: 0 smoke developed, 0 flame spread; 0 fuel contribution.
- Friable: There is a concern that, at standard density, the cured insulation is fairly friable and may degrade if exposed to significant vibration—such as in a building along a busy street with heavy truck traffic.

Radiant Barriers and Other Miscellaneous Insulation Materials

Along with conventional types of insulation, there are a few miscellaneous types that deserve mention in this report.



A radiant barrier roll

Radiant Barriers

Radiant barriers work by reflecting heat radiation or by not emitting thermal radiation as readily as other materials (see page 11). As a result, radiant barriers only work when positioned next to air spaces—a phenomenon that is very important and sometimes not understood. Be aware that the insulative performance of radiant barriers is very dependent on the configuration (the benefit in a horizontal installation is greater than the benefit in a vertical installation because of convection dynamics) as well as the proximity to an air space. Also be aware that manufacturers often exaggerate the energy benefits of radiant barriers. Finally, since radiation is a surface phenomenon, any change to the surface significantly affects its performance. Dirt, dust, moisture or any change to the texture of the surface increases the material's emissivity and reduces its impact as a radiant barrier.

Insulation forms

- Single-layer radiant barrier: Usually an aluminum-foil layer adhered to plastic (usually polyethylene or polyester); may be reinforced. May be reflective on one or both sides; often perforated to increase permeability. Can be attached to underside of rafters or top chords of roof trusses (foil facing up or down), secured to the underside of floor joists, or used in other applications where the foil will face an air space.
- Foil facing on insulation: Polyisocyanurate insulation is commonly faced with foil, and some fiberglass batts have foil facing. The very-low-permeability foil helps retain the low-conductivity blowing agent in the polyiso insulation. With both polyiso and fiberglass, foil facing will moderately improve energy performance if it is next to an air space.
- Foil facing on sheathing and other substrates: Radiant oriented-strand board (OSB) and paperboard (e.g., ThermoPly) sheathing can achieve much the same benefit as a separate radiant layer but with just one component (the sheathing).
- Reflective bubble-pack insulation: Using aluminized plastic in a bubble-pack configuration with the reflective surface facing the air space of the bubble-pack significantly improves performance compared with a stand-alone radiant barrier or bubble-pack without the reflective surface. Products with two layers of bubble pack are also available, further improving performance in the right application. With some products, rather than a bubble-pack product, the foil is attached to a polyethylene foam, with a lot of tiny bubbles.
- Radiant barrier paints: So-called radiant-barrier or ceramic paints have not been demonstrated to provide appreciable energy benefit, or even to technically qualify under the definition of radiant barriers (emissivity of 0.1 or less). The oft-repeated claim "tested by NASA" is evidence of exaggeration. A radiant coating may provide a huge benefit in outer space—where radiant heat flow is the only form of heat transfer (because there is no air) and where differences in temperature between inside and outside a space vehicle are huge—but those savings are not relevant to terrestrial applications.

Health and environmental attributes

Raw materials and recycled content

- Little if any recycled aluminum in most radiant barriers. Manufacturers claim that the very thin layer of these foils and the need for a highly reflective surface preclude the use of recycled content.
- Some manufacturers offer reflective bubble-pack products with some recycled polyethylene.

Pollution from manufacture

- Aluminum production is energy-intensive, and mining the raw material, bauxite, is highly destructive in some tropical regions.

Health considerations

- Offgassing and other health concerns from radiant barriers are not considered significant.

Performance

- R-value: Insulation contributed by a radiant barrier is highly dependent on configuration. There is greater benefit with horizontal applications than vertical because of convective loops within the airspace provided by the radiant barrier. Reduction in downward heat flow is greater than reduction in upward heat flow. Scrutinize R-value claims very carefully.
- Radiant barriers vs. thermal insulation: In attics—the most common application for radiant barriers—the benefit from radiant barriers is inversely proportional to the amount of thermal insulation in place. With more insulation (fiberglass, cellulose, etc.), the radiant barrier will have less effect. Most claims of significant benefit from radiant barriers assume very little insulation. In most cases, it makes more sense to install additional insulation than to install a radiant barrier.
- Cooling load reductions: In unheated attics, radiant barriers installed on the underside of the roof sheathing (with an air space) or on the bottom face of rafters or roof trusses, there will be some benefit in reduced heat gain from sunlight striking the roof, though with a reasonable amount of insulation in the floor of the attic the actual benefit from the radiant barrier will be low.
- Moisture: Radiant barrier products typically involve plastic sheeting and foil that are impermeable to vapor flow. These materials are inherently resistant to moisture damage (although when combined with a material like polyiso, may not be moisture-resistant) but also restrict drying potential of building assemblies.

TRADE ASSOCIATION AND SAMPLING OF MANUFACTURERS

Reflective Insulation Manufacturers Association International (RIMA-I)
www.rimainternational.org

Fi-Foil Company
(Silver Shield Attic Radiant Barrier)
www.fifoil.com

Innovative Energy, Inc.
(AstroShield and astroECO reflective bubble-pack)
www.insul.net

Innovative Insulation,Inc.
(Super R radiant barriers, TempShield radiant bubble-pack)
www.radiantbarrier.com

LP Building Products (TechShield radiant-barrier OSB sheathing)
www.lpcorp.com

continued on the next page

Photo: SOLEC-Solar Energy Corporation

Reflective paints can, properly chosen, help reduce solar gain in attics and are easier to install than foils. However, they don't qualify as radiant barriers and don't offer any benefit in most applications.

TRADE ASSOCIATION AND SAMPLING OF MANUFACTURERS

RadiantGuard (radiant barrier and reflective insulation)
www.radiantguard.com

Reflectix, Inc. (Reflectix line radiant barriers and reflective bubble-pack)
www.reflectixinc.com

RoyOMartin (Eclipse radiant barrier OSB sheathing)
www.royomartin.com

Gas-Filled Panels

Gas-filled panels represent a new type of insulation, borrowing from the window industry. Metalized polyethylene is used to create airtight honeycomb baffles that hold low-conductivity gas, based on technology developed by Lawrence Berkeley National Laboratory (LBNL) and licensed to FiFoil, (a manufacturer of radiant barriers) the sole producer of such a product. The panels are filled onsite with argon, krypton, or xenon gas, or they are allowed to inflate passively with air. The reflective (low-emissivity) properties of the material aid in its energy performance.

Insulation form

- Honeycomb baffles of metalized polyethylene creating one-inch-thick insulation panels with three or four layers of air or low-conductivity gas. Product is shipped flat (unexpanded) and inflated onsite, either passively with air or using canisters of low-conductivity gas.

Health and environmental attributes

Raw materials and recycled content

- Not known to contain any recycled content

Pollution from manufacture

- Aluminum production is energy-intensive, and mining the raw material, bauxite, is highly destructive in some tropical regions.

Health considerations

- Offgassing and other health concerns from radiant barriers are not considered significant. Low-conductivity gases (argon, krypton, and xenon) are inert—non-reactive—so do not pose a risk to occupants if they leak out.

Performance

- R-value for 1” panels up to R-11. See table below.

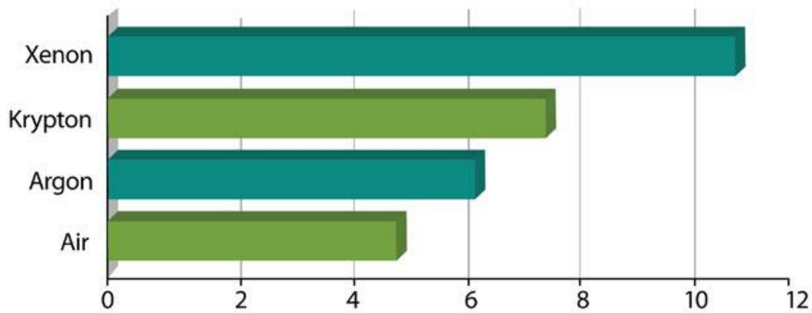
Photo: University of California

Sample gas-filled panel

MANUFACTURER

Fi-Foil Company
(GFP Insulaiton)
www.fifoil.com

Figure 3: R-value for Gas-Filled Panels Using Different Gases



Source: Fi-Foil Company

Transparent Insulation

Often referred to as "transparent insulation" these are really *translucent* (allowing diffuse light to pass, but not see-through) panels and can be used for glazing applications where diffused daylighting is desired along with reasonably high insulation. They are used primarily in commercial buildings but are not common.

They provide a relatively high R-value yet can transmit more than 50% of sunlight striking the panels. Thus, in addition to providing thermal insulation, these transparent insulation systems provide daylighting and solar heat gain; depending on the application, they can provide a greater net energy benefit than opaque insulation—though potential for unwanted solar heat gain is also a consideration.

Insulation forms

- Glazing panels containing silica aerogel: Silica aerogel is the lightest-weight solid known, and it insulates better than any other insulation material (other than vacuum panels), due to the low conductivity of the silica, the high percent of gas (as opposed to solid), and the circuitous path of conductive heat flow across the material. Cabot Corporation makes a granular silica aerogel (Lumira) that is used in these glazing panels made by various manufacturers.
- Glazing panels containing fiberglass: At least one manufacturer, Kalwall Corporation, offers daylighting panels that use translucent fiberglass to boost insulation levels.
- Glazing panels with acrylic honeycomb matrix interlayer: Advanced Glazings, Ltd., produces transparent insulation in which an acrylic honeycomb matrix is secured between two layers of glass. The glazing diffuses light, yet insulates reasonably well and provides significant solar heat gain. (Advanced Glazings also provides a glazing panel insulated with Lumira aerogel.)

Health and environmental attributes

Raw materials and recycled content

- There is some recycled content in Kalwall products. No recycled content is known to be in Advanced Glazings' products.

Pollution from manufacture

- Unknown

Health considerations

- Some glazing systems containing transparent or translucent insulation (from manufacturers other than Kalwall or Advanced Glazings) use polycarbonate, which contains bisphenol-A (BPA), an endocrine disruptor.

MANUFACTURERS

Advanced Glazings, Ltd. (Solera)
www.advancedglazings.com

Kalwall Corporation
www.kalwall.com

Cabot Corporation (Nanogel)
www.cabotcorp.com

Performance

- For 2”-thick Kalwall glazing panels with fiberglass-reinforced polyester glazing (translucent fiberglass sheet) and Lumira (silica aerogel) fill, the U-factor is as low as 0.05 (R-20), with visible light transmittance from 12%–20%, solar heat gain coefficient (SHGC) of 0.12–0.22, and acoustic insulation of 35 STC.

- Kalwall glazing panels are also offered with fiberglass insulation fill, resulting in lower R-values and lower light transmission relative to those filled with aerogel.

- Advanced Glazings also offers Solera products using aerogel. These products incorporate an acrylic honeycomb interlayer with U-factors as low as 0.04 (R-22), visible light transmittance as high as 20%, and a solar heat gain coefficient as high as 1.9. Sound transmission class may exceed 52, according to the company. Performance ranges widely depending on glass specified. Advanced Glazings also offers Solera products without aerogel; these have U-factors as low as 0.47 (R-2.7). Light transmittance on these is as high as 62%, SHGC goes up to 0.58, and STC is up to 40.

Vacuum Insulation

Like Thermos bottles, a vacuum insulation panel (VIP) works by removing air molecules from a mostly hollow panel. With little air, both gas-phase conductivity and convection of heat are greatly reduced, leaving radiant heat transfer and conduction through the edges of panels as the primary means of heat flow. With low-emissivity interior surfaces such as stainless steel in a vacuum panel, radiant heat transfer is also reduced. Most VIPs include a rigid substrate, often fumed silica (a solid matrix of aggregated amorphous silica particles that result in tiny air spaces—and often referred to as "microporous"), that insulates reasonably well even without the vacuum; that substrate is wrapped with stainless steel.

Even with a relatively modest vacuum, VIPs can provide up to R-50 per inch in the center of panel (though considerably lower when factoring in greater thermal conductivity at the panel edges). Most vacuum insulation today is produced for specialized applications, such as cryogenic (super-low-temperature) refrigeration and industrial applications, but some vacuum insulation panels are finding their way into appliances, exterior doors, and building envelopes. With some applications, such as refrigeration, the high cost is justified by the much thinner profiles and resultant space savings.

R-50 Insulation Systems is now offering a 1.5" VIP with two layers of high-density polyiso for protection. It has an R-value of 50 and sold primarily as a commercial roofing insulation, but it could also be used with cladding systems that do not require nailing or penetrating the insulation. Kingspan also has VIPs with a similar R-value.

Insulation form

- Rigid stainless steel panel with structural support keeping the skins from sucking together. After vacuum is drawn, panels are hermetically sealed.

Health and environmental attributes

Raw materials and recycled content

- Recycled content can be assumed in the stainless steel.

Pollution from manufacture

- Stainless steel manufacturing involves chromium, the mining and processing of which may carry environmental and health burdens. Steel also has a high carbon footprint.

Health considerations

- No blowing agents or other chemical constituents are used in achieving insulating properties.

Performance

- R-value: Center-of-panel R-value for 1.5" panels currently used in architectural applications is approximately R-50.
- In vacuum insulation panels with a microporous substrate, such as fumed silica, if the vacuum is lost, the R-value can still be as high as R-8 per inch.
- A much softer vacuum, which is easier to contain, could achieve nearly as good performance if drawn across silica aerogel—which is the highest insulating material under standard atmospheric conditions.
- Vulnerability: Even a pinhole leak in most vacuum insulation panels will drop its insulating performance dramatically, so this is a fairly vulnerable insulation material, particularly when used in buildings.

MANUFACTURER

NanoPore Insulation
www.nanopore.com

Panasonic (U-Vacua)
eu.industrial.panasonic.com

Va-Q-tec AG
www.va-q-tec.com

Vacu-Isotec KG
www.vacu-isotec.de

Key Environmental and Performance Factors for Insulation Materials

Insulation Type		R-value Per Inch*	Vapor Permeability†	Air Barrier‡	Environmental Notes (see below for legend)
FIBER, CELLULOSIC, AND GRANULAR					
Fiberglass	Batt	3.3	Class III: Semi-Permeable	Not an air barrier—batts especially susceptible to air infiltration	
	Blown-in	3.8			
	Spray-applied	3.7–4.2			
Cellulose	Spray-applied	3.8–3.9	Class III: Semi-Permeable	Not an air barrier, but dense-packed cellulose enhances air resistance of an assembly	
	Loose fill	3.6–3.7			
Mineral wool		3.3	Class III: Semi-Permeable	Not an air barrier	Avoid formaldehyde binders for interior products
Cotton		3.4	Class III: Semi-Permeable	Not an air barrier	
Sheep's wool		3.5	Class III: Semi-Permeable	Not an air barrier	Natural, biobased product, but requires water and harsh detergents for processing
Perlite		2.4–3.7	Class III: Semi-Permeable	Not an air barrier	Rare, but does not require flame retardants or pesticides

About the Environmental Notes

Green indicates significant **recycled content** or renewable material. Red indicates little or no recycled content and fossil-fuel-based materials in typical products.

Green indicates low **embodied energy**. Red indicates high embodied energy and/or embodied carbon.

Green indicates relatively low **toxic emissions** during use from typical products. Red indicates potential high toxic emissions from typical products.

Red indicates high toxic emissions during manufacturing or application.

Blue in all cases indicates ambiguity—explanatory notes are provided in all cases.

Notes are provided for red indications in some cases.

Please see page 87 for endnotes.

Continued on the next page

Insulation Type	R-value Per Inch*	Vapor Permeability†	Air Barrier‡	Environmental Notes (see below for legend)
RIGID BOARDSTOCK				
Polyisocyanurate	6–6.5	Class II: Semi-Permeable Class I: Impermeable (Foil-faced)	Air barrier material	High global warming potential for urethane-core SIPs Chlorinated flame retardant (otherwise fairly inert) Potentially hazardous manufacturing process
Phenolic Foam	7–8	Class II: Semi-Permeable	Air barrier material	Phenol formaldehyde content, but low emissions
Extruded polystyrene (XPS)	4.8–5	Class II: Semi-Permeable (>1″) Class III (<1″)	Air barrier material	Potentially hazardous manufacturing process Some still contain high-global-warming-potential blowing agents
Expanded polystyrene (EPS)	3.7–4.5	Class II Vapor Retarder	Not an air barrier	Potentially hazardous manufacturing process
Mineral wool	2.4–3.3	Class III Vapor Retarder	Not an air barrier	Choose low-emitting products Formaldehyde (a carcinogen) binders are common
Fiberglass	3.6–4.5	Class III Vapor Retarder	Not an air barrier	Formaldehyde (a carcinogen) binders are common

About the Environmental Notes

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Please see page 87 for endnotes.

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Key Environmental and Performance Factors for Insulation Materials (cont.)

Insulation Type	R-value Per Inch*	Vapor Permeability†	Air Barrier‡	Environmental Notes (see below for legend)
RIGID BOARDSTOCK continued				
Cellular glass	3.0	Class I Vapor Retarder (Vapor barrier, unless perforated)	Air barrier material	
Expanded cork board	3.6	Class III Vapor Retarder	Not an air barrier	Shipped from Europe
Low-density wood fiber	3.1–3.7	Class IV Vapor Retarder (Permeable)	Some forms can be an air barrier	Shipped from Europe
Perlite board	2.7	Unknown	Air barrier material	Uses asphalt binder
FOAM-IN-PLACE				
Closed-cell polyurethane	3.3–5.0	Class II Vapor Retarder	Air barrier material	High-global-warming-potential blowing agents Offgassing under investigation by EPA Chlorinated flame retardant Highly toxic when applied
Open-cell polyurethane	3.3–5.0	Class III Vapor Retarder	Varies by type: some types are air barrier materials, some control air leakage but are not air barriers	Offgassing under investigation by EPA Chlorinated flame retardant Highly toxic when applied
Urea- and phenol-formaldehyde foam	4.5–4.8	Unknown	Performance over time unknown	
Cementitious foam (Air-Krete)	3.9	Vapor-permeable	Unknown—assumed to be air permeable due to fragile foam consistency	

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Key Environmental and Performance Factors for Insulation Materials (cont.)

Insulation Type	R-value Per Inch*	Vapor Permeability†	Air Barrier‡	Environmental Notes (see below for legend)
MISCELLANEOUS				
Vacuum panels	30–50	Class I Vapor Retarder (Vapor barrier)	Based on their configuration, these materials are usually air barriers but are not typically used at the building scale to create an air barrier assembly.	See body of report for more information. These materials tend to be used in specialized applications; difficult to compare impacts with other common insulation materials.
Radiant barriers	N/A	Class I Vapor Retarder (Vapor barrier unless perforated)		
Gas-filled panels	5–11 (Depends on type of gas fill)	Class I Vapor Retarder (Vapor barrier)		
Translucent panels	3.9	Class I Vapor Retarder (Vapor barrier)		

About the Environmental Notes

Green indicates significant **recycled content** or renewable material. Red indicates little or no recycled content and fossil-fuel-based materials in typical products.

Green indicates low **embodied energy**. Red indicates high embodied energy and/or embodied carbon.

Green indicates relatively low **toxic emissions** during use from typical products. Red indicates potential high toxic emissions from typical products.

Red indicates high toxic emissions during manufacturing or application.

Blue in all cases indicates ambiguity—explanatory notes are provided in all cases.

Notes are provided for red indications in some cases.

* Ranges reflect the variability of products, and for some spray-applied products, a range of installed densities.

** Cost estimates are provided by Vermeulens Cost Estimating and Davis Langdon, and are intended to be relevant throughout the U.S. However, we are not able to anticipate specific project conditions that may be relevant, such as scale, scope, new vs. retrofit, or unique design conditions. Use only as a rough guide to aid decision-making.

† Vapor retarders have four classes:
Class I: less than 0.1 perms – Impermeable (e.g., polyethylene)
Class II: 0.1–1.0 perm – Semi-impermeable (e.g., kraft paper)
Class III: 1.0–10.0 perms – Semi-permeable (e.g., latex paint)
Class IV: greater than 10.0 perms – Permeable (e.g,, Tyvek)

‡ The Air Barrier Association of America (ABAA) defines an air barrier material as having a maximum allowable air leakage rate of 0.02 liters/second/m^2 at 75 Pascals pressure difference.

Air-barrier materials must be joined with other air-barrier materials to make an air-barrier assembly, and assemblies join to form a continuous air-barrier system for a building. Air-barrier insulation materials can contribute to those assemblies; insulation materials that are not air barriers may be part of the assembly, but other materials should be relied upon for the air barrier.

See the text of this report for more detail on all attributes.

For more background on which insulation products perform well in different applications, and our overall recommendations on materials, see the table on page 86.

Sources: Material data compiled from *ASHRAE Fundamentals* and from other industry sources. This is only a guide: check with specifier, manufacturer, and contractor on specific expectations for your project. Simply specifying the material may not get you the R-value shown above, due to variations in products and installation practices.

Bottom-Line Insulation Material Recommendations

This table presents BuildingGreen's top picks of insulation materials for different applications. Our recommendations are focused on insulation materials, not insulation design and best practices. It is critically important to address moisture dynamics, airflow, and how different materials in the assembly—including insulation—interact to deliver the desired performance and durability. Thermal properties, control of air leakage, and moisture management (see page 27) all interact and should be considered together. Doing so ensures durability of the overall assembly and building—a major environmental benefit that transcends material choice. Use this table as a reference for choosing materials, alongside other resources, including professional help.

Recommended Insulation Materials	Environmental Issues	Performance and Cost Issues
COMMERCIAL CAVITY FILL None of the following recommended products are air barriers; include a continuous air barrier separately from the insulation with all cavity-fill insulation options. All of the following products are vapor-permeable, although hygroscopic properties differ considerably. Insulation choices may be affected by the cavity design, framing materials, and other factors.		
✓ **BuildingGreen Top Pick** **Spray-applied or dense-packed fiberglass**	Spider Plus from Johns Manville has 35% post-consumer recycled content. Higher embodied energy than cellulose. Fire-resistant without flame retardants.	Impedes air leakage, not susceptible to moisture. Installation in an open cavity may be possible without netting. "Blow-in-Blanket" systems require netting on the interior faces of framing members.
Formaldehyde-free mineral wool batts	Higher recycled content than fiberglass but higher embodied energy than cellulose and potential formaldehyde emissions. Formaldehyde-free products are now available.	Excellent fire and acoustical qualities. Compared to spray-applied fiberglass, greater potential for gaps and poor installation; follow manufacturer guidelines.
Dense-packed cellulose	Higher recycled content and lower embodied carbon than fiberglass.	Recommended for wall cavities with good moisture management and drying potential in at least one direction.
RESIDENTIAL STUD AND JOIST CAVITY FILL See note above on similar considerations relevant to commercial cavity fill. Also note that due to fire codes and other considerations in residential construction, our recommendations here are somewhat different.		
✓ **BuildingGreen Top Pick** **Dense-packed cellulose**	Low embodied energy and carbon. Renewable, high recycled content. Some concern over borate flame retardant toxicity.	Fills cavities completely, impedes air leakage. Settling is not a factor with dense-packing. Hygroscopic: can help manage moisture by seasonally absorbing and releasing water vapor as long as at least one side of the assembly is vapor-permeable, and as long as the wetting rate does not exceed the drying rate on an annual basis.
Spray-applied or dense-packed fiberglass	Higher embodied energy than cellulose. High recycled content but not a renewable material.	Fills cavities completely, impedes air leakage at higher densities.

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Recommended Insulation Materials	Environmental Issues	Performance and Cost Issues
RESIDENTIAL STUD AND JOIST CAVITY FILL (cont).		
Mineral wool batts	Higher embodied energy than cellulose. Some emissions concerns from formaldehyde-based binder. Formaldehyde-free batts are now available.	Use when greater fire rating is desired or as a superior option (compared to fiberglass batts) for small jobs. Harder to source than fiberglass.
Air-Krete, cotton batts, or dense-packed wool	Use when the owner has unique air quality concerns about other options.	More expensive than other options and harder to source. Specific performance downsides by insulation type: see body of report.
Fiberglass batts	Higher embodied energy; often poorly installed (see performance issues).	Difficult to install well (requires time to cut carefully around irregularities). Use only for budget-conscious jobs too small for an insulation contractor and where mineral wool batts are not available.
EXTERIOR INSULATING SHEATHING Exterior insulation should be thick enough to maintain the dew point within the material (recommended thickness depends on climate and other factors). Note that the products recommended here have different vapor permeability: polyiso is impermeable if foil-faced, and mineral wool may be impermeable depending on the facing. Design assemblies appropriately for moisture management (see page 26).		
✓ **BuildingGreen Top Pick** **High-density rigid mineral wool**	Available with high recycled content. Excellent sound control; insect- and moisture-resistant; some concern about formaldehyde emissions.	Available faced or unfaced. Can be difficult to source and requires tricky detailing for many types of siding.
Low-GWP extruded polystyrene (XPS)	Now made with low-GWP blowing agents. Pollution issues during manufacturing. HBCD flame retardant has been replaced with a polymeric one, but the replacement is still halogenated and persistent in the environment.	Use if rigid mineral wool is unavailable or there is strong resistance to its use. Specify higher-density EPS than standard. Type II or Type IX is recommended.
Phenolic Foam	No flame retardant; made with phenol formaldehyde.	Highest R-value of non-vacuum boardstock insulation materials. On foil-faced products, benefit of radiant barrier if installed with strapping.
Foil-faced polyisocyanurate	Commonly used in roofing applications. Halogenated flame retardant in most products.	High R-value. Affordable. Adds the benefit of a radiant barrier if installed with strapping.
EXTERIOR FOUNDATION WALL		
✓ **BuildingGreen Top Pick** **High-density rigid mineral wool**	Hydrophobic, so it provides an excellent drainage layer.	Harder to install and cover than more common options. Sourcing may be a challenge.
Cellular glass	High compressive strength, impermeable to moisture, no blowing agents or flame retardants.	High cost—use if budget permits. Special installation required, including protection during backfilling and exterior protective coating. Follow manufacturer's instructions.

Continued on the next page

Recommended Insulation Materials	Environmental Issues	Performance and Cost Issues
EXTERIOR FOUNDATION WALL **(cont.)**		
Low-GWP extruded polystyrene (XPS)	Now made with low-GWP blowing agents. Pollution issues during manufacturing. HBCD flame retardant has been replaced with a polymeric one, but the replacement is still halogenated and persistent in the environment.	Use if rigid mineral wool is unavailable or there is strong resistance to its use. Specify higher-density EPS than standard. Type II or Type IX is recommended.
Expanded polystyrene (EPS)	Pollution issues during manufacturing. HBCD flame retardant has been replaced with a polymeric one, but the replacement is still halogenated and persistent in the environment.	Use if rigid mineral wool is unavailable or there is strong resistance to its use. Specify higher-density EPS than standard. Type II or Type IX is recommended.
INTERIOR FOUNDATION WALL		
✓ **BuildingGreen Top Pick** **Polyisocyanurate**	Relatively high embodied energy, but blowing agents with high global warming potential (GWP) have been eliminated. Contains flame retardant.	Use on poured concrete and CMU walls that provide a relatively flat surface. After one layer of foam board, adding a stud wall with mineral wool or fiberglass is recommended for added insulation depth.
Low-GWP extruded polystyrene (XPS)	Now made with low-GWP blowing agents. Pollution issues during manufacturing. HBCD flame retardant has been replaced with a polymeric one, but the replacement is still halogenated and persistent in the environment.	Use if rigid mineral wool is unavailable or there is strong resistance to its use. Specify higher-density EPS than standard. Type II or Type IX is recommended.
Phenolic Foam	No flame retardant; some concern about formaldehyde emissions.	Highest R-value of non-vacuum boardstock insulation materials. On foil-faced products, benefit of radiant barrier if installed with strapping.
Closed-cell spray polyurethane foam (SPF)	Most closed-cell SPF has high global warming potential (GWP) and chlorinated flame retardant, but products now available with low-GWP HFO blowing agents.	May be the only viable option for installing insulation against uneven wall surfaces. Install only 2”-thick “lifts” to avoid high-temperature risks.
SUB-SLAB RIGID INSULATION		
✓ **BuildingGreen Top Pick** **High-density rigid mineral wool**	No blowing agents or flame retardants.	Manufacturers all used to recommend against this application, but at least one, Rockwool, now accepts sub-slab for its high-density Comfort Board.
Cellular Glass	No blowing agents or flame retardants. Available as aggregate, so it doubles as insulation and fill.	Relatively high cost and hard to source. High compressive strength; impermeable to moisture. Bitumen facing is available for greater abrasion resistance during installation. Special installation is required; follow manufacturer’s instructions.

Continued on the next page

Bottom-Line Insulation Material Recommendations (cont.)

Recommended Insulation Materials	Environmental Issues	Performance and Cost Issues
SUB-SLAB RIGID INSULATION **(cont.)**		
Low-GWP extruded polystyrene (XPS)	Now made with low-GWP blowing agents. Pollution issues during manufacturing. HBCD flame retardant has been replaced with a polymeric one, but the replacement is still halogenated and persistent in the environment.	Use if rigid mineral wool is unavailable or there is strong resistance to its use.
Expanded polystyrene (EPS)	Pollution issues during manufacturing; HBCD flame retardant has been replaced with a polymeric one, but the replacement is still halogenated and persistent in the environment.	Use if rigid mineral wool or cellular glass is unavailable or unacceptable. For greater strength and reduced moisture absorption, specify higher-density EPS: Type II or Type IX is recommended.
ATTIC FLOOR INSULATION A continuous air barrier is often critically important at the attic floor; none of the following recommended products provide that. For good detailing, use drywall or oriented-strand board with taped joints, or selectively apply spray polyurethane foam. Wind-washing, in which convection through attic insulation reduces effective R-value, can be a problem with some products—use practices and products that prevent this.		
✓ **BuildingGreen Top Pick** **Loose-fill cellulose**	Low embodied energy and carbon. Renewable; high recycled content.	Vapor-permeable; impedes airflow better than loose-fill fiberglass. Use “stabilized” cellulose with a small amount of acrylic binder to prevent settling, or install extra thickness to allow settling while maintaining desired R-value.
Spray-applied fiberglass	Higher embodied energy than cellulose; use if particularly concerned about moisture accumulation.	JM Spider fills penetrations well, impedes airflow relatively well and reduces wind-washing. The binding power of the timber structure prevents settling.
Perlite	Moderate embodied energy from mining, transporting, and expanding perlite, but lower than most other insulation materials except cellulose.	Use if low-density (high R-value) perlite is available regionally. Potential for wind-washing, so install a convection barrier, such as a 3" (min.) layer of loose-fill cellulose on top of the perlite layer. Reusable.
RAFTER INSULATION (CATHEDRAL CEILING) Refer to building codes for specific design requirements for vented and unvented assemblies.		
✓ **BuildingGreen Top Pick** **Dense-packed cellulose**	Low embodied energy and carbon. Renewable; high recycled content.	Fills cavities completely, effective at blocking air leakage. Dense-packed installations maximize R-value while preventing settling.
Spray-applied or dense-packed fiberglass	Higher embodied energy than cellulose but lighter-weight.	Use if there is strong concern about moisture accumulation or the weight of cellulose.
Open-cell polyurethane	Higher embodied energy than cellulose. Contains chlorinated flame retardant.	Use in situations where superb air-sealing would otherwise be difficult.

Continued on the next page

Bottom-Line Insulation Material Recommendations (cont.)

Recommended Insulation Materials	Environmental Issues	Performance and Cost Issues
RAFTER INSULATION (CATHEDRAL CEILING) (cont.)		
Fiberglass batt	Higher embodied energy than cellulose. Often poorly installed (see performance issues).	Difficult to install well (requires time, cutting carefully around irregularities). Use only for budget-conscious jobs too small for an insulation contractor.
LOW-SLOPE ROOF INSULATION (COMMERCIAL CONSTRUCTION)		
✓ **BuildingGreen Top Pick** **Organic- or fiberglass-faced polyisocyanurate**	Relatively high embodied energy, but high-GWP blowing agents have been eliminated.	High R-value per inch; can serve as an air barrier with taped joints. Widely available; known to contractors. Not suitable for Inverted Roof Membrane Assembly (IRMA) due to moisture properties.
High-density rigid mineral wool	Relatively high embodied energy; fire-resistant without flame retardants.	Thicker layer required compared with polyiso to achieve same R-value— extra thickness also adds weight. Check with the manufacturer about suitability for IRMA.
Phenolic Foam	No flame retardant; some concern about formaldehyde emissions.	Highest R-value of non-vacuum boardstock insulation materials. On foil-faced products, benefit of radiant barrier if installed with strapping. Little experience with product in North America; may be harder to source.
Low-GWP extruded polystyrene (XPS)	HBCD flame retardant has been replaced with a polymeric one, but the replacement is still halogenated and persistent in the environment.	Recommended if doing an IRMA installation for performance reasons and other options are not feasible.

BuildingGreen's Building Envelope Energy Performance Recommendations

How much insulation is enough? How airtight should a home be? What window and door specifications should you look for? BuildingGreen's building envelope recommendations (see table above) are aimed at defining high-performance goals for homes and low-rise buildings that we believe all buildings can reasonably achieve.

Coupled with wise selection of appliances, lighting, and mechanical systems, these insulation levels should achieve performance suitable for net-zero-energy buildings using rooftop or ground-mounted solar-electric (PV) modules. (In some cases they may be enough to qualify for Passive House certification, but Passive House design requires more detailed specifications.)

Our recommendations have been influenced by numerous sources, including Building Science Corporation, Vermont Energy Investment Corporation, and various building codes. They apply most directly to new construction, but can be used with deep energy retrofits of existing buildings as well.

For comparison, we include prescriptive energy conservation standards from the International Energy Conservation Code (IECC 2012), published by the International Code Council. Our recommendations are organized by climate zone: Hot (U.S. Department of Energy Zones 1–2); Moderate (Zones 3–4); Cold (Zones 5–6); and Coldest (Zones 7–8). In some cases, the IECC 2012 requirements are more finely segregated, in which case you will see two numbers or sets of numbers for our climate zone groupings.

Besides our goal of recommending a very high level of performance, there are a few assumptions we made that are worth explaining.

Round numbers

While IECC requirements are often specific to actual products (R-19 or R-38 being relevant to fiberglass batts, for example), we have avoided that and aimed for round numbers, partly in the belief that fiberglass batts are rarely a good choice for building insulation. Our numbers are also whole-wall or whole-unit values, so an R-19 recommendation, tied to a specific product, doesn't make sense.

What About Cost?

The high insulation levels that we recommend may cost more, but the cheapest time to add more insulation is when you first build, and more insulation can reduce mechanical system size and operating costs. What is the right level of insulation from a cost perspective? There's no single right answer to that, but we argue that aiming high is justified: relying on payback analyses based on today's energy prices is misguided when energy prices fluctuate widely, and the effects of climate change are already apparent. Also, resilience benefits are achieved with high levels of insulation—keeping occupants safe in the event of an extended power outage. Elsewhere we have explored the idea of using the cost of onsite photovoltaics as a benchmark for how much one should reasonably spend on energy conservation.

> The cheapest time to add insulation is when you first build.

Attic vs. Roof

Our recommendation for installing more insulation in an attic than in a roof (cathedral ceiling) recognizes differences in the cost of installations. It is generally a lot less expensive to install insulation in a flat ceiling (unheated attic floor), so more insulation can be economically justified than when the insulation goes into a roof system.

Whole-Wall Design Flexibility

The IECC requirements for both cavity-fill and rigid insulation in above-grade walls make sense in addressing thermal bridging, but our recommendations address thermal bridging by focusing on whole-wall insulation recommendations. It may be difficult to achieve a whole-wall insulating value of R-25 in Zone 4, for example, without installing some rigid insulation, but it can be done with double-studs that are offset or a system with non-structural trusses hung off the structural wall. Whole-wall recommendations give the designer or builder flexibility.

Fenestration by Climate and Orientation

With fenestration, the variables we address are U-factor and solar heat-gain coefficient (SHGC). Low U-factors block more heat from escaping through windows, so are particularly important in colder climates. Solar gain contributes to passive solar heating of buildings, which can be beneficial on southern orientations (especially in cold climates, but not limited to cold climates), to daylighting (high-SHGC glass may be desirable on all windows if the window area is small), and to overheating, particularly on east and west facades. Our recommendations reflect these differences by climate and orientation.

Goals for Doors

With doors there are few products today that achieve the listed performance recommendations, so those recommendations can be thought of as aspirational for manufacturers.

Airtightness

Our recommendations range from 1 ACH50 (air changes per hour at 50 pascals of pressure difference) in the coldest climates to 2 ACH50 in warmer climates. These standards aren't as tight as some—the Passive House standard is 0.6 ACH50—but are readily achievable and represent a huge improvement over conventional standards.

BuildingGreen's Recommended Thermal Design Values for Residential New Construction

This table compiles BuildingGreen's (BG) recommended thermal design values for residential new construction and compares them with IECC 2018 code requirements, by climate zone. See the notes below for details on interpreting this table.

<table>
<tr><th colspan="12">RECOMMENDATIONS BY DOE CLIMATE ZONES FOR NORTH AMERICA</th></tr>
<tr><th rowspan="2">Assembly Area</th><th colspan="3">Hot
(Zones 1–2)</th><th colspan="3">Moderate
(Zones 3–4)</th><th colspan="3">Cold
(Zones 5–6)</th><th colspan="2">Coldest
(Zones 7–8)</th></tr>
<tr><th colspan="2">IECC</th><th>BG</th><th colspan="2">IECC</th><th>BG</th><th colspan="2">IECC</th><th>BG</th><th>IECC</th><th>BG</th></tr>
<tr><th colspan="12">BUILDING ENVELOPE R-VALUES</th></tr>
<tr><td>Slab</td><td colspan="2">0</td><td>0</td><td>0</td><td>10</td><td>10</td><td colspan="2">10</td><td>15</td><td>10</td><td>25</td></tr>
<tr><td>Basement wall</td><td colspan="2">0</td><td>10</td><td>5/13</td><td>10/13</td><td>20</td><td colspan="2">15/19</td><td>30</td><td>15/19</td><td>40</td></tr>
<tr><td>Floor above vented crawl space</td><td colspan="2">NA</td><td>15</td><td colspan="2">NA</td><td>25</td><td colspan="2">NA</td><td>40</td><td>NA</td><td>50</td></tr>
<tr><td>Above-grade walls (wood-framed)</td><td colspan="2">13</td><td>15</td><td colspan="2">20 or 13+5</td><td>25</td><td>20 or 13+5</td><td>20+5 or 13+10</td><td>40</td><td>20+5 or 13+10</td><td>50</td></tr>
<tr><td>Ceiling – Flat</td><td rowspan="2">30</td><td rowspan="2">38</td><td>50</td><td rowspan="2">38</td><td rowspan="2">49</td><td rowspan="2">40</td><td colspan="2" rowspan="2">49</td><td rowspan="2">60</td><td rowspan="2">49</td><td rowspan="2">70</td></tr>
<tr><td>Ceiling – Cathedral</td><td>40</td></tr>
<tr><th colspan="12">FENESTRATION</th></tr>
<tr><td>Window U-factor</td><td>NR</td><td>0.40</td><td>0.35</td><td colspan="2">.32</td><td>0.25</td><td colspan="2">0.30</td><td>0.2</td><td>0.30</td><td>0.15</td></tr>
<tr><td>Window SHGC – E, W, N</td><td colspan="2" rowspan="2">0.25</td><td><0.20</td><td rowspan="2">0.25</td><td rowspan="2">0.40</td><td>0.50</td><td colspan="2" rowspan="2">NR</td><td>NR</td><td rowspan="2">NR</td><td>NR</td></tr>
<tr><td>Window SHGC – South</td><td>>0.30</td><td>>0.40</td><td>>0.4</td><td>>0.4</td></tr>
<tr><td>Exterior door (unit U-factor)</td><td colspan="2">NA</td><td>0.30</td><td colspan="2">NA</td><td>0.30</td><td colspan="2">NA</td><td>0.25</td><td>NA</td><td>0.20</td></tr>
<tr><th colspan="12">AIRTIGHTNESS</th></tr>
<tr><td>Airtightness (ACH50)</td><td colspan="2">NA</td><td>2.0</td><td colspan="2">NA</td><td>2.0</td><td colspan="2">NA</td><td>1.5</td><td>NA</td><td>1.0</td></tr>
</table>

Notes on IECC requirements:

- Divided columns indicate that requirements differ by the two climate zones shown, with the hotter climate zone appearing first.
- "15/19" means R-15 continuous insulation on the interior or exterior of the home or R-19 cavity insulation at the interior of the basement wall. "15/19" can be met with R-13 cavity insulation on the interior of the basement wall plus R-5 continuous insulation on the interior or exterior of the home.
- "13+5" means R-13 cavity insulation plus R-5 continuous insulation or insulated siding.
- While including prescriptive requirements such as installation of a continuous air barrier, IECC 2012 does not mandate a specific air-tightness performance figure.
- NR: No recommendation
- NA: Not applicable. IECC does not have specific requirements.

Notes on BuildingGreen recommendations:

- R-values for whole-wall or true R-values in which thermal bridging through higher-conductivity materials has been taken into account.
- For R-values, recommendations are for equal or greater than listed values.
- For U-factors, recommendations are for equal or lower than listed values.
- For SHGC values, recommendations may be greater or lesser than listed values, so greater-than or less-than symbols are shown.
- Unvented crawlspaces should be insulated at the perimeter using basement wall recommendations.

Insulation Options for LEED and the Living Building Challenge

Responding to the shift to LEED v4 and the growing popularity of the Living Building Challenge (LBC), insulation manufacturers are now offering a number of products that comply with various elements of these rating systems.

Evaluating the Impact of Insulation

One of the major changes in LEED v4 was the shift in how building materials are evaluated. The Building Product Disclosure and Optimization (BPDO) credits in the Materials & Resources category emphasize transparency of a product's life-cycle impacts on environmental and human health. Under v4.1, the credits have become easier to meet (and the BPDO part of the credit names has gone away).

When it comes to insulation, some of the new requirements are easy to meet under v4 while others are not. Environmental Product Declarations (EPDs), required by the EPD credit, MRc2, are available for all common insulation types.

Industry-wide or product-specific EPDs are available for mineral wool, polyisocyanurate, extruded polystyrene (XPS), expanded polystyrene (EPS), and spray polyurethane foam (SPF) products. Of the foam insulation types, polyiso and XPS products have the certifications necessary to contribute toward the material ingredients credit, MRc4. But other than a few XPS products that contain recycled content, there are currently no foam products that would contribute toward the sourcing of raw materials credit, MRc3.

There are no products of any type that currently contribute to Option 1 in v4's MRc3, and this transparency option has been removed in v4.1.

Best options: Fiberglass, cellulose, mineral wool

Based on a review of the current marketplace, the best overall options in terms of availability and attributes contributing toward LEED credits are fiberglass, cellulose, and mineral wool products. EPDs are available for several products in these categories. Most fiberglass, cellulose, and slag-based mineral wool products contain a significant amount of recycled content, contributing toward Option 2 of MRc3. Several of these products are also Declare Red List Free, contributing to MRc4 and meeting the requirements of the Materials Petal in the Living Building Challenge.

Wool, Cotton, Cork: Innovating with Biobased Materials

Several biobased insulation products have emerged in recent years. You can now find insulation products made of sheep's wool, recycled denim (cotton), wood, hemp, and cork. Some manufacturers are even developing products made with seaweed and mushrooms.

Under v4, however, none of these products would contribute toward the biobased material criteria in MRc3, which requires that biobased products meet the Sustainable Agriculture Network's (SAN's) Sustainable Agriculture Standard (even though the standard was retired in 2018). This has changed under v4.1, which merely requires ASTM testing verifying the percentage of biobased content for the purposes of credit achievement—but so far, manufacturers don't seem to be pursuing testing.

PRODUCTS

There are several resources for LEED and LBC project teams looking for insulation products that currently comply.

The Clean Economy Manufacturing Center (CEMC) provides a list of products, organized by insulation type, that have published transparency documents or that have been certified by programs like Declare and Cradle to Cradle (C2C).

Teams can also search the Declare Product Database and the HPD Public Repository for insulation products that will contribute toward MRc4.

Our table, on page 97, provides detail on a material-by-material and credit-by-credit level.

Insulation Materials Under LEED v4 and the Living Building Challenge

Insulation type	LEED v4 and v4.1: Building product disclosure and optimization – environmental product declarations	LEED v4 and v4.1: Building product disclosure and optimization – sourcing of raw materials	LEED v4 and v4.1: Building product disclosure and optimization – materials ingredients	Living Building Challenge 4.0 Red List
Fiberglass	Product-specific and industry-wide EPDs are available.	Most fiberglass products contain 40%–60% recycled content.	Some products have a Declare label or HPD.	Fiberglass had historically contained formaldehyde, but it has been phased out of batts, and many rigid board products. Some products are LBC Red List Free.
Cellulose	Industry-wide EPDs are available.	Most cellulose products contain 80% or more recycled content.	Some products have a Declare label or HPD.	Some products are Declare Red List Free, and this product type is unlikely to include Red List chemicals anyway.
Mineral wool	Some products have an EPD.	Most rock wool products contain 10%–15% recycled content, Most slag wool products contain 70%–90% recycled content.	Some products have a Declare label or HPD.	Many rigid mineral wool products contain formaldehyde, but LBC currently offers an exception for this in mineral wool insulation in exterior applications. Some batts are Declare Red List Free or Red List Approved.
Cotton	Does not meet relevant criteria.	Cotton products are likely to contain recycled material. There are no products meeting the SAN Standard for biobased products. Testing for biobased content is possible but has not been pursued by any manufacturers.	Does not meet relevant criteria.	Check with your manufacturer, but cotton insulation products are unlikely to contain Red List chemicals. However, none have Declare labels.
Sheep's wool	Does not meet relevant criteria.	Though currently there are no products meeting the SAN Standard for bio-based products this may change in the future.	Some products have a Declare label.	Some products are Declare Red List Free, and this product type is unlikely to contain Red List chemicals anyway.
Cellular glass	Some products have an EPD.	Most cellular glass products contain recycled content.	Some products have a Declare label.	Check with the manufacturer, but cellular glass is unlikely to contain Red List ingredients.
Polyisocyanurate	Some products have EPDs.	Does not meet relevant criteria.	Several products have a Declare label or HPD.	Some polyiso products are Declare Red List Free because they have no ohalogenated flame retardants. Almost all other foam insulation products include halogenated flame retardants (HFRs), which are banned. But an exception allows for foam with HFRs in certain applications, including structural insulated panels (SIPS), spray insulation for renovation projects, under-slab insulation, and roof and exterior insulation.
Extruded polystyrene (XPS)	Has industry-wide EPD.	Some XPS products contain recycled content.	Some products have a Declare label.	
Expanded polystyrene (EPS)	Has industry-wide EPD.	Does not meet relevant criteria.	Does not meet relevant criteria.	
Spray polyurethane foam (SPF)	Some products have EPDs.	Does not meet relevant criteria.	Some products have an HPD and/or Cradle to Cradle certification	
Aerogel	Some products have an EPD.	Does not meet relevant criteria.	Does not meet relevant criteria.	Does not meet relevant criteria.
Cork	Some products have EPDs.	There are no products meeting the SAN Standard for bio-based products. Testing for biobased content is possible but has not been pursued by any manufacturers.	Does not meet relevant criteria.	Products are unlikely to contain Red List substances.

Source: BuildingGreen, Inc.

AFTERWORD

Z Smith
Eskew+Dumez+Ripple

Architects are generally obsessed with the parts of their buildings that everyone can see, but have less interest in the parts no one sees. So it takes a special kind of writing to make a guide about insulation a real page-turner for architects. In a world where product claims fly freely and where yesterday's wonder-material is today's health hazard, Alex Wilson's writing provides an invaluable resource of balanced information in context.

Whether architects acknowledge it or not, recent developments in insulation are changing face of architectural practice, especially the interactions between building envelopes, the environment, and building occupants.

In the classic work "*American Building: The Environmental Forces that Shape It*", James Marston Fitch made the case that a primary job of buildings is to provide a means of sheltering the human body from the environment: preventing the body from losing too much heat to the environment when it is cold or gaining too much heat when it's hot.

Robert Geddes, among others, has written that if clothing functions as our "second skin," then building envelopes function as our "third skin." In both these conceptions, the building envelope modulates the flow of heat between our bodies and the world outside. In this worldview, the best insulation is something that literally isolates the inside from the outside, preventing the flow of heat entirely.

Yet, in his provocative book *Insulating Modernism*, Kiel Moe questions this premise. While stopping heat flow is the goal for the wall of a refrigerator—where the appliance must maintain one constant temperature inside while it stands in a room being held at another constant temperature—a building faces a different task: to provide a comfortable interior environment as the exterior environment goes through large changes in temperature and solar radiation.

Moe makes the case that the optimal role of a building envelope may not always be one of *isolating* the interior from the exterior, but rather, working *with* available energy flows. A typical example involves using un-insulated high thermal mass walls in climates where there are large temperature swings. In such conditions, building envelopes with relatively poor steady-state thermal resistance (R-value) can still provide great comfort.

I lived for a time in a poorly insulated but thickly plastered home in the dry climate of California's Central Valley, where temperatures on a typical July day might swing from 55°F at night to 93°F in the afternoon. I can attest the thermal mass of those walls kept the temperature around the average—a comfortable 74°F—with little insulation and no air conditioning.

But the story changed when the cloudy, damp winter rolled around, with daily lows of 38°F and highs of 54°F. When the average daily temperature is well outside the range of human comfort, then an un-insulated, heavy-mass wall will result in an uncomfortable radiant environment for occupants. It is then that one learns to appreciate the virtues of insulation.

If Moe's writings remind us that we should pay attention to the dynamic nature of the *exterior* thermal environment in order to make use of "free" energy flows, the Passive House movement has us pay attention to the dynamic nature of the interior environment. Occupants themselves produce "free" heat , as well as generate waste heat from the appliances and lighting they use. In a Passive House located in a cool or cold climate, the insulation value of the building envelope is raised to the point at which conduction through the building skin can be largely balanced by the heat output of building occupants, appliances, and solar energy gained through windows.

We don't really care about making *buildings* comfortable. We care about making *people* comfortable. And the point in time in which we want comfortable temperatures usually aligns with when free heat sources from occupants and appliances are available. Buildings that employ high levels of exposed thermal mass—a concrete floor, thick plaster, or masonry—can actually be problematic, because if allowed to drift colder when unoccupied, they will be slow to warm back up when the occupants arrive.

The Passive House movement has also served to shine light on two dirty little secrets about conventional building envelopes—thermal bridging and air infiltration. When the R-values of wall and roof insulation materials were relatively low, these effects could often be ignored. But the more we raise insulation values, the more important these factors become.

Designers are just beginning to appreciate the subtleties of thermal bridging, and manufacturers are innovating to minimize it.

For decades, insulation was the material that got stuffed haphazardly between the studs. For those practicing primarily stick-frame wood construction, the thermal bridging effect of heat passing more easily through the wood framing than through the insulated cavities is real but modest—reducing a nominal R-19 wall to, say, R-16.

But for those practicing construction using light gauge steel studs, the effects are huge—reducing a nominal R-19 wall to R-6.5. For this reason, both residential and commercial building and energy codes increasingly require at least a portion of the insulation to be continuous (not interrupted by structural or framing members), preferably located outside the building structure. Good in theory, but since insulation itself is rarely a cladding material, there typically needs to be some sort of mechanism—whether clips or girts or tie-backs—that penetrate this 'continuous' insulation to allow cladding to be attached. Likewise, it does little good to clad a building in R-30 walls if concrete floor slabs and balconies punch through to act as giant radiator fins.

Designers are just beginning to appreciate the subtleties of thermal bridging, and manufacturers are innovating all manner of connectors and anchors to minimize it.

High levels of insulation are also of little value if building envelopes allow air to leak in and out. The most recent versions of building energy codes require that building envelopes provide continuous air sealing, some requiring that the level of air sealing achieved be verified through field testing. While air infiltration has been a topic of discussion in residential construction for decades, only recently has testing shown that commercial building envelopes are often every bit as leaky.

This has consequences not just in terms of the energy consumed by mechanical systems to heat, cool, and humidify or dehumidify all this leaking air, but also in terms of the risk for mold and building envelope failure.

For a time, many practitioners sought to prevent the possibility of moisture flow by using low-permeability coatings, only to find that such coatings merely trap moisture that enters through cracks and other real-world penetrations, leading to well-documented disasters. Many architects appear to be shifting toward vapor-permeable, airtight materials that allow vapor drive to aid in drying when water inevitably reaches undesirable locations.

Some insulation materials, such as spray foams, offer the promise of a single system that provides both thermal insulation and air sealing—though these are not always vapor-permeable. Other insulation materials provide little in the way of air sealing and must be combined with a separate air barrier. Architectural practice nationwide is still coming to terms with simultaneously controlling the flow of heat and air and moisture infiltration consistently and relentlessly at every twist, turn, and penetration of the building envelope.

The paradox of insulation materials is that the very best insulation we can imagine would be, literally, nothing. A vacuum would effectively eliminate conduction as a mode of heat flow and also control convection—two of the three modes of heat transfer. The next best options appear to be lightweight materials that trap air or gasses in small bubbles to minimize convective heat transfer. While vacuum panels and exotic materials such as aerogel show promise for the future, most insulation materials in common use are in fact a pretty odd collection of choices, many of them fraught with health concerns and negative environmental impacts.

The very best insulation we can imagine would be, literally, nothing.

As summarized in the tables in this publication on pages 82–89, only a few choices have high recycled content, low embodied energy, and low toxic emissions during use, manufacture, or application. And even these options tend to be down-cycled from other materials streams rather than being amenable to closed-loop reuse. The inherent low density of most insulating materials helps make them hard to economically recycle: a truck full of used insulation from a job demolition site is carrying very little weight of material with comparatively little value as a feed stock for re-manufacturing. If vacuum insulation ever becomes commonplace, there will be literally nothing to recycle! Plenty of nothing.

Faced with all these trade-offs, designers might be sorely tempted to throw up their hands in despair. Thankfully, this guide provides a set of “Bottom-Line Insulation Materials Recommendations” on pages 86–89. These represent the best available choices based on what we know about the choices available today. We give thanks that the authors of this guide have been willing to hold all the conflicting pieces of information and competing goals in their mind and come to some common-sense conclusions. We know that our options and our judgments a decade or two in the future will be different, but this guide helps inform solid decisions based on today’s conditions.

– Z Smith, AIA, LEED Fellow
Eskew+Dumez+Ripple

Z Smith is Principal and Director of Sustainability and Building Performance at Eskew+Dumez+Ripple. His built work includes academic, laboratory and residential buildings earning LEED Gold and Platinum certification, and winners of the RAIC Green Building Award and the AIA COTE Top Ten.

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Alex Wilson, BuildingGreen, Inc.

Alex Wilson

Alex Wilson is the founder of BuildingGreen, Inc. in Brattleboro, Vermont, and for many years was the executive editor of *Environmental Building News* (now BuildingGreen.com). He is a widely published writer, a LEED Accredited Professional, and an instructor with Boston Architectural College's Sustainable Design Institute. He is author of *Your Green Home* (New Society, 2006) and coauthor of the *Consumer Guide to Home Energy Savings* (ACEEE, first edition, 1990, 10th edition 2012) and *Green Development: Integrating Ecology and Real Estate* (John Wiley & Sons, 1998). He has lectured widely on a wide range of topics related to green building, including insulation materials. Alex served on the national board of the U.S. Green Building Council from 2000 through 2005 and received the organization's 2008 Leadership Award for Education. In 2010, he received the second annual Hanley Award for Vision and Leadership in Sustainablity. In 2012, Alex also founded the Resilient Design Institute, a a nonprofit organization working to advance the resilience of buildings and communities.

Continuing Education

AIA and GBCI approved continuing education units (CEUs) for reading this report are available at BuildingGreen.com.

This course has the following learning objectives. Readers will be able to:

- discuss how insulation works to increase the energy efficiency and environmental sustainability of buildings;
- explain why certain materials make more sense than others in particular applications relative to environmental, embodied carbon, human health, and performance criteria;
- summarize how insulation performance is measured and reported;
- describe a variety of assembly details that combine high performance with environmental considerations.

Take the CEU quiz on BuildingGreen.com »