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# Avoiding the Global Warming Impact of Insulation

**Insulation is key to reducing carbon emissions from buildings. But the blowing agents in extruded polystyrene and spray polyurethane foam offset much of that benefit.**

*by Alex Wilson*

TWO COMMON FOAM INSULATION materials are produced with hydrofluorocarbon (HFC) blowing agents that are potent greenhouse gases—extruded polystyrene (XPS) such as Dow Styrofoam of Owens Corning Foamular, and standard closed-cell spray polyurethane foam (SPF). While all insulation materials reduce greenhouse gas emissions (by saving energy), insulating with thick layers of either of these two particular foams results in very long "payback periods" for the global warming potential of the insulation, thwarting even the best attempts to create carbon-neutral buildings. The bottom line is that designers and builders aiming to minimize the global warming impacts of their buildings should choose fiber insulation (cellulose, fiberglass, or mineral wool) or non-HFC foam insulation.

"The more insulation the better" is a common refrain in the green building industry. *EBN* has long advocated very high levels of insulation, particularly in residential and small commercial buildings, which are skin-dominated. At the furthest end of the spectrum is the Passive House movement (see *EBN* Apr. 2010), where it is not uncommon to provide R-50 under a floor slab, R-60 in the walls, and as much as R-100 in the attic. High levels of insulation are seen as a key strategy for achieving net-zero-energy and carbon-neutral performance—the latter meaning that the building will have no net contribution to climate change.

How we achieve high levels of insulation is a very significant issue, however. We rarely pay attention to the fact that insulation materials themselves contribute to greenhouse gas emissions and global warming. This happens in two ways: through the embodied energy of the insulation (the energy use and greenhouse gas emissions that result from manufacturing

*(continued on p. 9)*

Photo: Bensonwood

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

## In This Issue



*Quote of the month:*

**"Specifying a high-GWP insulation completely defeats the point of using it."**

– Scott Shell, FAIA of EHDD Architecture commenting on new information on the global warming potential of insulation materials (page 12)

## Avoiding the Global Warming Impact of Insulation *(from page 1)*

and transporting the material); and, with some foam insulation materials, through the leakage of blowing agents that are highly potent greenhouse gases.

## *Understanding Embodied Energy and GWP*

Researcher Danny Harvey, Ph.D., of the University of Toronto, sounded the alarm about the climatic impacts of blowing agents used in certain foam insulation materials in a technical paper in the August 2007 issue of the journal *Building and Environment*. Daniel Bergey of Building Science Corporation presented a synopsis of Harvey's research at the Northeast Sustainable Energy Association (NESEA) Building Energy Conference in March 2010.

With the help of Bergey and John Straube, Ph.D., P.Eng., of Building Science Corporation, *EBN* reexamined the assumptions Harvey used, included new information about the blowing agents in use today (which differ from what Harvey assumed), and calculated the payback on the lifetime global warming potential (GWP) of insulation materials.

All insulation materials take energy to manufacture and transport—something we refer to as *embodied energy*. We consulted the Inventory of Carbon and Energy (ICE), developed by Geoff Hammond and Craig Jones of the Department of Mechanical Engineering at the University of Bath in the U.K., for values of embodied energy and embodied carbon for different insulation materials. Although its figures are based on European (rather than North American) data on the energy used to produce and transport building materials, ICE offers the most accessible, current information available on embodied energy. Using this data and information about insulation performance, we can calculate the *embodied GWP* of these insulation materials. Currently, ICE does not address blowing agents.

### Blowing agents

When insulation materials are made with halocarbon blowing agents (compounds containing halogens, such as chlorine or fluorine), the GWP of those gases far outweighs the embodied GWP that results from the embodied energy of the insulation materials.

Blowing agents create tiny bubbles of low-conductivity gas in closed-cell foam insulation materials. Chlorofluorocarbons (CFCs) were originally used as blowing agents for polyisocyanurate (polyiso), extruded polystyrene (XPS), and closed-cell spray polyurethane foam (SPF). After it was discovered in the 1970s and '80s how damaging CFCs are to the Earth's protective ozone layer, they were replaced with "second-generation" hydrochlorofluorocarbon (HCFC) blowing agents, which had lower ozone depletion potential (ODP), as required by provisions of the *Montreal Protocol on Substances That Deplete the Ozone Layer.*

These second-generation HCFC blowing agents were required by the Montreal Protocol to be phased out at the beginning of 2010; some have been replaced with "third-generation" HFC blowing agents. While these HFCs have zero ozone depletion potential, they are quite potent greenhouse gases. Initially, there was little focus on this property of halocarbon blowing agents, but concern about GWP of foams is growing. Blowing agents

### Table 1. ODP and GWP Values 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 | 4,750 |
| 2nd Generation | HCFC-141b | 9.3 | 0.11 | 725 |
| 3rd Generation | Pentane, cyclopentane | A few days | 0 | 7[3] |
| **Spray Polyurethane** | | | | |
| Original | CFC-11 | 45 | 1 | 4,750 |
| 2nd Generation | HCFC-141b | 9.3 | 0.11 | 725 |
| 3rd Generation | HFC-245fa | 7.2 | 0 | 1,030 |
| 3rd Generation | $CO_2$ | variable | 0 | 1 |
| **Extruded Polystyrene (XPS)** | | | | |
| Original | CFC-12 | 100 | 1 | 10,900 |
| 2nd Generation | HCFC-142b | 17.9 | 0.065 | 2,310 |
| 3rd Generation | HFC-134a[4] | 13.8 | 0 | 1,430 |

1. Ozone-depletion potential (ODP) 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 EPA using IPCC Fourth Assessment Report values; 100-year time horizon assumed. GWP values are relative to $CO_2$, 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. Despite repeated inquiries, XPS manufacturers declined to say what their post-HCFC blowing agent is, and MSDS information has not been updated; the blowing agent is assumed here to be HFC-134a, though it may be a mix of HFC and hydrocarbon.

used in common foam insulation materials—both historically and today—are shown in Table 1 on previous page.

### Lifetime GWP of insulation materials

By combining information about the GWP of the blowing agent in foam insulation (the quantity used in the foam and assumptions about how much leaks out over time) with the embodied GWP based on the embodied energy, we can calculate the *lifetime GWP* of an insulation material. Lifetime GWP is presented in Table 2 below. The data in this table has been normalized by square-foot R-value (far right column) to provide a common basis for comparison. Note that the values are highly dependent on assumptions; we chose conservative assumptions—key among them the assumption that 50% of the HFC blowing agent in foam will never leak out over the lifetime of the insulation. (Harvey assumed more rapid loss of blowing agents in his analysis.) In our analysis, we don't address the *rate* of loss, per se, only that 50% of the gas will leak out over its *lifetime*—which could be 50 years or 500 years; what happens to the foam during disposal has a significant effect on whether the blowing agent is released into the atmosphere. There is currently very little information on the lifetime of blowing agents in foam insulation; we hope that the U.S. Environmental Protection Agency or manufacturers will conduct research on this issue, which has tremendous bearing on the lifetime GWP of insulation materials.

### Calculating GWP payback

The next step is calculating the "payback" of the lifetime GWP in insulation materials. By reducing heat loss and unwanted heat gain, any insulation material reduces the use of fossil fuels or electricity required for heating and cooling buildings. In so doing, these insulation materials reduce emissions of carbon dioxide ($CO_2$), a greenhouse gas that contributes to global climate change. We want to know how many years of energy savings it will take to *pay back* the lifetime GWP of the insulation to figure out whether it's a good idea to use that insulation material in our low-energy buildings. Another way to think about this is how many years of energy savings will be required to "break even" on the GWP of the insulation.

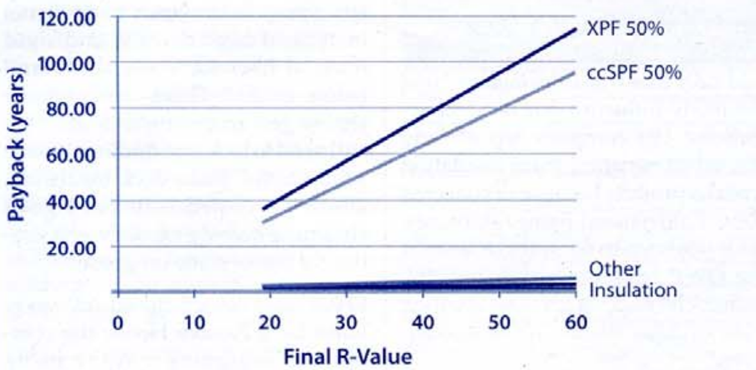
In the graphs on page 11, we have plotted this GWP payback of various insulation materials. These calculations are climate-specific and based on computer modeling. The graphs show the payback of the lifetime GWP of different insulation materials plotted as a function of final R-value in the moderately cold climate of Boston. We assume that

## Table 2. Embodied GWP of Common Insulation Materials

| Insulation Material | R-value R/inch | Density lb/ft³ | Emb. E MJ/kg | Emb. Carbon $kgCO_2/kg$ | Emb. Carbon $kgCO_2/ft^2 \cdot R$ | Blowing Agent (GWP) | Bl. Agent kg/kg foam | Blowing Agent GWP/ bd-ft | Lifetime GWP/ $ft^2 \cdot R$ |
|---|---|---|---|---|---|---|---|---|---|
| Cellulose (dense-pack) | 3.7 | 3.0 | 2.1 | 0.106 | 0.0033 | None | 0 | N/A | 0.0033 |
| Fiberglass batt | 3.3 | 1.0 | 28 | 1.44 | 0.0165 | None | 0 | N/A | 0.0165 |
| Rigid mineral wool | 4.0 | 4.0 | 17 | 1.2 | 0.0455 | None | 0 | N/A | 0.0455 |
| Polyisocyanurate | 6.0 | 1.5 | 72 | 3.0 | 0.0284 | Pentane (GWP=7) | 0.05 | 0.02 | 0.0317 |
| Spray polyurethane foam (SPF) – closed-cell (HFC-blown) | 6.0 | 2.0 | 72 | 3.0 | 0.0379 | HFC-245fa (GWP=1,030) | 0.11 | 8.68 | 1.48 |
| SPF – closed-cell (water-blown) | 5.0 | 2.0 | 72 | 3.0 | 0.0455 | Water ($CO_2$) (GWP=1) | 0 | 0 | 0.0455 |
| SPF – open-cell (water-blown) | 3.7 | 0.5 | 72 | 3.0 | 0.0154 | Water ($CO_2$) (GWP=1) | 0 | 0 | 0.0154 |
| Expanded polystyrene (EPS) | 3.9 | 1.0 | 89 | 2.5 | 0.0307 | Pentane (GWP=7) | 0.06 | 0.02 | 0.036 |
| Extruded polystyrene (XPS) | 5.0 | 2.0 | 89 | 2.5 | 0.0379 | HFC-134a[1] (GWP=1,430) | 0.08 | 8.67 | 1.77 |

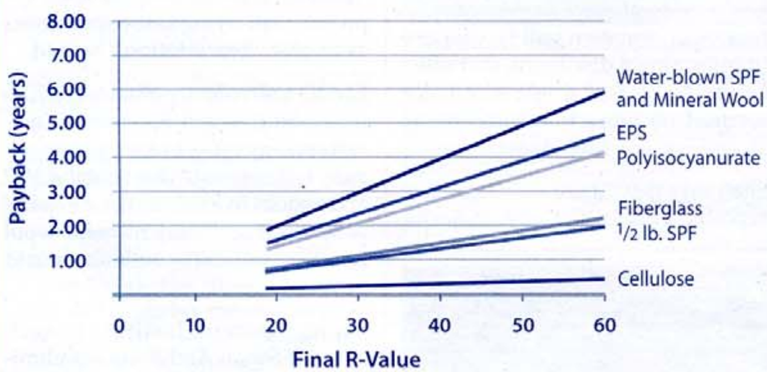
1. XPS manufacturers have not divulged their post-HCFC blowing agent, and MSDS data have not been updated. The blowing agent is assumed here to be HFC-134a.

## Figure 1. Lifetime GWP Payback XPS & SPF




*The lifetime GWP payback of extruded polystyrene (XPS) and standard closed-cell spray polyurethane foam (SPF), both of which are produced with HFC blowing agents, compared with other insulation materials. The analysis assumes that 50% of the blowing agent is lost over the life of the material.*

## Figure 2. Lifetime GWP Payback – Other Insulation




*The lifetime GWP payback of various non-HFC insulation materials shown at a scale allowing comparison. In this analysis, closed-cell, water-blown SPF and rigid mineral wool are nearly identical, so those graphs cannot be distinguished.*

heat is provided by a 90%-efficient gas furnace, and we do not account for any change to airtightness as a result of adding insulation. To provide a consistent basis of comparison, we assume that the insulation in question is added to a 2x6 wall insulated with fiberglass insulation (whole-wall R-value of R-14). This is a common application for foam insulation materials, though not for fiber insulation materials, such as fiberglass and cellulose.

The results show, first of all, that the GWP payback is very rapid for all insulation materials that are produced without HFC blowing agents. In adding R-25 of polyiso (about 4 inches) to an insulated 2x6 wall, for example, the payback of the lifetime GWP of the polyiso is about 2.7 years; going all the way to R-60 with 7.5 inches of polyiso would increase that GWP payback to only slightly over 4 years. With cellulose, the GWP payback is always less than one year, even at R-60.

With XPS and standard closed-cell SPF (produced with HFC-245fa), the GWP payback is much longer. With one added inch of XPS (R-5) the GWP payback is about 36 years; with two inches, the payback is 46 years; and with four inches the payback jumps to 65 years. Adding the same R-value increments of standard closed-cell SPF yields GWP paybacks of 30, 38, and 54 years respectively. (Because the R-value per inch of this SPF is somewhat higher than R-5/inch, those GWP paybacks result from somewhat thinner layers.)

Assumptions are key in this analysis. In a climate colder than Boston's, the energy savings from the insulation will be greater, so the time required to pay back the lifetime GWP of the insulation will be shorter. In a warmer climate, the payback will be longer. If we were to assume that 100% of the HFC blowing agent leaks out over the life of the insulation, the payback periods of XPS and standard SPF would nearly double.

### Assessment of the *Incremental* GWP Payback from Added Insulation

In his original journal article in *Building and Environment,* Harvey examined not only the global warming payback of insulation materials on a *total* basis (examining the payback from the lifetime GWP of the entire amount of insulation in the system) but also the *incremental* GWP payback from adding insulation. In the latter analysis, he models the energy savings for lifetime GWP of the last increment of insulation—and the results are far more dramatic: paybacks in the hundreds of years for high-R-value increments. Building science experts John Straube and Terry Brennan argued that this is a flawed approach. "You need to look at the overall package, not the marginal," Brennan told *EBN*. Life-cycle assessment (LCA) expert Greg Norris agreed that the focus on total insulation was more appropriate than on marginal additions of insulation. For this reason, we are presenting only results that show the payback on the total insulation.

## What This Means for the Way We Build

*EBN* spoke with several environmentally concerned designers and builders about the issue of GWP payback of insulation materials. Even though it's a complex and confusing issue, we found that interest is strong (at least among this subset of the building industry), and the information could significantly change building practices.

According to Scott Shell, FAIA, a principal at EHDD Architecture in San Francisco, "combating global warming is the most critical issue, and specifying a high-GWP insulation completely defeats the point of using it." Shell told *EBN* that he had become aware of this issue and his company is "moving aggressively to eliminate these [HFC-blown foams] on all of our projects."

"This information will influence our product selection profoundly," says David Foley, of Holland and Foley Architecture in Northport, Maine. "We do what we do for many reasons, but anthropogenic climate change is among the most important," he told *EBN*. "Talk about an inconvenient truth!"

Larry Strain, FAIA, of Siegel & Strain Architects in Emeryville, California, told *EBN* that this information "will definitely influence our product selection." His company has already started eliminating foam insulation from its projects because of concerns about halogenated flame retardants. "If it takes up to 60 years to recover the GWP from manufacturing the foams," he said, "it gives us another, even stronger, reason to find alternatives."

Nico Kienzl, of the environmental design consulting and lighting design firm Atelier Ten in New York City, told *EBN* that his firm has looked qualitatively at embodied energy and GWP in the past, and that has influenced what the company recommends ("our preferred choice being mineral wool"). "More quantitative information will be valuable in informing a discussion that often seems to be too single-mindedly focused on more insulation being always better," Kienzl said.

Shell says that "there are reasonable replacements in the vast majority of cases: polyiso for roof insulation, dense-pack cellulose or low-density spray foam (such as Icynene) instead of high-density, and rigid mineral fiber for walls above and below grade." There remain some challenges, according to Shell. "We still need to look into finding suitable products for plaza deck insulation, where paver pedestals need good structural bearing capacity; and similar for below slabs-on-grade."

EHDD just vetoed closed-cell spray foam for a Passive House the company is designing. "We're using Icynene in the framed floor over a crawl space, and dense-pack cellulose in walls and ceilings," said Shell. Rather than relying on SPF for air sealing on walls, Shell is sealing the joints of exterior sheathing with a self-adhered flashing, such as Vycor (from Grace Construction Products). "This is a better and cheaper approach than trying to use spray foam as an all-in-one solution," he said.

EHDD also recently eliminated XPS from the Packard Foundation net-zero-energy office building the company is designing," due to high GWP and toxics." In its place, the company is specifying Roxul mineral wool (see *EBN* Oct. 2009) both above and below grade.

On its Yosemite Institute project, Siegel & Strain Architects has eliminated almost all foam, except under slab and slab edge. "We may take another look at that now as well," says Strain.

Tedd Benson, president of Bensonwood in Walpole, New Hampshire, and a well-known leader in the timber-frame construction field, has been refining insulation systems for decades. "We have been trying to make our production more efficient and simultaneously improve the performance and environmental characteristics of our wall and roof systems," Benson told *EBN*. The company's current wall system—the OBPlus Wall—is the latest in

Photo: John Straube

*John Straube used a tongue-and-groove EPS instead of XPS for insulating beneath the concrete slab in a deep-energy retrofit of his home.*

that evolutionary process, relying entirely on cellulose insulation between wood I-studs. "We didn't have the benefit of your research when we developed the OBPlus Wall," says Benson, "but I was happy to see that we look even wiser now than we thought we were." The company's foam insulation decisions are focused on the use of SIPs on some of its roof assemblies and below-grade requirements. "Your article will definitely guide us toward better decisions in these areas."

Paul Eldrenkamp, of the residential remodeling company Byggmeister, in Newton, Massachusetts, and a Passive House consultant, had already been moving away from SPF when he heard Daniel Bergey's presentation at the NESEA Building Energy conference. He had done this for three reasons:

> First, spray foam (open-cell certainly, but also closed-cell) is much harder to install well than most people realize. We only began to understand this after we started testing every insulation job with a blower door. Second, installers do not protect themselves anywhere near well enough from the side effects of frequent exposure to the material before it's fully cured. And third, the high fossil fuel content probably means the price of spray foam will track the price of petroleum, whereas cellulose, for instance, will likely always be a fraction of the cost of spray foam for a given R-value—so we shouldn't forget how to insulate with cellulose.

Eldrenkamp notes that his company still does use a small amount of closed-cell SPF for strategic air sealing. "We believe that CCSF [closed-cell SPF] is uniquely effective and appropriate in old basements," he told *EBN*. "We have done one deep-energy retrofit in which we sprayed CCSF on the exterior cladding before adding new cladding; we've decided that, going forward, we'll strip the cladding and apply rigid PIR [polyiso] instead."

## Avoiding High-GWP Insulation Materials

| APPLICATION | ALTERNATIVE |
|---|---|
| **Alternatives to extruded polystyrene (XPS)** | |
| Wall sheathing | Polyisocyanurate installed on exterior or interior |
| | Expanded polystyrene (EPS) – higher-density recommended for greater compressive strength |
| | Avoid insulative sheathing; use cavity-fill insulation with control of thermal bridging (offset studs, etc.) and a separate air barrier |
| Below-grade foundation walls | High-density EPS on exterior |
| | High-density rigid mineral wool or rigid fiberglass on exterior |
| | Interior insulation (polyiso, rigid mineral wool, other fiber insulation) |
| Below-grade sub-slab | Rigid mineral wool if compressive strength is adequate (confirm with structural engineer) |
| | Foamglas (significant cost increase) |
| | EPS – some suggest a minimum 1.5 lb/ft$^3$ density for compressive strength and moisture resistance (may be difficult to find) |
| Roof sheathing (below membrane) | Polyisocyanurate |
| Roof – inverted membrane | Foamglas (significant cost increase) |
| **Alternatives to spray polyurethane foam (SPF) made with HFC-245fa blowing agent** | |
| Wall and roof cavity | Open-cell SPF (increased thickness to achieve comparable R-value) |
| | Cavity-fill fiber insulation (increased thickness to achieve comparable R-value) |
| Envelope air-sealing layer | Water-blown open-cell SPF or thin layer of closed-cell SPF with cavity-fill insulation |
| | Provide air barrier with separate layer, such as exterior panel sheathing with self-adhered flashing or tape over joints |
| Interior insulation over rough foundation wall | Water-blown closed-cell SPF (installation problems have been reported with water-blown formulations; obtain performance guarantee and inspect carefully for shrinkage or adherence problems). |

### *Other Concerns With XPS and SPF*

Along with the global warming potential of the HFC blowing agents in XPS and standard closed-cell SPF, there is also the issue of flame retardants. All foam insulation materials today are made with halogenated (chlorine- or bromine-based) flame retardants, and there is increasing concern about the health and environmental impacts of these compounds (see "Polystyrene Insulation: Does it Belong in a Green Building?" in *EBN* Aug. 2009 and "Flame Retardants Under Fire" in *EBN* June 2004).

If we replace HFC-blown foam insulation materials with fiber insulation alternatives, such as dense-pack cellulose installed in double-wall or Larsen-truss (curtain-truss) wall system, we can avoid the use of halogenated flame retardants. We can also continue pushing for foam insulation manufacturing to shift to safer, phosphorous-based flame retardants and composite manufacturing with layers that are fire-proof. While the foam insulation industry is transitioning to blowing agents that do not contribute significantly to global warming, it should also focus on addressing this other concern.

Other issues with SPF are quality control during installation and potential performance problems, particularly with the relatively new water-blown alternatives to HFC-blown SPF. With SPF insulation, the installer is essentially *manufacturing* the insulation in place. The process involves precisely mixing two components at the right temperatures and allowing the material to expand and cure (a process that uses water vapor from the air). Because curing SPF is an exothermic (heat-generating) reaction, manufacturers recommend installing no more than two inches (50 mm) at one time—and this is very hard to control, particularly in a cavity between framing members that are close together. If the foam builds up significantly thicker than two inches, there is potential for problems, such as offgassing of harmful chemicals or improper adherence or shrinkage. In short, proper installation of SPF requires a highly skilled installer and, even then, there are risks of performance and offgassing problems that are not well understood.

## The Future of Foam Insulation

Manufacturers are working to develop and deploy *fourth-generation* blowing agents that have zero or very low GWP while still providing the various performance and safety properties that are required. Such developments would alter the conclusions of this article. Both Dupont and Honeywell are working on hydrofluoroalefin (HFO) blowing agents. At the 2010 NESEA Building Energy Conference, Gary Loh of DuPont described a zero-ODP, low-GWP (less than 10), nonflammable, low-conductivity blowing agent, for SPF, FEA-1100, that is currently undergoing toxicity testing and should be introduced (if toxicity testing continues to demonstrate safety) sometime between 2013 and 2015. Honeywell already has a similar product on the market in Europe for one-component polyurethane foams (HFO-1234ze) and expects to broaden its family of HFO blowing agents. When these new products replace the HFC-blown insulations in the coming years, the argument for avoiding SPF and XPS on the basis of lifetime GWP should largely disappear. By then, manufacturers may also have replaced the halogenated flame retardants with safer compounds. Until that time, however, there are good reasons to limit use of XPS and closed-cell SPF.

## Final Thoughts

If our goal is to create buildings that have little or no net contribution to global warming, then the lifetime GWP of insulation materials is a key consideration. When designing highly insulated buildings or carrying out deep-energy retrofits (a top priority of green building and renovating), we should avoid insulation materials with high GWP—extruded polystyrene and spray polyurethane foam that is made with HFC-245fa—so that we aren't sacrificing the very environmental benefits we're trying to achieve. The table on page 13 lists some of these options.

Furthermore, the GWP of foam insulation materials is high enough (especially earlier-generation materials made with CFCs and HCFCs) that it may even make sense to consider the *capture and thermal degradation* of these blowing agents during building demolition. In the early 1990s, Northeast Utilities in Connecticut had a program to recover and thermally destroy the CFC blowing agents in the polyurethane insulation recovered from refrigerators that were turned in through an appliance rebate program. That program was implemented to prevent ozone depletion, but such a program could apply as well to greenhouse gas emissions. Most of the XPS, SPF, and even polyiso currently in place was produced with CFC or HCFC blowing agents with significantly higher GWP values than today's blowing agents, so there are considerable quantities of high-GWP foam "banked" in existing buildings, even accounting for leakage over the years.

As we consider alternatives to XPS and standard SPF, we should try to avoid options that reduce overall insulation levels. Achieving very high R-values in our building envelopes should remain a top priority of green design. In most applications, high R-values can be achieved without using high-GWP foams through thoughtful product specification or changes to construction details with little or no increase in construction cost. There remain challenging applications, however, such as sub-slab insulation, where affordable alternatives to XPS simply may not exist or where building officials balk at the alternatives.

In making these product substitutions or altering our construction details to avoid XPS or SPF, we should also pay careful attention to long-term durability. XPS and SPF have some very attractive properties relative to permeability and air barrier performance. In some cases, adding more complex framing systems, such as double-stud framing in residential construction, can create durability problems. If unsure about proper moisture management with new wall systems, seek advice from a knowledgeable building science expert.

### For more information:

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

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